Guide to

Selection and application of flowmeters for the measurement of fluid flow in closed conduits

Committees responsible for this British Standard

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Electricity Supply Industry in United Kingdom
Energy Industries Council
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Contents

Foreword

This British Standard has been prepared under the direction of the Industrial-process Measurement and Control Standards Policy Committee.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i to viii, pages 1 to 250, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

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Section 1. General

1.0 Introduction

Flow measurement is one of the most important of all process measurements. Millions of pounds worth of fluids are bought and sold each day, with the value being determined by flow measurement. The control of chemical and other process plants also relies heavily on the performance of a wide range of different types of flowmeters. Every year new designs and advances in applications extend the duties where flowmeters can be used. Meters are now available to operate with good reliability at high pressures, at high and low temperatures and with aggressive fluids. There are also many publications on flowmeter applications that appear in numerous journals which show that no single flowmeter is suitable for every application.

1.1 Scope

This British Standard provides guidance on the selection and application of flowmeters. It classifies them into ten major groups and covers the basic operating principles and application of each group. Also included is information on secondary instrumentation and some aspects of flowmeter calibration. The scope is restricted to closed conduit measurements in circular or non-circular cross section and therefore open channel systems are not included in the guide.

A bibliography containing details of the references in the text, is given in Appendix A.

NOTE The titles of the publications referred to in this standard are listed on the inside back cover.

1.2 Definitions

For the purpose of this standard the definitions given in BS 5875 apply, together with the following.

1.2.1 Flowmeter related terms

1.2.1.1
flowmeter

a flow measuring device which indicates the measured flow rate

NOTE The English language also uses the term flowmeter for a device that indicates the total amount of fluid passed during a selected time interval.

1.2.1.2
primary device

a device which generates a signal enabling the flow rate to be determined. Depending on the principle used, the primary device can be internal or external to the conduit

1.2.1.3
secondary device

a device which receives from the primary device a signal and displays, records, converts and/or transmits it as a measure of the flow rate

1.2.1.4
auxiliary device

a device which enables the necessary ancillary measurements to be carried out in flow measurement systems to determine the value of such factors as pressure, pressure difference, temperature and humidity

1.2.2 Fluid related terms

1.2.2.1
flow rate

the quantity of fluid passing through the cross-section of a conduit in a short period of time, divided by that time

1.2.2.2
volume flow rate

flow rate in which the quantity of fluid is expressed as a volume

1.2.2.3
volume flow

the volume of fluid that has passed through a cross section of a conduit over a period of time

NOTE Some types of meter indicate this quantity directly and are therefore commonly called quantity meters or bulk meters. Volume flow can also be obtained by integrating the flow rate signal from other types of meter over a known period of time. Thus flow rate meters can be made to indicate total volume flow passed with the use of suitable secondary devices.

1.2.2.4
mass flow rate

flow rate in which the quantity of fluid is expressed as a mass

NOTE There are no flowmeters that indicate total mass flow in the same way that positive displacement meters indicate total volume flow. The total mass passed can only be obtained from integrating the mass flow rate over a period of time.

1.2.2.5
compressibility factor

correction factor expressing numerically the deviation from the ideal gas law of the behaviour of a real gas under given pressure and temperature conditions

NOTE The correction factor, Z, is given by the following formula:

$$Z = \frac{pM}{\rho RT}$$

1.2.2.6
mean axial fluid velocity

the volume flow rate divided by the area of the cross section

1.2.2.7
point or local velocity

the velocity measured at a discrete point in the cross section of the conduit

1.2.3 Performance related terms

1.2.3.1
accuracy

the qualitative expression for the closeness of a measured value to the true value

NOTE The quantitative expression of accuracy should be in terms of uncertainty. Good accuracy implies small random and systematic errors.

1.2.3.2
repeatability (of a measurement)

the quantitative expression of the closeness of agreement between successive measurements of the same value of the same quantity carried out by the same method with the same measuring instrument at the same location at appropriately short intervals of time

1.2.3.3
repeatability (of a measuring instrument)

the quantity which characterizes the ability of a measuring instrument to give identical indications or responses for repeated applications of the same value of the quantity measured under stated conditions of use

1.2.3.4
linearity of a meter

the deviation (within preset limits) of a flowmeter's performance from the ideal straight line relationship between meter output and flow rate

1.2.3.5
uncertainty

an estimate characterizing the range of values within which the true value of a measurand lies

1.2.3.6
rangeability (turndown)

the ratio of the specified maximum to minimum flow rates

1.2.3.7
meter factor

the number of pulses generated per unit volume of fluid metered

1.3 Symbols

For the purpose of this standard the symbols given in Table 1.1 apply.

Table 1.1 — Symbols

Symbol	Represented quantity	Dimensions M: Mass L: Length T: Time θ: Temperature I: Electric current	SI unit
A	Cross-sectional area of the conduit under operating conditions	L^2	m^2
B	Magnetic flux density	$MT^{-2} I^{-1}$	tesla (T)
c	Velocity of sound in a medium	LT^{-1}	m/s
C	Discharge coefficient	dimensionless	
d	Orifice diameter or throat of primary element at operating conditions; diameter of head of a Pitot tube	L	m
d_r	Orifice diameter or throat of primary element at reference conditions	L	m
D	Diameter of the circular cross section of the conduit at operating conditions	L	m
D_m	Nominal meter bore	L	m
f	Frequency output of turbine	T^{-1}	Hz
g	Acceleration of free fall due to gravity	LT^{-2}	m/s^2
K	Calibration factor	L	m
K_m	Meter factor	L^{-3}	$pulses/m^3$
L_e	Distance between measuring electrodes	L	m
M	Molar mass of fluid	M	kg/mol
p	Absolute static pressure of the fluid	$ML^{-1} T^{-2}$	Pa
p_o	Stagnation or total pressure	$ML^{-1} T^{-2}$	Pa
Δp	Differential pressure	$ML^{-1} T^{-2}$	Pa
q_m	Mass flow rate	MT^{-1}	kg/s
q_v	Volume flow rate	L^3T^{-1}	m^3/s
r	Radius of the conduit	L	m
R	Universal gas constant	$L^2 T^{-2} \theta^{-1}$	J/kg·k
Re	Reynolds number	dimensionless	
Re_D	Reynolds number based on conduit dimensions	dimensionless	
t	Temperature of primary device at flowing conditions	θ	K
t_r	Temperature of primary device at reference conditions	θ	K
T	Fluid absolute temperature	θ	K
u	Velocity of fluid	LT^{-1}	m/s
U	Mean axial fluid velocity	LT^{-1}	m/s
V	Flow signal (E.M.F.)	$L^2 MT^{-3} I^{-1}$	V
v	Local velocity of fluid	LT^{-1}	m/s
Z	Compressibility factor	dimensionless	
β	Diameter ratio, $\beta = \frac{d}{D}$	dimensionless	
ϵ	Expansibility (expansion) factor	dimensionless	
κ	Isentropic exponent	dimensionless	
λ	Linear expansion coefficient of primary device material	$L \theta^{-1}$	m/k
ν	Kinematic viscosity of the fluid	L^2T^{-1}	m^2/s
ρ	Density of the fluid	ML^{-3}	kg/m^3
τ	Period of vibration	T	s
ω	Angular velocity	T^{-1}	rad/s

Table 1.1 — Symbols

Symbol	Represented quantity	Dimensions M: Mass L: Length T: Time θ: Temperature I: Electric current	SI unit
Subscripts			
Symbol	**Quantifying**		
1	Upstream		
2	Downstream		
r	Reference conditions		
c	Centreline		
NOTE Other symbols used in this standard are defined at their place of use.			

1.4 Flowmeter classification

There are many different types of flowmeter available commercially. No one meter type is ideal for all applications and skill and knowledge is required to select the appropriate meter for a particular application. As there is a need to cover a wide range of industrial and research applications, several main operating principles have evolved. These operating principles conveniently form the basis for classifying flowmeters. Flowmeters considered in this standard are arranged in ten major closed conduit groups, as given in Table 1.2.

Table 1.2 — Flowmeter classification

Group	Description
1	Orifices, venturis and nozzles
2	Other differential pressure types
3	Positive displacement types
4	Rotary turbine types
5	Fluid oscillatory types
6	Electromagnetic types
7	Ultrasonic types
8	Direct and indirect mass types
9	Thermal types
10	Miscellaneous types

Table 1.3 gives a detailed listing of the metering technologies covered in this guide and the group into which they have been placed. The group number has also been used to designate clause numbers in sections 3 and 4, enabling the reader to locate information quickly.

Table 1.3 — Group designations of flowmeters

Group[a]	Metering technology
1	*Conventional differential pressure types* Sharp edged concentric orifice (corner tapping, *D* and *D*/2 pressure tapping and flange tapping designs) Venturi tubes (classical venturi tube and venturi-nozzle) Flow nozzles (ISA and long radius designs)
2	*Other differential pressure types* Annular orifice Eccentric or segmental orifice Integral orifice Gentile tube Spring loaded aperture meters Elbow meter Linear resistance meter Dall tube Proprietary flow nozzles Multi-port averaging pitots Wedge meter Pitot tube Variable area flowmeter Target meter Sonic nozzles Conical entrance and $\frac{1}{4}$ circle orifice plates
3	*Positive displacement types* Reciprocating piston Sliding vane Nutating disc Bi- and tri-rotor designs Roots type meters Diaphragm meters Rotary piston Oval gear Helical rotor meter Liquid metering pumps Wet gas meters Bellows meters
4	*Rotary turbine type meters* Axial turbine meter Mechanical helix meter Bearingless turbine Propeller meters Insertion turbine Twin rotor turbine meter Multi jet or vane type meter Pelton wheels Cup anemometers
5	*Fluid oscillatory types* Vortex shedding meter Swirlmeter Insertion vortex Fluidic oscillator Fluid deflection meter

Table 1.3 — Group designations of flowmeters

Group[a]	Metering technology
6	*Electromagnetic types* a.c. types d.c. types Velocity probe types
7	*Ultrasonic types* Time-of-flight meters Sing-around Reflex meters Doppler meters Long wave acoustic
8	*Direct and indirect mass types* Indirect methods Angular momentum turbine Parallel venturi Gyroscopic meter Driven angular momentum Coriolis type Wheatstone bridge
9	*Thermal types* Heat loss types Hot wire film anemometers Thermal profile meters Calorimetric heat grid
10	*Miscellaneous types* Cross correlation meters Nuclear magnetic resonance Gas ionization Laser anemometer Tracer injection meters Weighting methods Velocity area techniques

[a] For group description see Table 1.2.

1.5 Proprietary names

Some types of flowmeters are known by their trade names, particularly where there is only one manufacturer of a particular design. Examples are Gilflo® (a linear differential pressure device) and Hoverflo® (a bearingless turbine type meter), etc. The inclusion of any trade name is not an endorsement of the meters by either this Guide or the British Standards Institution.

NOTE The following trade names are used within the standard.
"Dall tube" is the registered trade mark of ABB-Kent plc
"Rotary Shunt" is the registered trade mark of ABB-Kent plc
"Litre Meter" is the registered trade mark of Litre-meter Ltd
"Rotameter" is the registered trade mark of KDG Mobrey Ltd
"Gilflo" is the registered trade mark of Gervase Instruments Ltd
"Wedge meter" is the registered trade mark of ABB-Kent plc
"Roots meter" is the registered trade mark of Dresser Industries Inc
"Hoverflo" is the registered trade mark of B. Rhodes & Son Ltd
"Swirlmeter" is the registered trade mark of Fischer & Porter Co.
"Hastings" is the registered trade mark of Teledyne Hastings — Raydist Inc.

Section 2. General selection procedure

2.0 Introduction

The selection of a flowmeter for a required duty is complex and the consequences of an incorrect selection are loss of performance, time and money, with the possibility of damage to the equipment and installation. This section makes use of figures and tables to indicate (by a process of elimination) those metering techniques which do not match the user's application.

The aim is to restrict the choice of meter(s) to those that meet or nearly meet the requirements. If the latter point is reached then reference to the manufacturer may well provide a solution by the manufacture of a special version of the meter, which may be a simple modification.

The selection procedure can also act as a checklist to the experienced flowmeter user to ensure that all variables have been considered. In difficult cases it may be found necessary to consult with a flowmeter manufacturer or an independent evaluation authority.

The starting point of the selection is the consideration of the type of fluid to be metered, i.e. liquid, gas or miscellaneous fluid (see Table 2.1). The procedure is then to examine in more detail the five basic areas which define the application, as follows:

a) performance considerations (see **2.0**)

b) fluid property considerations (see **2.3**)

c) installation and maintenance considerations (see **2.4**)

d) environmental considerations (see **2.5**)

e) economic considerations (see **2.6**)

Within each basic area are a number of factors that have to be taken into account when considering a flowmeter specification (see Table 2.3 to Table 2.7 inclusive). It is recommended that the factors be reviewed together since the five areas are interactive. This is discussed further by Bailey (1980) and Spitzer (1984).

NOTE In basic meter selection not only should normal process conditions be considered but also extraordinary conditions should also be taken into account. These could include cleaning procedures, shut down, purging and other processes which occur on an occasional basis and which may have an adverse effect on the meter.

2.1 Basic meter selection

To select a flowmeter for a specific application, it is necessary to use a process of elimination, when the requirement of the application is compared with the published specification for all meters. When a meter specification does not meet the requirement of the application in one of the five listed areas, it is eliminated from the selection process.

NOTE It is important that the application is defined comprehensively, Table 2.2 should be used to ensure that all relevant factors are considered.

Table 2.1 — Broad areas of application

		Application																	
		Liquids (see note 1)								Gases (see note 2)					Miscellaneous (see note 3)				
Group	**Type**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**J**	**K**	**L**	**M**	**N**	**P**	**Q**	**R**	**S**	**T**
1	Orifice	✓	?	✓	✓	✓	✓	✓		✓	?	✓	✓	✓	?	✓	?	?	?
	Venturi	✓		✓	✓	✓	✓			✓	?		?	?	?	✓	?	?	?
	Nozzle	✓		✓	✓	✓	✓			✓	✓	?	?	✓	?	✓	?	?	?
2	VA	✓	✓			#	?		✓	✓	✓							?	
	Target	✓				#				✓				✓	?	✓	?		
	Averaging pitot	✓		✓	✓	✓	?	✓		✓		✓	✓	✓		✓	?	?	?
	Sonic nozzle									✓	✓	?	?						
3	Sliding vane	✓		#			✓		✓							?			
	Oval gear	✓	✓	#		#	✓		✓							?		✓	
	Rotary piston	✓	?			#	✓		✓							?		#	
	Gas diaphragm									✓	✓								
	Rotary gas									✓	✓								
4	Turbine	✓		✓	#	✓	?	✓	✓	✓		✓				?	?	#	
	Pelton	✓	✓			✓		✓		?	?					?		?	
	Mechanical meter	✓													#	?			
	Insertion turbine	✓		✓	✓	✓		✓		✓		✓	✓	?		?	?		
5	Vortex	✓				✓		✓	✓	✓		?	✓	✓		?			
	Swirlmeter	✓								✓									
	Insertion vortex	✓		✓	✓	?		?	?	✓		✓	?	✓		✓		?	?
6	Electromagnetic	✓	✓	✓	✓	#	?		✓						✓	✓	?	✓	
	Insertion electromagnetic	✓		✓	✓	?			✓						?	✓	?	✓	
7	Doppler	✓		?	?	#			?						✓	✓	?	?	
	Transit time	✓	?	✓	✓	#	?	#	✓	#					?	?		#	#
8	Coriolis (direct)	✓				#	✓		✓	?					?	?		#	
	Twin rotor (indirect)	✓																	
9	Anemometer	✓		?	?	#				✓									
	Thermal mass		#							✓	✓								
10	Tracer	✓	#	✓	✓	✓	✓	✓		#		#	✓	✓		?	✓	#	#
	Laser	✓		?	?														

Key

✓ is suitable; generally applicable
? is worth considering; sometimes applicable
is worth considering, limited availability or tends to be expensive
A blank indicates unsuitable; not applicable

NOTE 1 Liquid applications are indicated by the following:
- A General liquid application (< 50 cP) (< 0.05 Pa·s)
- B Low liquid flows (< 0.12 m^3/h) (< 2 L/min)
- C Large liquid flows (> 1 000 m^3/h) (> 1.7×10^4 L/min)
- D Large water pipes (> 0.5 m bore)
- E Hot liquids (temperatures > 200 °C)
- F Viscous liquids (> 50 cP) (> 0.05 Pa·s)
- G Cryogenic liquids
- H Hygienic liquids

NOTE 2 Gas applications are indicated by the following:
- J General gas applications
- K Low gas flows (> 150 m^3/h)
- L Large gas flows (> 5 000 m^3/h)
- M Hot gases (temperatures < 200 °C)
- N Steam

NOTE 3 Miscellaneous applications are indicated by the following:
- P Slurries and particle flows
- Q Liquid/liquid mixtures
- R Liquid gas mixtures
- S Corrosive liquids
- T Corrosive gases

Table 2.2 — Selection procedure variables

Performance considerations	Accuracy Repeatability Linearity Rangeability (turndown) Pressure drop Output signal characteristics Response time Uncertainty
Installation considerations	Orientation Flow direction Upstream and downstream pipework Line size Location for servicing Effects of local vibration Location of valves Electrical connections Provision of accessories (e.g. filters, straighteners, air eliminators, pressure and temperature transducers) Hazardous atmospheres Effect of pulsations/unsteady flow
Fluid property considerations	Liquid or gas Temperature Pressure Density Specific gravity Viscosity Lubricity Chemical properties Surface tension Compressibility Real gas effects Abrasiveness Presence of other phases Presence of other components
Environmental considerations	Ambient temperature effects Humidity effects Safety factors Pressure effects Electrical interference
Economic considerations	Purchase price Installation costs Operation costs Maintenance costs Calibration costs Meter life Spares cost and availability Pumping power and headloss Technical optimization[a]
[a] See (a) and (b) of Figure 2.5.	

The first consideration is the area of application. Table 2.1 lists 18 typical applications, broken down into the three major categories of liquid, gas and miscellaneous applications. This shows whether the more commonly available meters from each group are applicable. In the table, a ✓ indicates that a meter is generally suitable, a ? indicates three possible options:

a) further thought should be given;

b) checking is required as there is often doubt that the requirement can be met;

c) other types in the group may be suitable.

A blank space in the table indicates that the type of meter considered is generally not suitable for the application. This table allows groups of meters that are clearly unsuitable to be eliminated, to give a short list of meter types to be considered further. An example of each would be that electromagnetic flowmeters (group 6) cannot be used on gases (applications J to N) because they need a conducting fluid and thermal mass meters (group 9) cannot be used on liquids (applications A to H) because they are available only for gas applications. Those meter types remaining in the short list can then be evaluated in detail in the five areas listed in **2.0**.

Table 2.2 gives a detailed list of the factors that require consideration when evaluating those meters still present in the list of possibles. More detailed information on each of these factors can be found in **2.2** to **2.6**. The tables and figures presented are for general guidance only and in some cases do not indicate the variations that occur between types of meter within a group or even variations between manufacturers for the same types of meter. Hayward (1979) also gives a comprehensive applications data table.

The initial requirements of the application may be so restrictive that the initial specification may need to be relaxed to enable suitable methods to be identified. It is important in specifying a flowmeter not to ask for a feature that is clearly difficult to achieve. For example, a flow range in excess of 100 : 1 is normally not required in an industrial application. If this is retained in the specification when clearly not needed, the meter chosen may not be ideal compared to one selected with a less stringent specification. Poor initial specification of the application could result in a meter being chosen which is far from ideal. Under-specifying could lead to a meter being chosen which is actually unsuitable and over-specifying could lead to an expensive meter being used where a cheaper alternative would have fulfilled the application.

Unfortunately we have yet to find the universal flowmeter and often the final choice is a compromise between several influencing factors [see for example Grebe (1984), Hayward (1975, 1982) or DeCarlo (1984)]. Flowmeter systems usually consist of primary and secondary devices and auxiliary instrumentation. The selection should therefore be made on a system basis and not merely limited to the characteristics of the primary device. One area not listed in Table 2.2 is personal preference. In some cases this may dominate the selection. Where quantities of one particular type of meter have been used in one application with generally good success, the selection of meters for another application may be influenced by this fact. This may or may not result in the optimum meter being chosen for the new application.

Table 2.3 — Performance factors in meter selection

Group	Type	Linearity (%)	Repeatability (%)	Rangeability	Pressure[a] drop at maximum flow	Flow parameter measured	Response time
1	Orifice	#	#	3 or 4 : 1	3/4	*R*	#
	Venturi	#	#	3 or 4 : 1	2	*R*	#
	Nozzle	#	#	3 or 4 : 1	2/3	*R*	#
2	Variable area	± 1 % *FS* to ± 5 % *FS*	± 0.5 % *FS* to ± 1 % *FS*	10 : 1	3	*R*	No data
	Target	NS	NS	3 : 1	3	*R*	NS
	Averaging pitot	#	± 0.05 % *R* to ± 0.2 % *R*	#	1/2	V_m	#
	Sonic nozzle	± 0.25 %	± 0.1 %	100 : 1	3/4	*R*	NS
3	Sliding vane	± 0.1 % *R* to ± 0.3 % *R*	± 0.01 % *R* to ± 0.5 % *R*	10 to 20 : 1	4/5	*T*	> 0.5 s
	Oval gear	± 0.25 % *R*	± 0.05 *R* to ± 0.1 % *R*		4	*T*	< 0.5 s
	Rotary piston	± 0.5 % *R* to ± 1 % *R*	± 0.2 % *R*	10 to 250 : 1	4/5	*T*	> 0.5 s
	Gas diaphragm	No data	No data	100 : 1	2	*T*	> 0.5 s
	Rotary gas	± 1 %	± 0.2 %	25 : 1	2	*T*	> 0.5 s
4	Turbine	± 0.15 % *R* to ± 1 % *R*	± 0.02 % *R* to ± 0.5 % *R*	5 to 10 : 1	3	*R*	5 ms to 25 ms
	Pelton	± 0.25 % *R* to ± 2 % *R*	± 0.1 % *R* to ± 0.25 % *R*	4 to 10 : 1	4	*R*	5 ms to 25 ms
	Mechanical meter	No data	± 1 % *FS*	10 to 280 : 1	3	*R*	50 ms
	Insertion turbine	± 0.25 % *R* to ± 5 % *R*	± 0.1 % *R* to ± 2 % *R*	10 to 40 : 1	1/2	V_p	5 ms to 25 ms
5	Vortex	± 1 % *R*	± 0.1 % *R* to ± 1 % *R*	4 to 40 : 1	3	*R*	0.5 s minimum
	Swirlmeter	< ± 2 % *R*	NS	10 to 30 : 1	3	*R*	NS
	Insertion vortex	± 2 %	± 0.1 % *R*	15 to 30 : 1	1	V_p	5 ms
6	Electromagnetic	± 0.5 % *R* to ± 1 % *R*	± 0.1 % *R* to ± 0.2 % *FS*	10 to l00 : 1	1	*R*	> 0.2 s
	Insertion electromagnetic	± 2.5 % *R* to ± 4 % *R*	± 0.1 % *R*	10 : 1	1	V_p	NS
7	Doppler	No data	± 0.2 % *FS*	5 to 25 : 1	1	V_m, *R*	
	Transit time	± 0.1 % *R* to ± 1 % *R*	± 0.2 % *R* to ± 1 % *FS*	10 to 300 : 1	1	*R*	0.02 s to 120 s
8	Coriolis	NS	± 0.1 % *R* to ± 0.25 % *R*	10 to 100 : 1	2/5	*R*	0.1 s to 3 600 s
	Twin rotor	No data	No data	10 to 20 : 1	3/4	*R*	50 ms
9	Anemometer	No data	± 0.2 % *FS*	10 to 40 : 1	2	V_p	No data
	Thermal mass	± 0.5 % *FS* to ± 2 % *FS*	± 0.2 % *FS* to ± 1 % *R*	10 to 500 : 1	2	*R*	0.12 s to 7 s
10	Tracer	No data	No data	Up to 1 000 : 1	1	V_m	No data
	Laser	No data	± 0.5 % *R*	Up to 2 500 : 1	1	V_p	No data

R is the flow rate
T is the volume flow
V_m is the mean velocity
Vp is the point velocity
% *R* is the percentage flow rate
% *FS* is the percentage full scale
NS indicates not specified
is dependent on differential pressure measurement

[a] 1 is low; 5 is high

Obtaining precise process data to select a meter is difficult but essential. In many applications the fluid composition, pressure and temperature variations and other variables may not be known and often only a best estimate of conditions can be made. Familiarity with the process is valuable, since the process operator has data and experience which often aids the instrumentation engineer in compiling the outline specification. Flowmeter selection should wherever possible involve two or more engineers to ensure that the correct specification is drawn up.

When the selection procedure is complete, it is advisable to reappraise the specification, modify it as necessary and go through the selection process again.

2.2 Performance considerations

2.2.1 General

The performance of flowmeters can vary significantly depending on both the design and type of meter. Table 2.3 indicates typical data for the more common meters listed in Table 2.1. These are ranges of figures for each of the meter types and it is possible to find suppliers with products that are better or worse than those given. New products are continually appearing on the market and improvements in performance are being made all the time.

Flowmeter performance is often judged from accuracy and repeatability figures. They are very frequently, though incorrectly, used synonymously. Accuracy is required for custody transfer and material balance applications. If a meter is consistently accurate then it is also repeatable. However, repeatability by itself does not guarantee accuracy.

2.2.2 Meter accuracy

Accuracy is defined in **1.2.3.1**. It is an indication of performance but no real numbers can be associated with it since the standards against which meters are assessed have errors themselves. It is not possible to measure flow absolutely. (See also **2.2.6**).

Confusion surrounds the specification of flowmeters as some are quoted in terms of percentage of reading and others in terms of a percentage of full scale or of span. Figure 2.1 gives an example of how the actual error in flow measurement differs at various flow rates depending on which of the two methods is being used. It is important to note from this figure that percentage of reading is the error that applies over the stated flowrange of the meter. If the intention is to use a meter at the bottom end of the quoted range, it is prudent to calculate the actual errors over the range required.

2.2.3 Repeatability

Repeatability is defined in **1.2.3.2** and **1.2.3.3**. It can be affected by variations in temperature, pressure, viscosity and other fluid properties as well as external environmental influences. The variations in output deviate from a mean value in accordance with established statistical laws. These aspects are discussed in more detail in Appendix B.

2.2.4 Linearity

Linearity is often an important parameter in determining the selection of a flowmeter but it should not be confused with uncertainty. Two ways of showing linearity bands are given in (a) and (b) of Figure 2.2 where limits are drawn at ± A % apart. The linearity of the meter can then be quoted as ± A % of full scale for (a) and ± A % of reading for (b) of Figure 2.2.

NOTE An alternative indication of linearity, applicable to a turbine meter, is shown in Figure 3.4.2.

The value of good meter linearity is particularly important for pulse output meters, where a single value of meter factor can be used to indicate rate over the specified operating range. One fact commonly overlooked is the addition of ancillary instrumentation which frequently alters the linearity of the system.

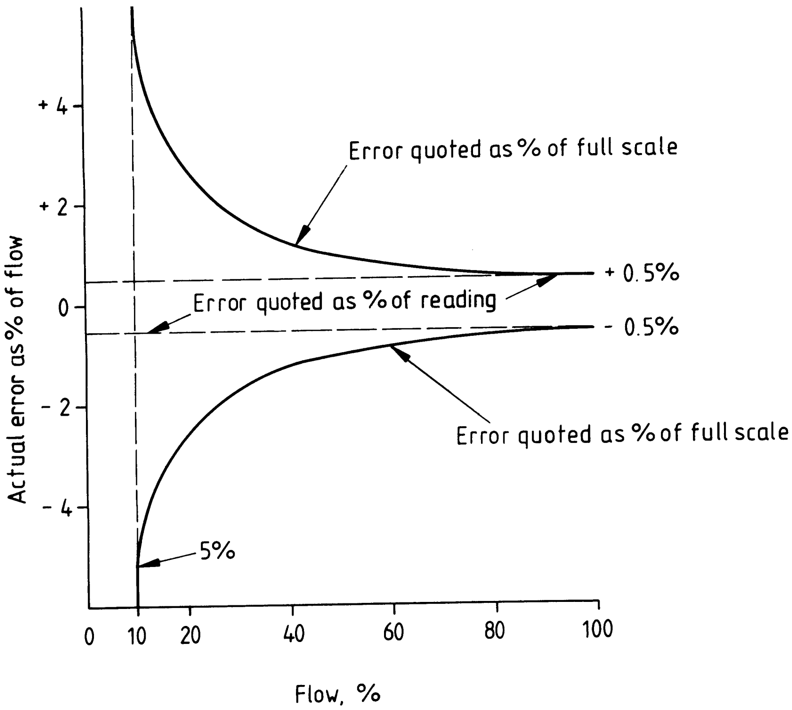
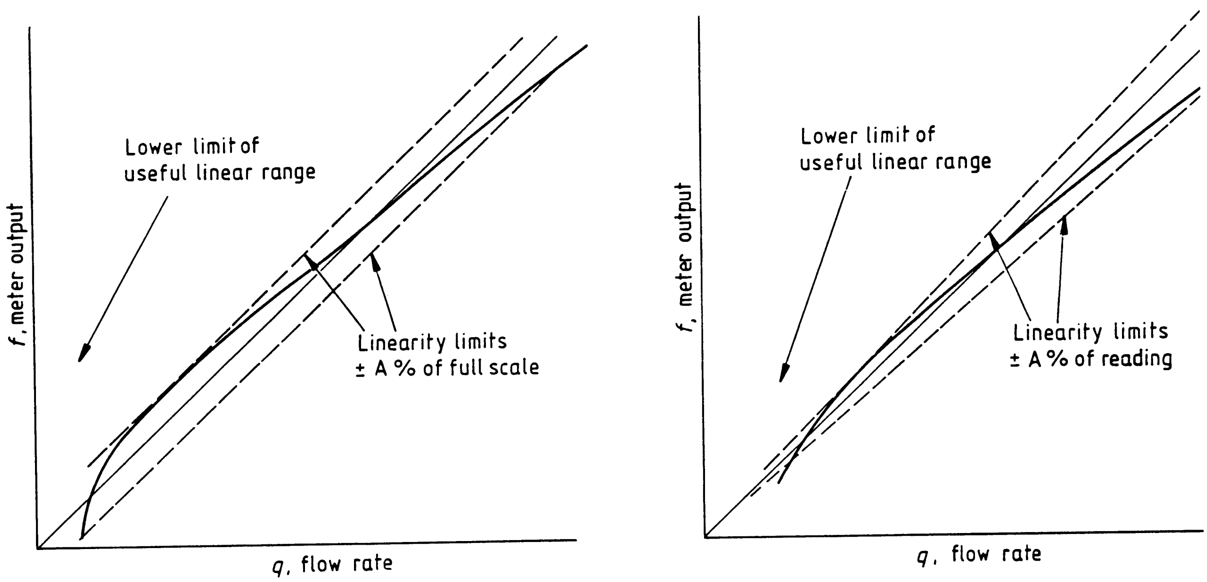


Figure 2.1 — Example of the effect of metering error on two methods of specifying flowmeter uncertainty



(a) Flowmeter linearity as percentage of full scale

(b) Flowmeter linearity as percentage of reading

Figure 2.2 — Flowmeter linearity

2.2.5 Flow rangeability (turndown)

Flow rangeability is defined in **1.2.3.6**. The ability of a particular meter to operate over a wide flow range is sometimes the major requirement. Modern meters such as turbine, mass and oscillatory meters can have a wide turndown. If a meter is highly repeatable but not necessarily linear, the output can be conditioned to increase the useful flow range. The manufacturer will often advise on the various ways to increase turndown for his product. Fluid property effects, particularly density and viscosity are also important since these may alter the linear operating range of the meter significantly.

The flow rate corresponding to the full scale output can be altered on many modern flowmeters. An example is the electromagnetic flowmeter where velocity ranges from 0 m/s to 1 m/s up to 0 m/s to 10 m/s are commonly available. It is not always clear if the quoted rangeability of 10 : 1 still applies when the meter output is changed to operate over the lowest range of flows.

2.2.6 Uncertainty

Meter performance is increasingly being expressed in terms of uncertainty and a confidence level. Uncertainty is defined in **1.2.3.5** and it gives the user a much better indication of the performance of the meter. It arises from both random and systematic errors as discussed in Appendix B. They are not normally separated by the flowmeter manufacturer when he specifies the performance of the instrument.

It is important to distinguish between error and uncertainty. Uncertainty can be calculated as detailed in Appendix B whereas error is the difference between true and indicated values. As the true value is not precisely known, then the measurement error is also unknown.

2.2.7 Output signal characteristics

Often the output signal dictates the choice of meter. Depending on design and type this could be a function of:

a) volume flow rate;

b) mass flow rate;

c) total volume throughput;

d) mean flow velocity;

e) point velocity.

Some meters generate voltage or current outputs while others give pulse outputs, each pulse corresponding to a discrete volume of fluid. Outputs from volume flowmeters are sometimes scaled in mass units and vice-versa. Pulse output meters are generally better suited to rate indication or flow totalization applications while analogue signals interface with control loop elements such as valves more easily. Output levels from analogue meters may vary considerably (for example from a few millivolts to several volts) while pulse outputs range from almost a direct current up to 10 kHz. The magnitude and type of output signal should also be examined for compatibility with flow computers, data loggers, alarm instruments and data transmissions systems. The complete system should be kept as simple as possible to minimize the number of sources of error. As discussed in section 6, this will reduce the total uncertainty of measurement from the complete system.

2.2.8 Pressure drop at maximum flow

Constraints on the maximum allowable pressure drop should be defined before meter selection. The application may have limited inlet pressure or pumping capacity and a high loss generated by selecting the wrong meter may affect process efficiency. Most flowmeters have a non-recoverable headloss which varies with flow rate. This can vary from close to zero to as high as several bar[1)]. In some liquid applications, notably high vapour pressure hydrocarbon liquids, excessive pressure drop may result in cavitation or vaporization of the liquid with the consequent loss of metering accuracy and possible damage to the meter.

[1)] 1 bar = 1×10^5 N/m^2 = 1×10^5 Pa.

2.2.9 Response time

The meter's response to step changes in flow could be important in those applications where flow fluctuations are present. In some cases it may be necessary for the output of the meter to follow the variations, in others a slower response output may be designed to provide an integrated average. Transient response is normally stated in the form of a time constant or simply a response time. Where the exact meaning of the figures is unclear clarification should be sought from the manufacturer. Published values for response time vary from a few milliseconds to several seconds. The addition of secondary instrumentation may lengthen this time considerably.

2.2.10 Performance selection data

Figure 2.3 gives an indication of typical performance data for each group of flowmeters. It has been compiled from a survey of a large amount of published literature and may be used to eliminate those types which cannot meet the required level of performance. For example, Doppler ultrasonic meters cannot be considered if an uncertainty of the order of 0.2 % of rate is required.

NOTE Not all meters in a group will meet the uncertainties quoted over the full range.

Table 2.3 gives more detailed information on the performance of the more common meters in each of the 10 groups. This indicates typical ranges of repeatabilities, linearities, turndowns and other factors. This table is for general guidance only and does not indicate the variations that occur between manufacturers. Reference to specific manufacturers' data sheets will give details of the performance of the meter(s) of interest.

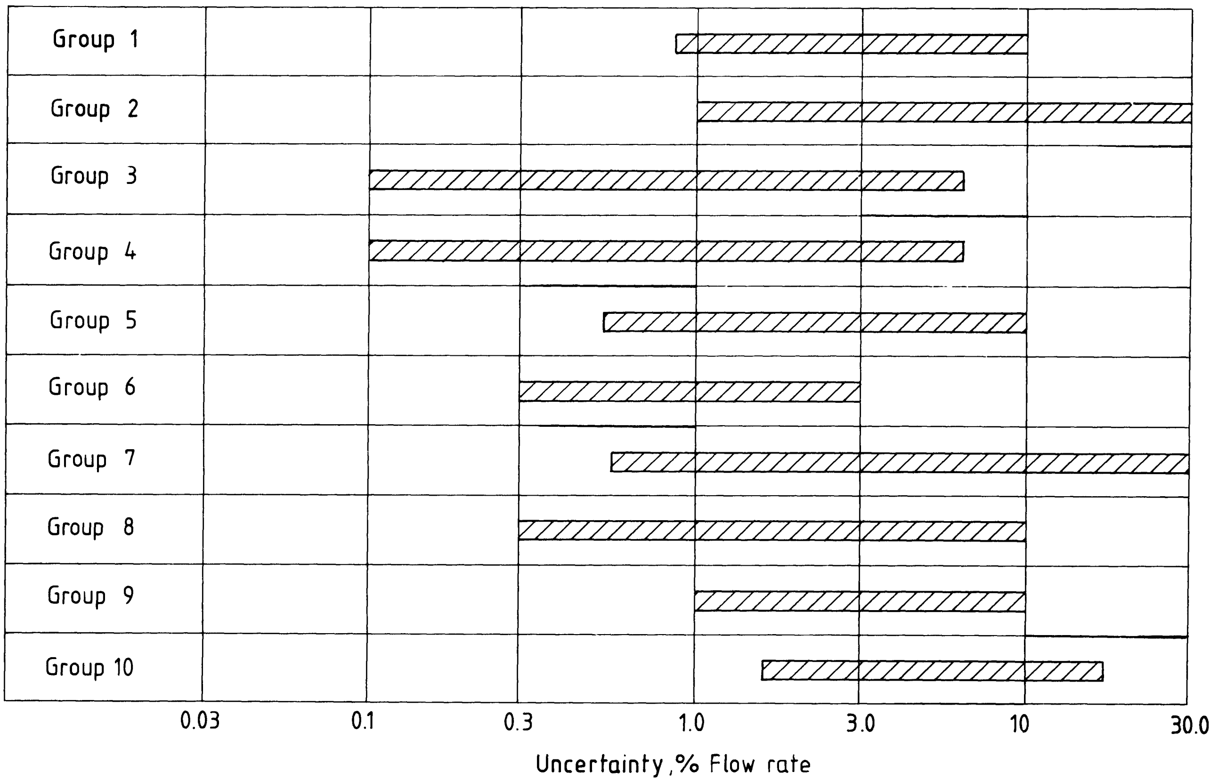


Figure 2.3 — Typical performance distribution of flowmeter groups

2.3 Fluid property considerations

2.3.1 General

All flowmeters are affected to some degree by one or more fluid properties. Therefore the nature of the fluid being measured has a large influence on the type of meter that can be chosen. For well known pure fluids, there are many reference texts and physical property data handbooks which list viscosity, specific gravity, vapour pressure and other parameters. This data can be compared against the meter specification to estimate the suitability of that particular flowmeter. Often the exact composition of the fluid stream, the temperature and pressure variations, and the nature of the stream are not known. This places a great burden on the user to quantify the fluid properties so that the manufacturer can assess whether his products are applicable or not. Table 2.4 gives pressure and temperature ranges, recommended minimum Reynolds numbers and the applicability of meters to liquids, gases and multi-phase flows.

2.3.2 Fluid temperature and pressure

The operating pressure and temperature at the flowmeter has to be carefully defined, especially in gas applications where large density variations may alter the selection of the measurement technology. Temperature and/or pressure compensation may be required if the variations in physical properties of the flow are large. Flowmeter body design is also influenced by the fluid pressure and temperature. Both the maximum and minimum pressure and temperature should be known, as the choice of materials of construction may also be affected. Where the application has large variations in fluid pressure or temperature, extra care in selection should be exercised.

Where applications involve meters being subjected to vacuum conditions, choice of both design and materials of construction are important. For example, some tube liners of magnetic flowmeters can collapse under vacuum.

2.3.3 Fluid density and specific gravity

For most liquid applications, the density or specific gravity is relatively constant but in instances where temperature variations are large, some form of compensation may be needed. This can be easily accomplished but the need should be identified as the metering technique may be influenced.

In gas applications the rangeability and linearity of some meters depend on the gas density, the value of which, at standard and flowing conditions, is generally required to be known in order to select the appropriate meter. Pressure and temperature transducers located close to the flowmeter enable on-line compensation of the gas density to be performed, or the density can be measured directly. They also permit conversion of the flowing conditions to some agreed reference. This is common in the case of custody transfer of hydrocarbon vapours. Low density applications can present difficulties to some methods, particularly those which use the momentum of the gas to operate the meter (group 4). Care is needed in sizing the meter correctly to ensure good performance.

2.3.4 Viscosity and lubricity

Meter performance is often a function of Reynolds numbers, which, in part, is established by the viscosity of the liquid.

Precise knowledge of gas viscosity is not as critical as for liquids. Gas viscosities, unlike those of liquids, do not change significantly with temperature and pressure. Gas viscosities are generally low, and the variation between different gases is also relatively small.

Viscosity can affect the rangeability of flowmeters in different ways. Most types of group 3 meters (displacement types) can increase in flow range as viscosity increases whereas some group 4 meters (inferential types) suffer from reduced rangeability as viscosity increases.

NOTE Inferential is the term given to group 4 meters (turbine type) where the flow rate is inferred from the speed of the rotor.

Knowledge of the temperature/viscosity characteristics is often required to assess meter applicability.

Some liquids are non-Newtonian in nature and their flow behaviour is very complex and not easily predictable. In these applications the selection of meters should be made with extreme caution and always in full consultation with the supplier.

Lubricity is a more difficult quantity to evaluate. Frequently, though sometimes incorrectly, a fluid with high viscosity is also assumed to have good lubricity. This parameter is important in meters with moving parts, for example groups 3 and 4. Some liquids, notably solvents, have poor lubricity and bearing life may be reduced which will affect both meter performance and rangeability.

Table 2.4 — Selection by fluid property constraints

Group	Type	Maximum pressure (bar)	Temperature range (°C)	Minimum Re_D	Gas (G) or Liquid (L)	Two or more phases
1	Orifice Venturi Nozzle	400 400 400	< + 650 < + 650 < + 650	$3 \times 10^4$1 10^5 2×10^4	L, G L, G L, G	P P N
2	Variable area Target Averaging pitot Sonic nozzle	700 100 400 400	– 80 to + 400 – 40 to + 120 < + 540 < + 650	No data 3×10^4 10^4 2.5×10^4	L, G L, G L, G G	N S N N
3	Sliding vane Oval gear Rotary piston Gas diaphragm Rotary gas	100 100 170 200 100	– 30 to + 200 – 15 to + 290 – 40 to + 170 – 30 to + 200 – 40 to + 150	10^3 10^2 10^2 2.5×10^2 10^3	L L L G G	N N N N N
4	Turbine Pelton Mechanical meter Insertion turbine	3 500 600 70 250	– 268 to + 530 – 225 to + 530 – 25 to + 200 – 50 to + 430	10^4	L, G L, G L, G L, G	N N N N
5	Vortex Swirlmeter Insertion vortex	260 100 70	– 260 to + 430 – 40 to + 110 – 30 to + 150	2×10^4 No data 5×10^3	L, G L, G L, G	P N N
6	Electromagnetic Insertion electromagnetic	300 20	– 60 to + 220 + 5 to + 25	No limit No data	L L	S/P N
7	Doppler Transit time	* 200	– 20 to + 80 – 200 to + 250	5×10^3 5×10^3	L L, G	S N/P
8	Coriolis Twin rotor	390 400	– 240 to + 400 – 240 to + 350	10^2 10^4	L L	P N
9	Anemometer Thermal mass	20 300	– 200 to + 400 0 to + 100	No data No data	L, G L, G	N N
10	Tracer Laser	No data *	No data No data	No limit No limit	L, G L, G	P N

Key
S is suitable
P is possible
N is not suitable
* is dependent on the rating of the pipe wall

2.3.5 Chemical properties

The chemical nature of the flowing stream can sometimes be critical. Certain fluids can promote corrosion, scaling of surfaces or electrolytic action on metal surfaces. All of these can affect the life of the meter and many manufacturers offer a choice of materials to withstand most fluids. Where chemical attack is expected, thicker body walls and strengthened components may be needed to ensure safe operation.

Certain chemicals can cause coating or crystallization on surfaces. This could affect clearances on moving parts, efficiency of sensing and transmission of ultrasound. Degradation of performance must be accepted where this cannot be avoided.

Radioactivity presents special problems. Here meters offering high reliability are required since it is often not possible to perform regular maintenance. This generally necessitates the use of meters with no moving parts and remote electronic secondary instrumentation. Special materials of construction may also be required.

2.3.6 Compressibility and other variables

For gas and vapour applications, compressibility data may be needed to determine the operating density of the fluid. This information is available for many fluids of constant composition allowing density calculation to be made using pressure, temperature, compressibility and composition data. For fluids of variable composition and for operation close to or in the supercritical region on-line measurement of density should be considered.

Certain metering techniques require consideration of specific fluid properties. For example group 6 meters (electromagnetic types) depend on sufficient electrical conductivity to function, and some group 9 meters require adequate thermal capacity and conductivity.

Fluids which are inflammable or react violently with other materials need flowmeters that are manufactured to a certified design. Acetylene gas for example has been known to ignite spontaneously where steep pressure and velocity gradients exist inside flowmeters.

2.3.7 Multi-phase and multi-component flows

The metering of multi-phase and multi-component flows should be approached with extreme caution. Experience has shown that performance can be very variable and in some cases is unknown. Usually the performance of the meter is assessed on single phase flows and there are no two phase standards to assess any systematic variations from the single fluid calibration. Meter life can also vary widely from that expected. Wherever possible phases should be separated to ensure lowest uncertainty of measurement, but there are applications where this is not practical, possible or desirable.

Sometimes the fluid itself is present in two phases, the most common example of which is wet steam. Here water droplets are carried along in a vapour medium. Ambient or process variations in temperature and pressure may alter the flowing state from that expected and the meter might not be able to cope with the fluid property variations. Meters are available for these applications but the specification requires greater care than for single phase applications.

Slurries can be handled by electromagnetic and special designs of mass, ultrasonic and differential pressure meters. It is important where possible to define the fluid conditions fully. This means defining particle size and concentration and the nature of solid phase. The solids may be abrasive, fibrous or non-uniform in size. Abrasive mixtures will cause steady erosion which can cause a steady increase in meter error and can ultimately result in meter failure.

When mixtures of liquids and gases are flowing the characteristics of the phases plus possible inter-phase phenomena affect the nature of the flow. The flow regime is dependent on the relative proportions of liquid and gas and the orientation of the pipe. The meter may be required to cope with many different flow patterns and often the exact distribution of the phases is unknown. The performance obtained in these cases is difficult to estimate but is usually many times worse than for single phase operation.

Often two or more liquids flow together and metering of the mixture is required. Where the liquids are miscible this does not present major problems. Where the liquids are immiscible, there is often a problem of homogeneity of the stream. The flow may exist as stratified or slug flow, with the actual flow pattern being dependent on the relative concentrations and the difference in density. As with gas/liquid flows the meter may be subjected to widely varying flow characteristics which are also dependent on the design of the installation.

2.4 Installation considerations

2.4.1 General

Installation requirements vary for the differing metering techniques. Some designs need long upstream straight lengths of pipe to ensure fully developed flow at the inlet to the meter (some group 1 and 4 meters for example) whereas others, notably group 3 meters are not influenced by the inlet pipework to the same extent. However some meters are specified without due consideration of the location of the meter in relation to flow direction, orientation, servicing and maintenance aspects or other parameters. Published data on flowmeter performance shows the strong influence of installation effects. Table 2.2 lists the various factors that need consideration under installation constraints. Table 2.5 gives data on installation requirements and indicates whether components such as filters or flow straighteners should be installed.

2.4.2 Pipework orientation

The orientation of the pipework can in some instances affect the choice of flowmeter. The performance of some meters may vary between horizontal and vertical installations. For example, severe effects may be noted in some downward vertical flows where loading on rotary components could lead to loss of linearity or poor repeatability. The orientation of most meters is specified by the manufacturer and these recommendations should be followed. Where the need to install the meter in other orientations is required further clarification should be sought from the supplier. The orientation may also be dependent on the nature of the flow. For example, settling of solid particles may occur in horizontal pipes, and therefore slurry metering is best performed in vertical lines.

Single phase flowmeters should be installed in horizontal lines wherever possible unless otherwise stated. This more closely approximates the installation in which the meter was probably calibrated. Some meters however are not affected significantly by orientation and Table 2.5 gives broad guidelines.

2.4.3 Flow direction

It is very important to note that some flowmeters operate in one direction only and incorrect installation could result in permanent damage. It is also important to identify the possibility of reverse flow existing in fault conditions. If so the installation may require non-return or check valves to safeguard the meter. The performance of those capable of bi-directional operation may vary between forward and reverse directions. Most flowmeters have the direction of flow clearly marked on the meter body. The manufacturers' calibration will apply only for use in this direction. Bi-directional meters should be calibrated in both directions.

2.4.4 Upstream and downstream pipework

Most flowmeters are affected to some degree by the inlet flow conditions and care should be taken to ensure good flow profiles. The design of pipework can introduce various types of flow disturbance, the most common being velocity profile distortion and swirl. Velocity profile distortion can be caused by an obstruction partially blocking the pipe, for example a valve, or by the influence of a bend. Swirl is commonly caused by two or more bends in different planes. These effects can be controlled either by ensuring an adequate straight length of pipe upstream of the meter or by installing a flow straightening device.

In badly designed installations, both effects will probably occur together and special flow conditioners will be required. It is not just the fitting immediately upstream of the meter that needs to be considered because combinations of fittings further up the line may in fact be the source of disturbances different to that produced by the nearest fitting. These effects can be reduced by introducing as long a distance as possible between the disturbance-producing components, rather than grouping them closely together, as often occurs. A very common example is a single bend downstream of a partly opened valve. It is also important to ensure that short unobstructed downstream straight lengths are also included to minimize flow effects at the outlet of the meter.

Cavitation and condensation are two more effects which can be caused by bad pipework. Such problems can be avoided by ensuring that no sudden large changes in pipework diameter or direction occur. Pipework configurations can also generate pulsations (see **2.4.12**).

Table 2.5 — Selection by installation constraints

Group	Type	Orientation	Direction	Quoted range of upstream lengths	Quoted range of minimum downstream lengths	Filter	Pipe bore range
							mm
1	Orifice	H, VU, VD, I	U, B	5*D*/80*D*	2*D*/8*D*	N	6 to 2 600
	Venturi	H, VU, VD, I	U	0.5*D*/29.5*D*	4*D*	N	> 6
	Nozzle	H, VU, VD, I	U	5*D*/80*D*	2*D*/8*D*		
2	Variable area	VU	U	0*D*	0*D*	P	2 to 600
	Target	H, VU, VD, I	U	6*D*/20*D*	3.5*D*/4.5*D*	N	12 to 100
	Averaging pitot	H, VU, VD, I	U, B	2*D*/25*D*	2*D*/4*D*	P	> 25
	Sonic nozzle	H, VU, VD, I	U	> 5*D*	> 0*D*	N	≥ 5
3	Sliding vane	H, VU, VD, I	U	0*D*	0*D*	R	25 to 250
	Oval gear	H	U	0*D*	0*D*	R	4 to 400
	Rotary piston	H, VU, VD, I	U	0*D*	0*D*	R	6 to 1 000
	Gas diaphragm	H	U	0*D*	0*D*	N	20 to 100
	Rotary gas	H, VU, VD, I	U, B	0*D*/10*D*	0*D*/5*D*	R	50 to 400
4	Turbine	H, VU, VD, I	U, B	5*D*/20*D*	3*D*/10*D*	P	5 to 600
	Pelton	H, VU, VD, I	U	5*D*	5*D*	R	4 to 20
	Mechanical meter	H, VU, VD, I	U	3*D*/10*D*	1*D*/5*D*	R	12 to 1 800
	Insertion turbine	H, VU, VD, I	U, B	10*D*/80*D*	5*D*/10*D*	P	> 75
5	Vortex	H, VU, VD, I	U	1*D*/40*D*	5*D*	N	12 to 200
	Swirlmeter	H, VU, VD, I	U	3*D*	1*D*	N	12 to 400
	Insertion vortex	H, VU, VD, I	U	20*D*	5*D*	N	> 200
6	Electromagnetic	H, VU, VD, I	U, B	0*D*/10*D*	0*D*/5*D*	N	2 to 3 000
	Insertion electromagnetic	H, VU, VD, I	U, B	25*D*	5*D*	N	> 100
7	Doppler	H, VU, VD, I	U, B	10*D*	5*D*	N	> 25
	Transit time	H, VU, VD, I	U, B	0*D*/50*D*	2*D*/5*D*	N	> 4
8	Coriolis	H, VU, VD, I	U	0*D*	0*D*	N	6 to 150
	Twin rotor	H, VU, VD, I	U	20*D*	5*D*	N	6 to 150
9	Anemometer	H, VU, VD, I	U, B	10*D*/40*D*	No data	R	> 25
	Thermal mass	H, VU, VD, I	U	No data	No data	R	2 to 300
10	Tracer	H, VU, VD, I	U, B	#	#	N	Unlimited
	Laser	H, VU, VD, I	U, B	0*D*	0*D*	P	

Key

H is horizontal flow
VU is upward vertical flow
VD is downward vertical flow
I is inclined flow
is mixing length
U is uni-directional flow
B is bi-directional flow
R is recommended
N is not necessary
P is possible

2.4.5 Line sizes

Very small or very large pipes often restrict the choice of flowmeter. Some flowmeters are not manufactured in a wide range of sizes and although one particular meter may match the users requirements, it may not be commercially available. Figure 2.4 gives the size ranges that are available for the 10 groups discussed and examples of the more common meter sizes within these groups is shown in Table 2.5.

Low velocities in large pipes or high velocities in small pipes can require a change of pipe diameter to produce a velocity which falls within the range of commercial flowmeters. Too low a velocity restricts the choice of meter and too high a velocity may cause damage through overspeeding or excess pressure drop.

2.4.6 Location for servicing

The importance of location for servicing is not always recognized. As a general rule all-round accessibility should be provided and the meter should be located to enable full replacement and servicing with the minimum of effort.

Some meters may be installed in environments which restrict servicing. These are usually hazardous areas, for example areas of high radiation. In these cases the choice of meter is influenced by the requirement for no servicing.

2.4.7 Local vibration

Some meters are susceptible to vibration and the design of proper pipework supports should be considered in all metering runs. Pulsation dampers may remove the effects of pumps and compressors but all instruments should be located well away from sources of vibration or pulsation. It is good practice to allow meter manufacturers to review the piping layout to advise on any modifications that may be required to minimize these effects.

2.4.8 Location of valves

Flowmeter lines generally have flow control valves and line isolation valves. The flow control valves should be located downstream of the meter to avoid any disturbance in flow profile or cavitation associated with the valves, affecting the meter. The valves, apart from controlling flow can also increase the back pressure on the meter. It is essential that the pressure in the meter is maintained significantly higher than the vapour pressure to avoid cavitation for certain types of meters, e.g. liquid turbines.

Upstream and downstream valves are frequently provided to isolate the meter for maintenance. The upstream valves should be full bore but even then should be located far enough upstream to avoid disturbance of the flow profile at the meter inlet. For custody transfer using multiple lines the downstream valves should be high integrity double block and bleed. A spare or by-pass line is often provided to permit flow when a meter is being maintained or calibrated.

2.4.9 Electrical connections

Most modern meter systems incorporate electronic equipment at or near the meter. It is important that the power source available is sufficient for the meter selected. When the level of the output signal generated by the meter is inadequate, preamplifiers, compatible with the application environment, should be used. All electrical connections should be protected against stray electrical interference (see **2.4.10**). Manufacturers can advise on electrical connections and types of cabling required.

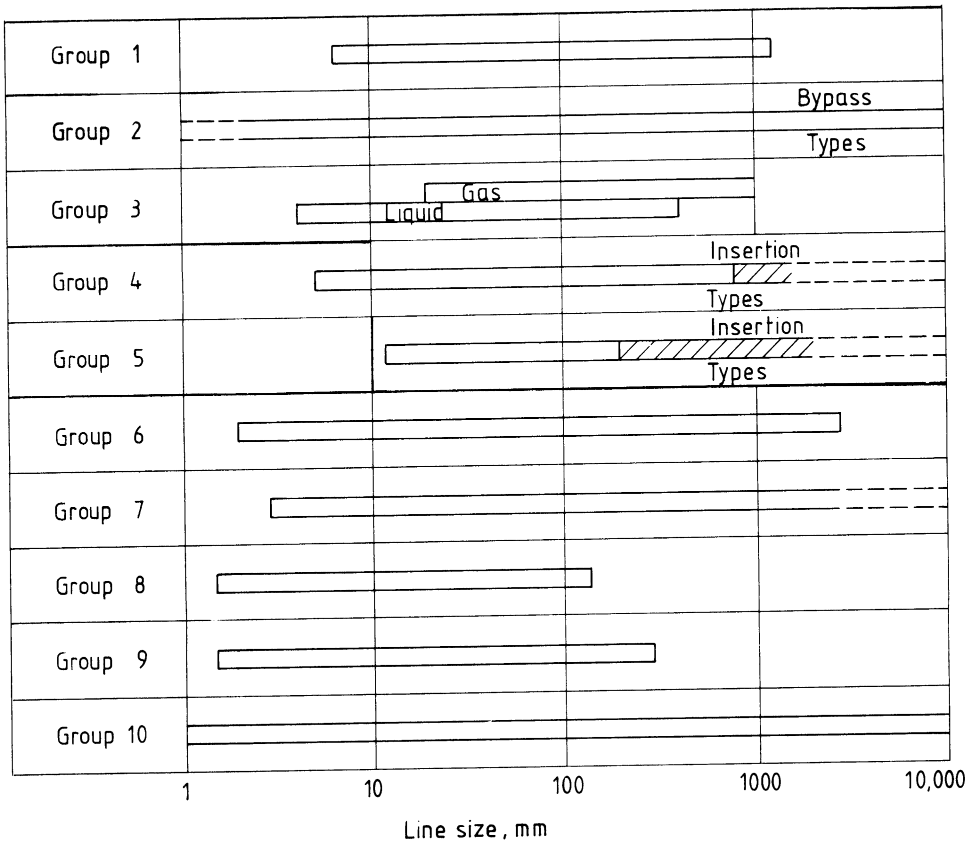
2.4.10 Electromagnetic interference

Output signals from some types of flowmeters are susceptible to the presence of large power sources. These power sources may produce surges in signal cables which are detected on the output pulses from the meter. They may also affect the electrical working of the meter, e.g. electromagnetic flowmeter field distortion. Signal cables should be routed well away from power cables and power sources to minimize the effects of electromagnetic interference (EMI) and radio frequency interference (RFI) effects.

2.4.11 Provision of accessories

Some metering installations may require additional equipment to guarantee satisfactory operation of the meter. For example, positive displacement (group 3) and turbine meters (group 4) generally require some form of filtration upstream of the meter.

Some applications may also require additional instrumentation to complete the measurement required. For example mass flow applications may use conventional volume flowmeters with temperature and pressure instrumentation. Alternatively pressure and temperature measurements may be required for compensation purposes, (see section 5).



NOTE The shaded areas represent the overlapping range of insertion and full bore meters.

Figure 2.4 — Size distribution of flowmeter groups

Other equipment could include gas detectors to provide a warning if the meter is not running full of liquid or trace heating to prevent freezing of the line fluid or to control condensation. More exotic pieces of equipment could include lightning arrestors or battery back-up systems.

2.4.12 Pulsations and unsteady flow

Pulsating flows should be avoided wherever possible since the majority of flowmeters over register in these applications. Common causes are the presence of displacement pumps, reciprocating compressors, oscillating valves or regulators, or hydraulic oscillations such as vortex shedding. If the presence of pulsations is suspected, the amplitude and frequency should be measured by a fast response device such as a hot-wire anemometer probe. This will determine whether the need for high response should be listed along with the other performance parameters before the start of the selection procedure. It is well known that differential pressure meters of all types are subject to pulsation errors as discussed in **4.1.5.4**, but it is less well known that turbine and vortex meters, for example, may give rise to over-registration errors just as serious as those incurred by orifice meters. It is also necessary to appreciate that there may be separate pulsation effects on the primary and secondary devices. Pulsation effects can be minimized by the installation of dampers as indicated in **4.1.5.4**. Unsteady flow is a less serious form of pulsation which may arise from, for example, the operation of oversized control valves. High frequency response flowmeters can usually tolerate low levels of flow unsteadiness.

2.5 Environmental considerations

2.5.1 General

The ambient conditions and possible variations in these conditions expected around the flowmeter should be considered in the selection procedure. Table 2.2 and Table 2.6 list the relevant factors.

2.5.2 Ambient temperature

The electronics and in some cases the meters can be affected by temperature change. The flowmeter may experience dimensional changes whilst affected components in the secondary electronics may lower its performance. Density or viscosity changes of the fluid may also occur due to heat transfer through the meter body. It is sometimes possible to locate the meter and readout devices in different places to protect the electronics from the effects of temperature. The use of environmentally controlled housings may be necessary in certain instances.

Thermal insulation of the pipework is required where ambient temperature changes affect the properties of the flow. When total uncertainty of flow measurement is being calculated, ambient effects can be one significant source of uncertainty. In addition, materials of construction of the meter and associated pipework need careful assessment when large variations of ambient and process temperatures occur.

2.5.3 Humidity

High humidity can accelerate atmospheric and electrolytic corrosion and can lower electrical insulation. Low humidity can induce static electricity. Problems arising from humidity can be caused by rapid ambient or process temperature changes. The user should know the range of expected variations and check that this does not lead to problems in operation, taking into account the meter being used.

2.5.4 Safety

In applications with hazardous environments, flowmeters should be selected with regard to atmospheric compatibility, electrical area classification and other safety regulations or standards that may apply. Details of the zone classifications and of equipment necessary to ensure safe operation of systems in hazardous areas are given in **5.5.7** (see BS 5501).

Chemically aggressive atmospheres can result in external corrosion of the meter or can affect the electronic readouts if not mounted remotely. Special enclosures should be considered in these cases and where flammable vapours or flammable dust particles are present. Large electrical energy sources should not be used in these environments. Waterproof enclosures for the meter and electronics may be required in many process applications. Often complete installations are hosed down during routine cleaning and the instrumentation has to be protected to ensure safe operation.

2.5.5 Electrical interference

Power cables, electric motors and process switchgear all produce EMI which may cause sources of error (see **2.4.10**).

2.6 Economic considerations

2.6.1 General

When looking at the full cost of metering several factors should be examined and not simply the purchase price. Table 2.2 includes a list of the economic variables to be considered, and Table 2.7 indicates the relative costs of the more important of these. These should be used with caution since the various designs within each group vary considerably in all the aspects listed. Discussions on specific economic considerations can be found in Baker (1986).

2.6.2 Purchase price

The purchase price for various liquid flowmeters, flowrates and pipe sizes is shown in a) and b) of Figure 2.5. These plot price against throughput, but with meter bore as an additional variable.
At 250 m^3/h for example, these figures show that a 200 mm orifice run, a 150 mm vortex meter or a 100 mm electromagnetic meter could be used. Thus the full costs of the complete installation can be more directly compared. Each data point is an average of prices from different suppliers. Figure 2.5 should be used for a relative indication only. The actual purchase price will depend on many variables such as pressure ratings, materials of construction, etc. Therefore a wide variation can be placed on each data point shown.

Table 2.6 — Selection by environmental constraints

Group	Type	Temperature effect[a]	Intrinsically safe version	Water and explosion proof version	EMI or RFI effect[a]
1	Orifice	4	#	#	1/2
	Venturi	3	#	#	1/2
	Nozzle	3	#	#	1/2
2	Variable area	3	A	A	1
	Target	3	NA	A	3
	Averaging pitot	3	#	#	2
	Sonic nozzle	3	A	NA	1/2
3	Sliding vane	4	A	A	1/3
	Oval gear	4	A	A	1/3
	Rotary piston	4	A	A	1/3
	Gas diaphragm	4	A	NA	1/3
	Rotary gas	4	A	NA	1/3
4	Turbine	3	A	A	4
	Pelton	3	A	A	4
	Mechanical meter	3	A	A	1
	Insertion turbine	3	A	A	4
5	Vortex	2	A	A	4
	Swirlmeter	2	A	A	3
	Insertion vortex	1	A	N	3
6	Electromagnetic	1	A	A	3
	Insertion electromagnetic	1	A	N	3
7	Doppler	3/4	A	A	4
	Transit time	3/4	NA	A	4
8	Coriolis	1	A	A/NA	4
	Twin rotor	2	No data	No data	4
9	Anemometer	3	NA	NA	2
	Thermal mass	4	A	A	2
10	Tracer	1	N	N	1
	Laser	1	NA	NA	4

Key
N is not necessary
A is available
NA is not available
is dependent on differential pressure measurement

[a] 1 is low
5 is high

2.6.3 Installation costs

Some metering methods require attention to flow conditioning and the provision of long inlet lengths to ensure good performance. Correct installation could require extra pipework or the provision of by-pass lines for routine maintenance and checking. An orifice plate plus differential pressure (DP) cell is relatively inexpensive but when correctly installed in a full metering run with the appropriate plate fittings, the full cost is many times the cost of the basic element. Other cost factors could include the need to purchase shut-off valves, filters or other ancillary equipment to complete the run. These all contribute to the complete installation costs, but are seldom considered in economic aspects of selection.

2.6.4 Calibration costs

Calibration costs generally increase in proportion to the level of performance required. For low uncertainty calibrations, certified test facilities are needed, and these may be expensive to build or hire. Calibration costs listed in Table 2.7 indicate this fact. The frequency of calibration affects the overall costs. Some meters require periodic recalibration while others need to be checked infrequently. Other types of meters require only visual inspection and dimensional checking (group 1 for example), and flow testing may not be required, provided the meters are designed and used in accordance with the appropriate standards. Again the required level of performance is important when examining calibration costs. The supplier can advise on the required frequency of calibration and the cost for specific applications.

2.6.5 Operation costs

Operation costs are mainly associated with the energy required to operate the meter system chosen. They may include the costs of power to drive the electronics within the system, (which is very low in most modern meters), as well as the pumping costs of actually driving the fluid through the meter. This means that meter headloss is important since in most cases this is not recoverable. Insertion meters, for example, offer considerable savings in costs over full bore meters in large pipes, because they offer much lower blockage ratios. Their performance however is not as good as that of the full bore meter and the selection may become a trade-off between these factors. Each application should be examined to determine whether savings can be made if different metering techniques meet all other criteria.

2.6.6 Maintenance costs

Maintenance costs are the expenses of keeping a flowmetering system functioning, once it has been installed and commissioned and has two major components, parts and labour. Meters with moving parts generally require more maintenance. Examples may be the periodic replacement of bearings, rotors, shafts or transmission gears that experience wear with time. However, meters with no moving parts may also require frequent attention, a common example being the checking of orifice plate edges.

2.6.7 Spares cost and availability

The cost of spares generally increases with the complexity of the meter and with those meters capable of good performance. Spare parts for meters manufactured abroad may cost more than locally produced instruments, and spares availability may also be more of a problem. The figures given in the last column of Table 2.7 can vary significantly depending on the source and design of the meter. Advice from several suppliers of the same type should be sought if spares cost and availability is important.

2.7 Examples of flowmeter selection

2.7.1 General

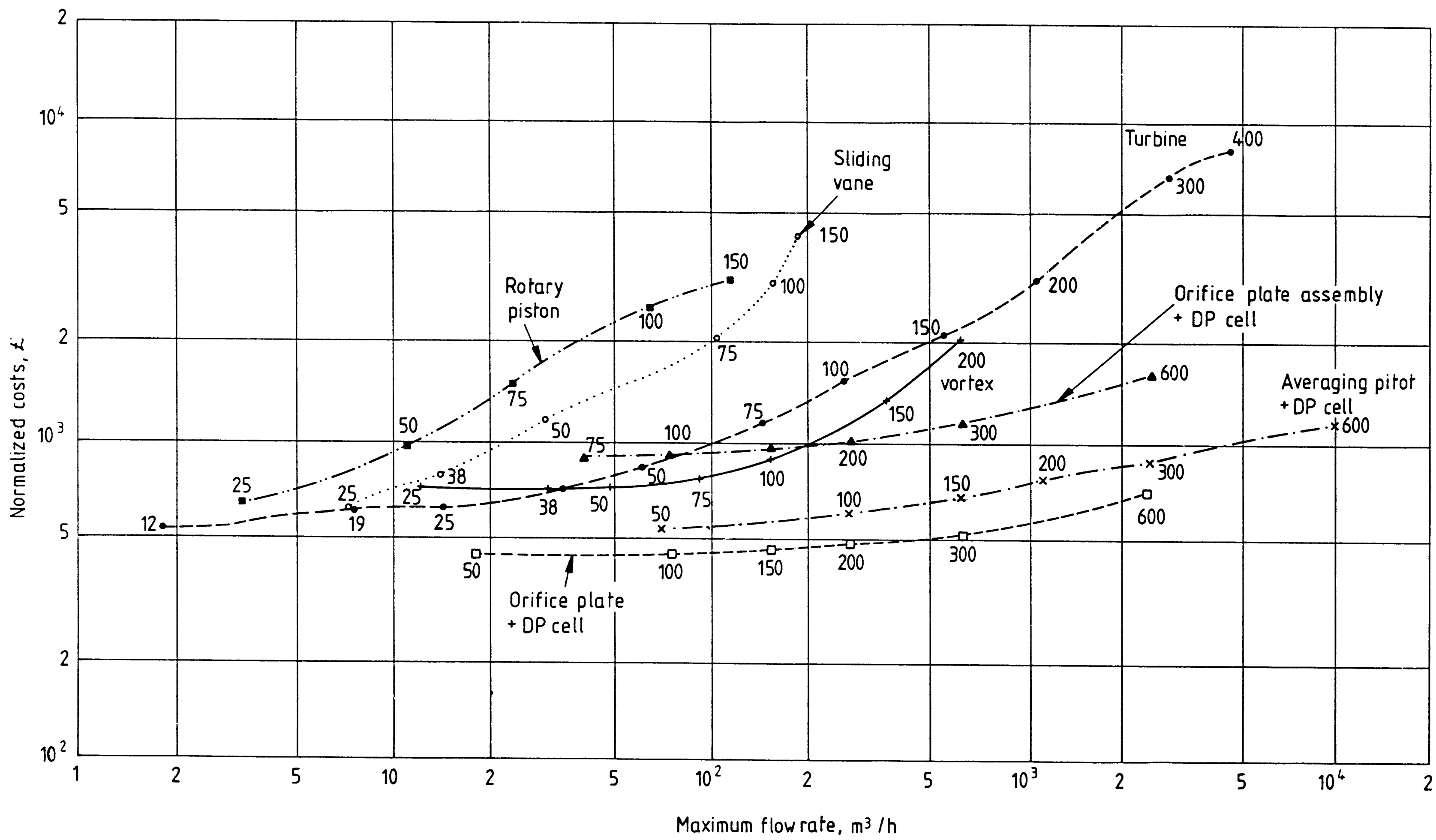
This section of the guide illustrates the use of the various data tables and figures. The examples will illustrate the important considerations and judgements to be made in selecting applicable techniques.

Table 2.7 — Selection by economic factors

Group	Type	Installation costs	Calibration costs	Operation costs	Maintenance costs	Spares costs
1	Orifice	2/4	1	3	2	1
	Venturi	4	1/4	2	3	3
	Nozzle	3	3	2	3	2
2	VA	1/3	2	2	1	1
	Target	3	3	2	3	3
	Averaging pitot	2	3	2	2	2
	Sonic nozzle	2	1	3/4	2	1
3	Sliding vane	3	5	4	4	5
	Oval gear	3	4	4	4	5
	Rotary piston	3	3	3	3	4
	Gas diaphragm	3	3	1	2	2
	Rotary gas	3	4	3	3	3
4	Turbine	3	4	3	4	4
	Pelton	4	3	3	4	3
	Mechanical meter	3	2	2	3	3
	Insertion turbine	2	3	2	2	3
5	Vortex	3	3	3	3	3
	Swirlmeter	3	4	3	3	3
	Insertion vortex	2	3	2	3	3
6	Electromagnetic	3	3	1	3	3
	Insertion electromagnetic	2	3	2	3	2
7	Doppler	1/3	1	1	3	2
	Transit time	1/3	3	1	3	2
8	Coriolis	3	4	4	3	3
	Twin rotor	3	3	3	3	3
9	Anemometer	3	2	1	3	3
	Thermal mass	3	4	2	4	3
10	Tracer	2	—	4	2	4
	Laser	5	—	4	5	5

Key
1 is low
5 is high

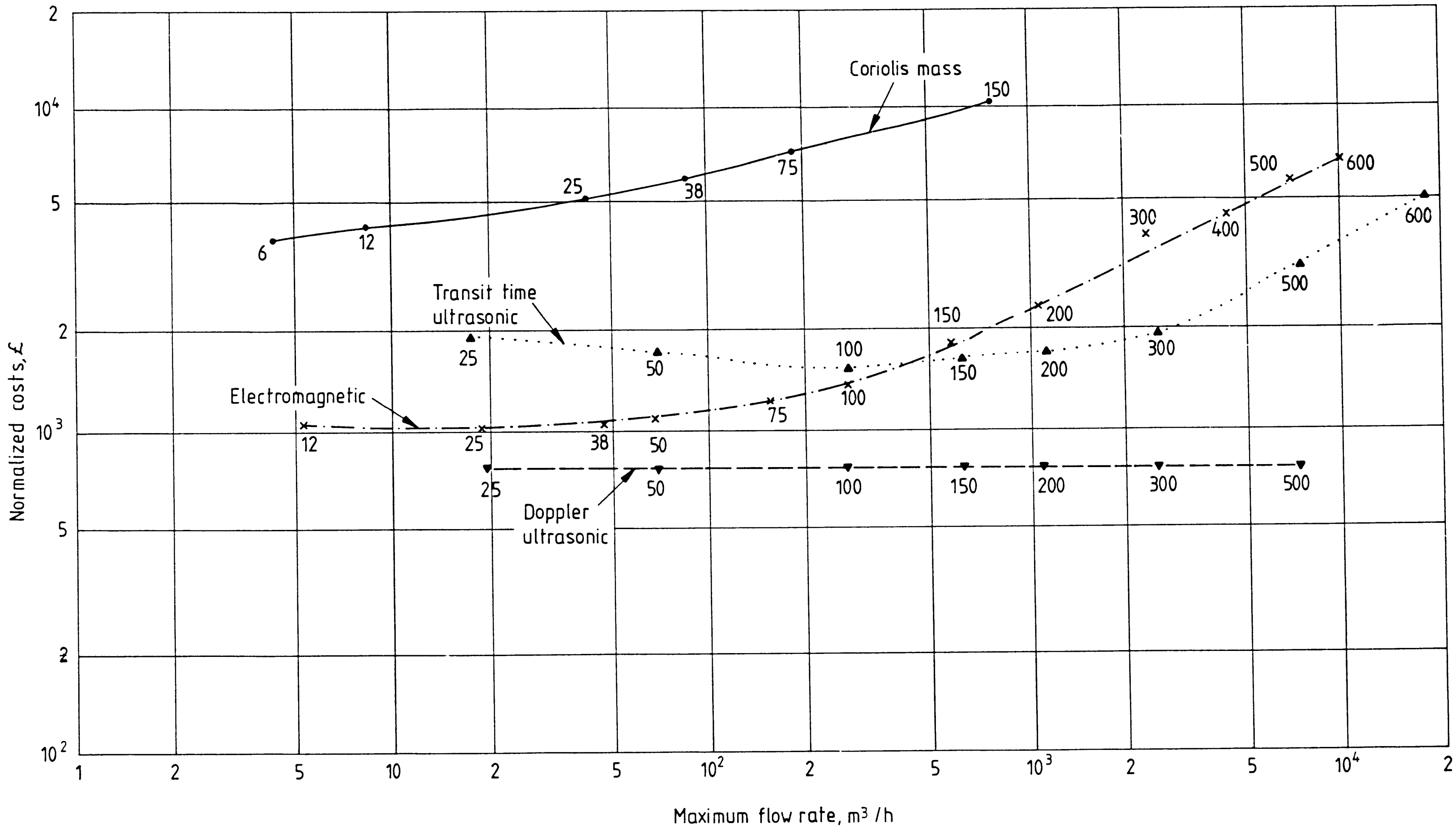
NOTE For purchase price see (a) and (b) of Figure 2.6.



NOTE Numbers on data points indicate pipe size in millimetres.

(a)

Figure 2.5 — Flowmeter purchase price comparison (liquids)



NOTE Numbers on data points indicate pipe size in millimetres.

(b)

Figure 2.5 — Flowmeter purchase price comparison (liquids) *(concluded)*

2.7.2 Example 1

The following outline specification of requirements was supplied by the process engineer of a chemical plant:

Application:	batch acid production
Line size:	25 mm
Fluid:	hydrochloric acid
Operating pressure:	3 bar
Operating temperature:	25 °C to 35 °C
Uncertainty required:	1 % actual flow rate
Flow rate:	3.5 m^3/h
Output signal:	to interface with process computer
Pipework constraints:	3*D* upstream, 3*D* downstream, pipe horizontal
Capital spend:	not critical

First step. Examine Table 2.1 to determine applicable groups of meters and Table 2.1 to confirm that all the applicable parameters are considered in the specification. Application S in Table 2.1 is the required duty.

Applicable groups: groups 1, 2, 3, 4, 6, 7, 8 and 10.

Second step. Examine Table 2.3 and Figure 2.3 to determine groups meeting the performance specification.

Applicable remaining groups: groups 1, 3, 4, 6, 7 and 8.

Third step. Examine Table 2.4 to investigate possible limitations of fluid properties, particularly Reynolds number, (calculating it if not already known), on remaining groups.

Temperature variation is small, pressure is low, all remaining groups from step two are still applicable.

Applicable remaining groups: groups 1, 3, 4, 6, 7 and 8.

Fourth step. Examine Table 2.5 to determine which types of flowmeter within the applicable remaining groups are suitable for the pipework constraints applying to this application.

Examination of Table 2.5 shows that only a limited selection of types of flowmeter are suitable from within the applicable groups. Thus, in group 1, only a Venturi meter is possible; in group 3, all except the gas meters are possible; in group 4, only a mechanical meter might be possible; in group 6, only an electromagnetic meter might be possible; in group 7, only a transit time meter might be possible, and in group 8, only a coriolis meter is possible.

Fifth step. Examine Table 2.6 for environmental constraints; this does not eliminate further groups, but indicates that groups 6 and 8 are less sensitive to temperature and all have similar response to EMI and RFI. The possible ranking is then:

1st choices groups 6 and 8, 2nd choice group 3.

Sixth step. Examine (a) and (b) of Figure 2.5 for indication of purchase price and Table 2.7 for economic factors to be considered.

Purchase costs indicate the following ranking:

1st: group 6; 2nd, group 3 and 3rd group 8.

Table 2.7 indicates installation and calibration costs are all comparable, group 6 has the lowest maintenance and spares costs.

Conclusion. Steps four, five and six indicate that group 6 (electromagnetic) is the first choice, with group 3 (positive displacement) second on economic factors, group 8 (coriolis meter) as a third option.

If research covering that particular installation has not been done or it suggests that the electromagnetic meter should not be located at 3D from the installation, a positive displacement meter would be suitable, with a coriolis meter as a possible option.

The final choice will be made after reading the relevant text in **3.3**, **3.6**, and **3.8** for technology limitations and **4.3**, **4.6** and **4.8** for application constraints.

Once the meter has been selected, any limitations of the chosen meter should be compared in detail with the requirements of the original specification. If the differences are significant, the selection procedure should be repeated after reviewing the original specification.

This application was relatively well defined and shows the importance of collecting as much process data as possible. The ranking of possible meters has been eased by the process engineer looking at the location of the required meter and the performance needed to meet production criteria.

2.7.3 Example 2

The discharge of steam from a plant boiler requires monitoring for billing purposes. Because this involves financial aspects, the Company accountant has decreed that metering to ± 0.5 % of reading is required. The plant engineer drew up the process specification as follows:

Application:	plant steam billing
Line size:	0.3 m
Fluid:	superheated steam
Operating pressure:	40 bar approx. (600 psi)
Operating temperature:	300 °C
Uncertainty required:	0.5 % actual flow rate
Flowrate:	4 kg/s to 45 kg/s
Output signal:	pulse preferred for totalization
Pipework constraints:	not specified
Capital budget:	very limited

First step. Examine Table 2.1 to determine applicable groups. Application N in this table is the required duty.

Applicable groups. Groups 1, 4(?), 5 and 10.

Second step. Examine Figure 2.3 to determine groups meeting the performance specification.

Applicable remaining groups: groups 4(?) and 5.

Third step. Examine Table 2.4 to investigate possible limitations of fluid properties on remaining groups.

Temperature and pressure variations are not specified, but both line pressure and temperature are high.

Applicable remaining groups: groups 4(?) and 5.

Fourth step. As pipework installation constraints are not specified no further elimination is made. However, examination of Figure 2.4 shows that group 5 meters (fluid oscillatory) are not available in the required line size unless an insertion type is used.

Fifth step. The choice of meters is now limited to two groups; reference to **3.4**, **3.5**, **4.4** and **4.5** shows that only insertion types are available. These sections also indicate that other factors such as installation, headloss, reduced rangeability need further consideration. Furthermore, insertion meters have a performance outside the required specification. This means that the required performance specification has to be relaxed.

Conclusion. No meter is applicable to meet the requirements of the specification. Re-evaluation of actual needs plus complete re-specification is required before selection can be made. All the factors given in Table 2.2 now become an essential check list before selection can be undertaken properly.

Section 3. Flow measurement techniques

3.0 Introduction

3.0.1 General

This section of the guide looks at the basic principles of operation of the flowmeters covered. The aim is to emphasize the essential features of the design and construction of the more common types of meter within the 10 groups discussed. Theory has been kept to a minimum so that the limited space available can be used to summarize the essential features of the various flowmeters. Not all the commercially available flowmeters are described, because there are many adaptations and variations available.

Some indication of typical performance for each meter is given, but this should not be taken as an indication of installed performance. The limitations on application and the possible resulting change in behaviour can be found in section 4 of the guide and the reader is encouraged to study both section 3 and 4 for full details of the flowmeter of interest.

As no flowmeter can satisfy all flowmeter requirements, advantages and disadvantages of each type are given. These should be used along with the comprehensive list of factors given in section 2 to decide if the meter offers the characteristics to meet the application. Some indication of materials of construction are given as some types of flowmeter can be made from a wide range of materials. In some instances this can affect both the performance (in terms of possible flow range and/or pressure drop) and the application.

3.0.2 Layout

The section looks in turn at each of the eleven major types of flowmeter. Wherever possible illustrations have been used to support the text and to enable the reader to appreciate the design and construction of flowmeters. The clause numbers have been designated to match the group number, so for instance **3.6** indicates that group 6 meters (electromagnetic) are being discussed.

3.1 Group 1 meters: orifices, venturis and nozzles

3.1.1 General

Orifice, venturi and nozzle meters are some of the most common flowmeters currently in use. The vast majority of these are square edged orifice plates but the basic theory applies to all types in this group. For many years these meters were the only way of measuring flow with reasonable performance, good reliability and at a moderate cost. The principle of operation is based on the use of a restriction in the flow. The resulting pressure drop across the restriction is used as a measure of flow rate.

3.1.2 Differential pressure meter theory

The complex flow distribution through an orifice plate is shown in (a) of Figure 3.1.1 and will be used to discuss the general performance of this class of meter. The diameter of the restriction is $d = \beta D$. The fluid continues to converge downstream of the restriction to a minimum flow area of $c \frac{\pi}{4} d^2$.

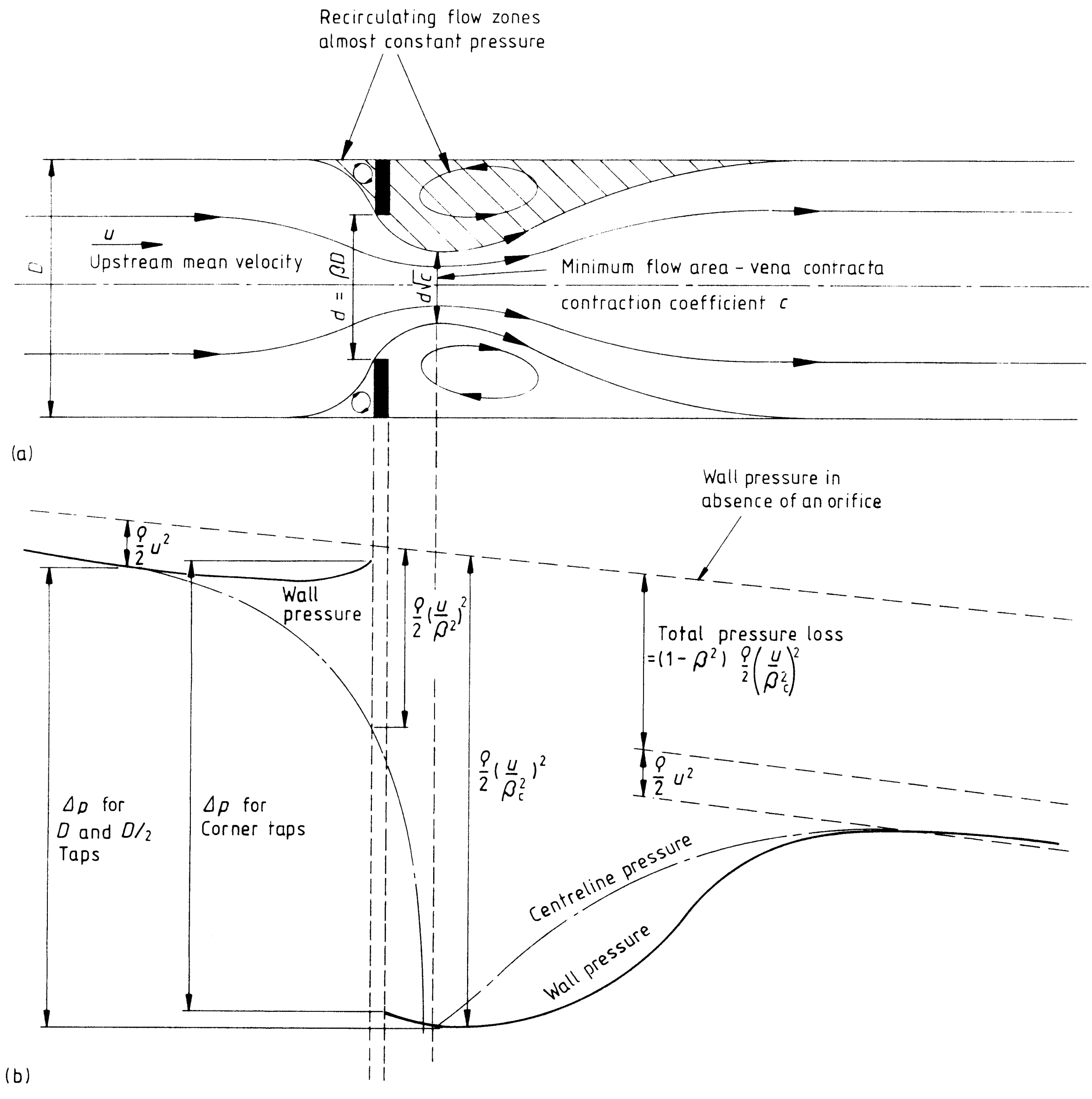


Figure 3.1.1 — Pressure profile and flow pattern through an orifice meter

The acceleration of the fluid up to the maximum velocity gives a reduction in pressure according to Bernoulli's energy equation. As the fluid diverges further downstream, losses become significant and Bernoulli's equation no longer applies. Immediately upstream and downstream of the plate, there are zones of slowly recirculating fluid. Within these the pressure variations are relatively very small. The pressure variation along the centre line of the flow and along the pipe wall are shown in (b) of Figure 3.1.1. If Δp is the pressure drop measured at the wall on either side of the plate,

$$\Delta p \approx \frac{\rho}{2}\left(\frac{u}{\beta^2 \ c}\right)^2$$

or

$$q_{\mathrm{m}} = \frac{\pi}{4} D^2 \rho u \approx c\frac{\pi}{4} d^2 (2\rho \ \Delta p)^{1/2} \qquad (3.1.1)$$

where

c is the contraction coefficient

The discharge coefficient, C, is defined by the following:

$$q_m = C\frac{\pi}{4} d^2 \left(\frac{2\rho\Delta \rho}{1-\beta^4}\right)^{1/2} \quad (3.1.2)$$

Comparing these equations shows that, if $\beta << 1$, $C \approx c$. The actual value of C will depend on the type of meter, the precise location of the pressure tappings, the value of β, the Reynolds number, and the detailed flow distribution in the upstream section of the pipe. C has been obtained empirically and is found to be about 0.6 for orifice plates and slightly less than 1 for venturis and nozzles. Values of C for orifice plates, nozzles and venturi tubes are given in BS 1042-1.1.

It should be noted that the measured Δp is proportional to the square of the flow rate. If, for instance, a flow rate of 1/10 of maximum is to be measured, the pressure drop will only be 1/100 of maximum. To maintain accuracy at low flow rates, the instrument used to measure differential pressure has to retain a sufficiently high accuracy at the bottom of the required range. Alternatively, the meter range should be divided and separate measuring instruments used for each subdivision. This is fundamental to all differential pressure meters.

The theory outlined so far has been for an incompressible fluid. When a gas or vapour is being metered, an adjustment is necessary to allow for a change in density through the contraction. The fluid density changes as a result of both velocity and pressure changes, and compressibility effects are therefore extremely important. Deriving the basic equation from first principles results in the following expression:

$$q_m = C\frac{\pi \ d^2}{4} \epsilon \left[\frac{2\rho_1 \ \Delta p}{(1- \ \beta^4)}\right]^{1/2} \quad (3.1.3)$$

The interesting feature of this expression is the similarity with equation 3.1.2. The only difference between liquids and gases is the inclusion of an expansion factor ϵ. The density used in this equation is the upstream value ρ_1. For nozzles and venturis the assumption of an isentropic expansion is reasonable and the value of ϵ can be calculated in accordance with **9.1.6.3** of BS 1042-1.1:1992.

There are restrictions given in BS 1042 for the applicability of the equation used for such a calculation. Test data exists for air, steam and natural gas only. In the case of orifice plates, the expansion involves turbulent shear flow and does not conform to the isentropic assumption, particularly for small β ratios or large pressure differentials. Instead an empirical relationship for ϵ is used:

$$\epsilon = 1 - (0.41 + 0.35 \ \beta^4)\frac{\Delta p}{Kp_1} \quad (3.1.4)$$

Some values of ϵ have been tabulated in BS 1042-1.1 and Miller (1982). Provided the ratio of the plate and the actual operating pressure differential are known, the value of ϵ can be used directly from the tables. The expansion factor calculation can also be based on the downstream pressure and temperature conditions. Tables exist for ϵ_2 (downstream) values as well as ϵ_1 (upstream) in the references cited. For mixtures of gases it is usual to use upstream conditions.

3.1.3 Orifice plates

3.1.3.1 *Basic design and construction*

The flowmeter in most common use throughout the world is the square-edged concentric orifice. Its design specifications have been standardized and are fully described in such documents as BS 1042-1.1 and BS 1042-1.2. Figure 3.1.2 shows a common type of industrial installation, where the orifice plate is clamped between pipe flanges. The most important features of the design are as follows.

a) The sharp, square upstream edge. The discharge coefficient is highly dependent on the edge profile. The edge radius should not be greater than 0.0004 d and should be inspected regularly to check that it has not become eroded, corroded or otherwise damaged during use.

b) A cylindrical throat concentric with the pipe bore. The axial length of the throat is specified in the standards and must be sufficiently short for re-attachment of the fluid jet formed at the throat inlet edge to be impossible. Eccentricity of the orifice can result in significant changes in discharge coefficient especially if single tappings are used.

c) A flat upstream face and plate thickness sufficient to withstand buckling.

d) When bevelled plates are used the tabulated coefficients are for flow with the sharp edge facing upstream. If reverse flow should occur or the plate is installed the wrong way round, the indicated flow will be about 20 % below the true flow.

Other possible sources of error are buckling, edge effects and flow profile effects.

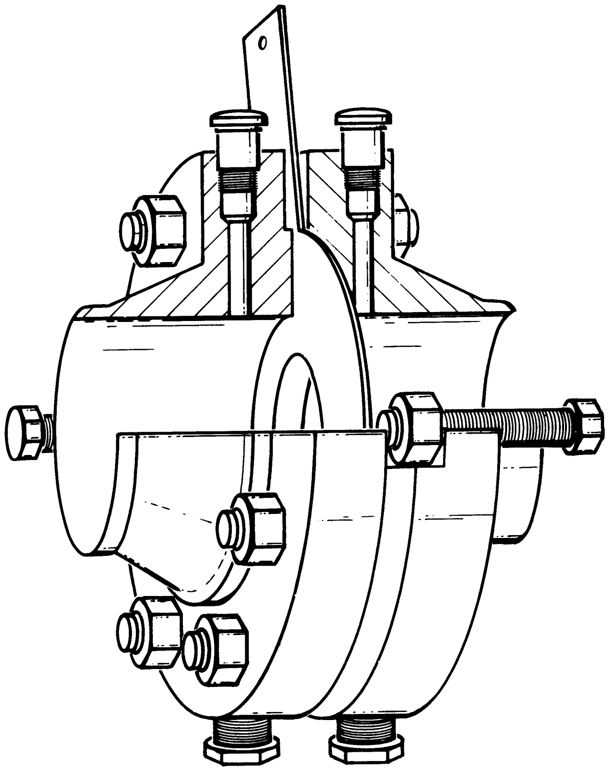


Figure 3.1.2 — Typical orifice plate installation

3.1.3.2 ***Pressure tappings***

The three types of pressure tappings covered by BS 1042 are the corner, flange and *D* and *D*/2 types shown in Figure 3.1.3. Some are welded to the pipe and then drilled while others are prefabricated during construction. Any can be used provided the relevant standards are followed. There are no general universally accepted rules for selecting one type of tapping in preference to another but current practice tends to suggest that flange tappings are the most popular.

3.1.3.3 ***Vent holes***

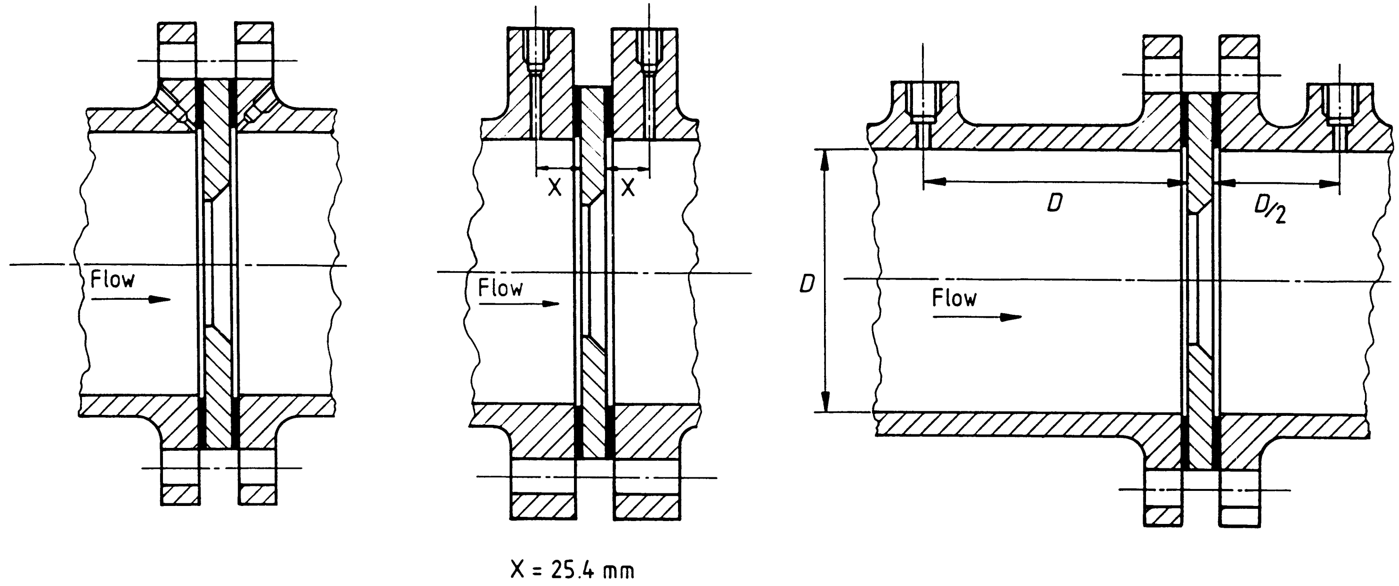
Some orifice plates may be specified with vent or drain holes for various applications. The vent hole permits any gas present in a liquid at the top of the pipe to pass through the plate. Similarly, drain holes permit any condensate present to pass through the plate. The diameter of the vent/drain hole and its discharge coefficient may be used to correct the orifice bore, see BS 1042-1.2. Where these holes are specified it is important to remember that they are liable to blocking which can affect performance. This is particularly common in gas lines with condensate present. The plate will act as a dam and uncertainty of measurement will increase significantly.

3.1.3.4 ***Performance***

The coefficient data for square-edged orifices is expressed in BS 1042-1.1 and BS 1042-1.2 in terms of a complicated empirical expression known as the Stoltz equation. The equation contains terms to allow for the dependence of the discharge coefficient on diameter ratio, Reynolds number and tapping position. The obvious advantage of an equation compared with tabulated coefficient data, is that it facilitates the use of a computer for flow rate and orifice design calculations.

The uncertainty in the basic data used to derive the Stoltz equation is around 0.6 %. When uncertainties in the expansibility factor, the measurement of orifice and pipe diameters and the measurement of differential pressure and density are taken into account together with variations in ambient and process conditions, it is unlikely that overall uncertainties much better than about 1 % full scale deflection will be achieved. A figure of about 2 % full scale deflection would be typical even when the installation complies with the requirements of the appropriate standard. This typical level of metering uncertainty is not generally appreciated. The uncertainty in the discharge coefficient may be reduced by calibration especially if the complete meter run (the meter plus the immediate up and downstream pipe work) can be tested in the calibration flow rig.

When the secondary instrumentation includes a flow computer the inherent non-linearity of the orifice tends to restrict the range but it is not a major problem. If the accurate range of a differential pressure cell is 10 then the meter range will be $\sqrt{10}$. The range can be extended by using two or more DP cells in parallel, or by the use of the new smart DP transmitter (see **5.1.6**).



(a) Corner

(b) Flange

(c) D and $D/2$

Figure 3.1.3 — Corner, flange and D and $\frac{D}{2}$ tap orifice designs

3.1.3.5 ***Advantages and disadvantages***

The advantages of the orifice meter are as follows.

a) a robust and simple primary device;

b) low manufacturing cost;

c) easy to install;

d) well established type of meter and enjoys universal confidence;

e) no need for calibration for standard installations;

f) can be used on liquids and gases, including steam.

The disadvantages of the orifice meter are as follows:

1) only 3 : 1 typical flow range;

2) erosion and damage to the upstream face or edge change calibration;

3) affected by upstream disturbances particularly for a large β ratio;

4) significant pressure loss increasing as area ratio decreases.

3.1.4 Venturi tubes

3.1.4.1 ***Basic design and construction***

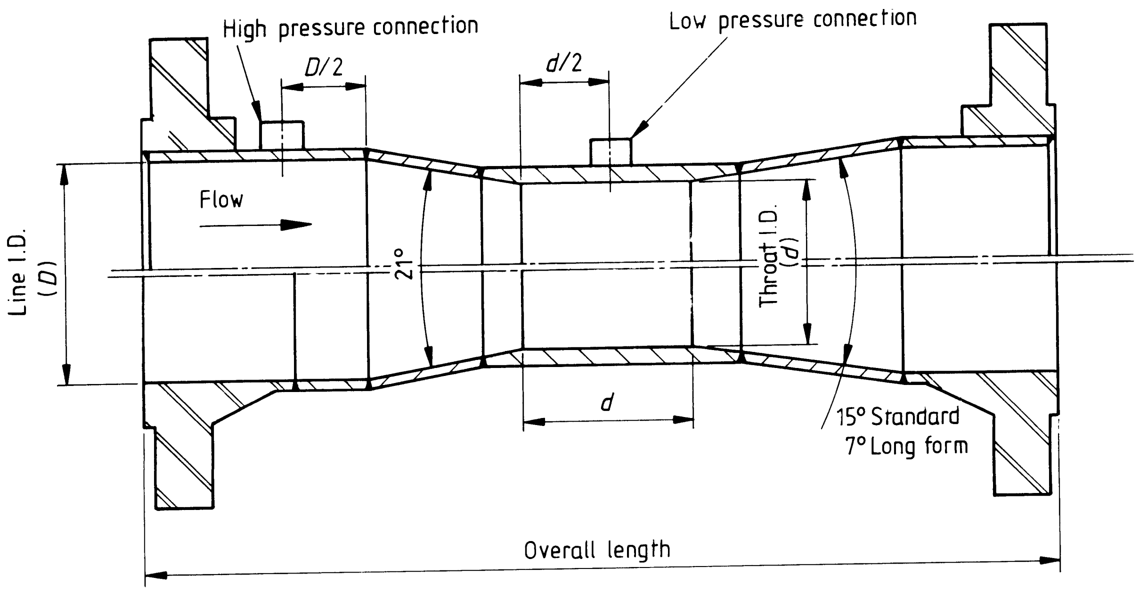
The classical venturi tube, shown in Figure 3.1.4, is a design standardized in BS 1042-1.1. There is a gradual change in section between the pipe diameter and the cylindrical throat. The differential pressure is measured between tappings in the entrance and the throat. The tolerance on the upstream tapping location, together with the blending radii between the conical and cylindrical sections, are specified in the standards for three different types of venturi, depending on the method of manufacture. These types are as follows:

a) classical venturi tube with a rough cast convergent section;

b) classical venturi tube with a machined convergent section;

c) classical venturi tube with a rough welded sheet-iron convergent section.

At both upstream and downstream locations there should be at least four equi-spaced tappings linked together. The main function of the divergent section is to decelerate the flow with maximum pressure recovery. However, it is possible to truncate the length of this section by up to 35 % without affecting the pressure recovery significantly. The overall pressure loss of the venturi tube depends on such factors as the throat/inlet diameter ratio, Reynolds number, divergent angle, surface finish, installation alignment, etc., and is generally between 5 % and 20 % of the measured differential pressure.



NOTE I.D. is the inside diameter.

Figure 3.1.4 — Classical venturi meter design

3.1.4.2 *Performance*

The discharge coefficients of venturi tubes are independent of diameter ratio and Reynolds number for the Reynolds number range 2×10^5 to 2×10^6. When manufactured and installed in accordance with the appropriate standards, the coefficient data for uncalibrated venturi tubes have uncertainties of:

0.7 % for tubes with rough case convergent sections

1.0 % for tubes with machined convergent sections

1.5 % for tubes with rough welded sheet-iron convergent sections

As with the orifice meter, these uncertainties can be reduced by flow calibration. The overall uncertainty in the flow measurement must allow for uncertainties in the expansibility, the throat and pipe diameters, the differential pressure and density measurements. Compared with the orifice the slightly greater uncertainty in the venturi discharge coefficient can be set against a smaller uncertainty in the venturi expansibility factor. The total measurement uncertainty achievable in liquid applications is around 2 % full scale and, in the comparatively rare applications in gases, around 3 % full scale.

3.1.4.3 *Advantages and disadvantages*

The advantages of the venturi tube compared with an orifice plate are as follows:

a) more robust than the orifice plate and less susceptible to particulate flows;

b) lower overall pressure loss than an orifice plate for the same differential pressure;

c) less sensitive to distorted velocity profiles and swirling flow, requiring shorter upstream straight lengths of pipe.

The disadvantages of the venturi tube compared with the orifice plate are as follows:

1) more expensive to manufacture;

2) occupies more space in the line, perhaps eight pipe diameters in length;

3) the larger sizes are more difficult to handle;

4) more susceptible to errors due to burrs or deposits round the throat tapping.

3.1.5 Nozzles

3.1.5.1 *Basic designs and construction*

There are two designs of nozzles in general use and both are standardized and described in BS 1042-1.1. These are the ISA 1932 nozzle and the long radius or ASME nozzle and are shown in Figure 3.1.5 and Figure 3.1.6 respectively. The ISA 1932 design is most commonly used in Europe whereas the ASME design is favoured in the USA. Both designs are intended for mounting between pipe flanges with the pressure tappings located in the pipe wall. Corner tappings are used for the ISA 1932 nozzle and D and $D/2$ tappings are specified for the long radius nozzle. The ISA 1932 nozzle profile is part of an ellipse.

The advantage in using a nozzle with throat taps is that a diffuser cone can be fitted to the downstream end to reduce pressure losses. This is done on a design known as a venturi nozzle standardized in BS 1042 and illustrated in Figure 3.1.7. The profile of the contraction in this device is that of the ISA 1932 nozzle.

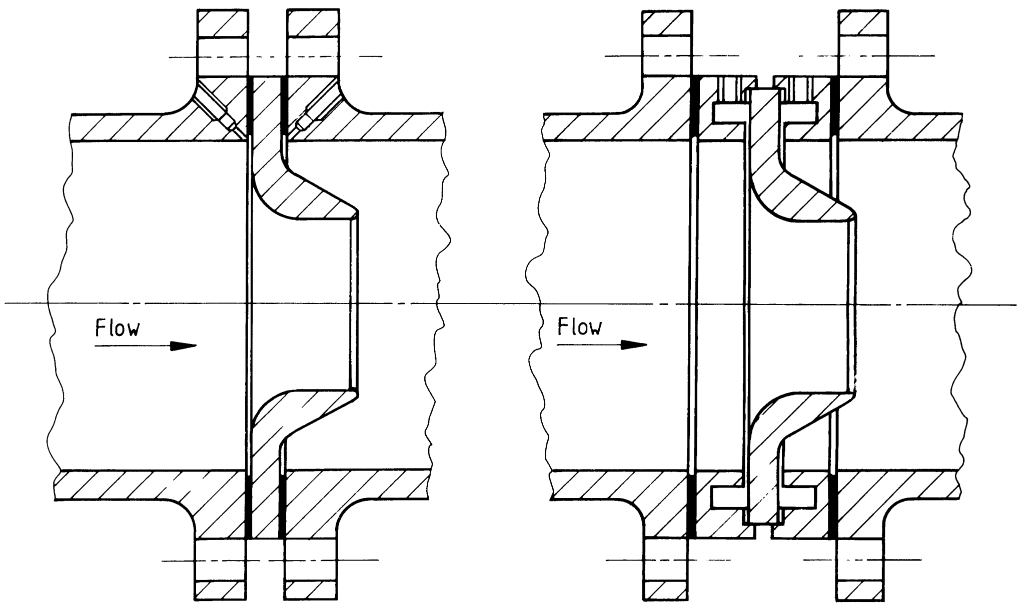


Figure 3.1.5 — ISA 1932 nozzle design

3.1.5.2 ***Performance***

The discharge coefficients of all the standard nozzles and venturi nozzles range between about 0.9 and 0.99 and depend on β ratio and Reynolds number. The uncertainty in the coefficient data varies both with the nozzle design and β ratio. BS 1042-1.1 gives the following typical values:

0.8 % for ISA 1932 nozzles ($\beta \approx 0.6$)

2 % for long radius nozzles ($0.2 \approx \beta \approx 0.6$)

Further data can be found in the relevant clauses of BS 1042-1.1. When combined with the other factors which contribute to total uncertainty an overall performance figure of around 3 % full scale at best is realized. This can be reduced significantly by flow calibration at operating conditions.

3.1.5.3 ***Advantages and disadvantages***

The advantages of nozzles compared with orifice plates are as follows:

a) no sharp edge to erode;

b) better retention of calibration for long periods.

The disadvantage of flow nozzles compared with orifice plates are as follows:

1) they are more expensive to manufacture;

2) they are more difficult to install and remove from the pipe;

3) throat tap type nozzles are more susceptible to errors due to burrs or deposits round the throat tapping.

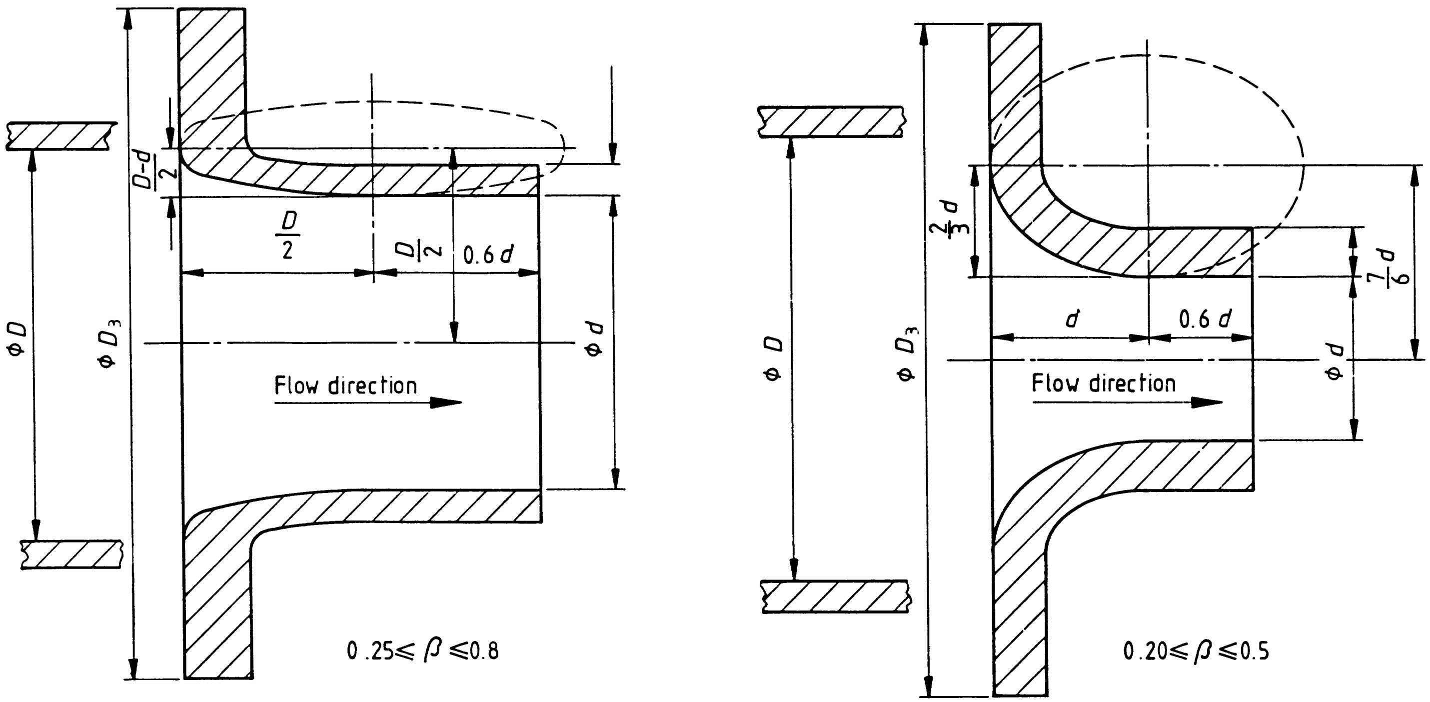


Figure 3.1.6 — Long radius flow nozzles

3.2 Group 2 meters: Other differential pressure types

3.2.1 General

This group of meters all operate on the differential pressure (DP) principle but consist of a variety of different designs. Some of these meters are not thought of as DP type meters while others are special adaptations of the basic orifice, venturi and nozzle meters discussed in **3.1**. Probably the most important type listed in this group is the variable area meter (**3.2.4**). Many thousands of these meters are sold each year and they find very varied and widespread use as flow indicators as well as meters. Multi-port averaging pitot tubes (**3.2.5.5**) are also beginning to sell in some quantity and several designs are now available.

3.2.2 Low loss meters

Although the venturi tube has a much lower pressure loss than orifice plates and nozzles, there are other differential pressure devices which have even lower losses for a given differential pressure. Many of these special devices achieve this by locating the upstream tapping in a near-stagnation region and the downstream tapping in the low pressure region on the inside of the flow curvature around a very short or curved throat. The differential pressure generated is much higher than that measured in a venturi tube of the same beta ratio and overall pressure loss expressed as a percentage of the differential pressure is significantly less.

One of the best known of these devices and probably the most commercially successful in the UK is the Dall tube® shown in Figure 3.2.1 (see Miner 1956). The low pressure tapping is in an annular slot at the junction of the inlet and diffuser cones. The presence of the slot allows the flow to re-establish itself on the diffuse cone surface to give excellent pressure recovery. The discharge coefficient of a Dall tube® is in the range 0.75 to 0.6 and depends on the β ratio. The overall pressure loss is between 2.5 % and 10 % of the measured differential pressure. The performance depends on the precision of manufacture and for this reason the Dall tube® is not usually made in sizes below about 150 mm diameter. The Dall short insert works on the same principle as the Dall tube® but is very much shorter. The pressure recovery is not as good however, and the overall loss is in the region of 10 % to 20 % of the differential pressure.

Other examples of proprietary low pressure loss devices are the Universal Venturi tube, the Lo-Loss tube (Figure 3.2.2), the Epiflo (Figure 3.2.3), and the Gentile tube (Figure 3.2.4). The Universal Venturi is somewhat different from the other types in that no attempt is made to increase the differential pressure; its discharge coefficient is similar to that of a Classical Venturi tube, but losses in the inlet are reduced by means of the double-cone contraction. This latter feature is claimed to make the Universal Venturi insensitive to upstream flow disturbances.

The devices described in this section are usually selected because they have low pressure-loss characteristics. It should be remembered, however, that there are non-differential pressure meter types that incur less or even zero pressure loss.

Disadvantages of low-loss differential pressure devices are that they are much more expensive than orifice plates and tend to be more sensitive to upstream disturbances than classical venturi tubes.

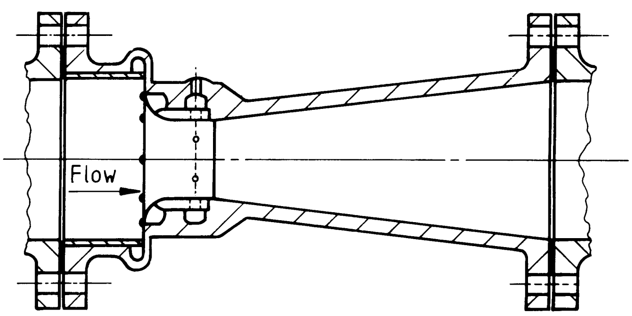


Figure 3.1.7 — Venturi nozzle

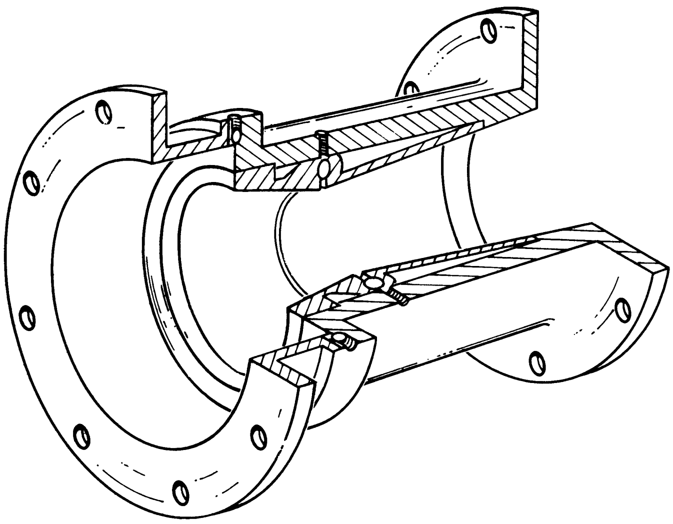


Figure 3.2.1 — Dall tube®

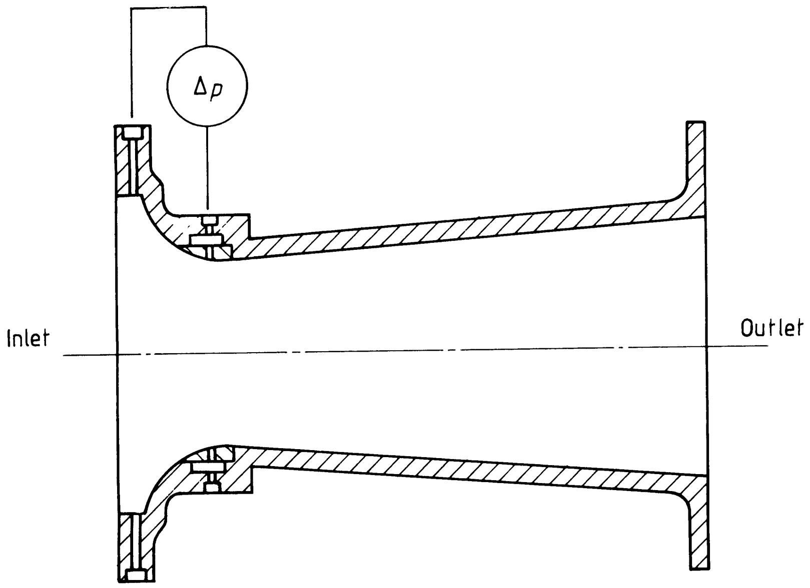


Figure 3.2.2 — Lo-Loss flow tube

3.2.3 Special designs of differential pressure meter

3.2.3.1 *General*

There are special designs of DP meter which find use in specific applications. The following are among the more important of the many designs commercially available.

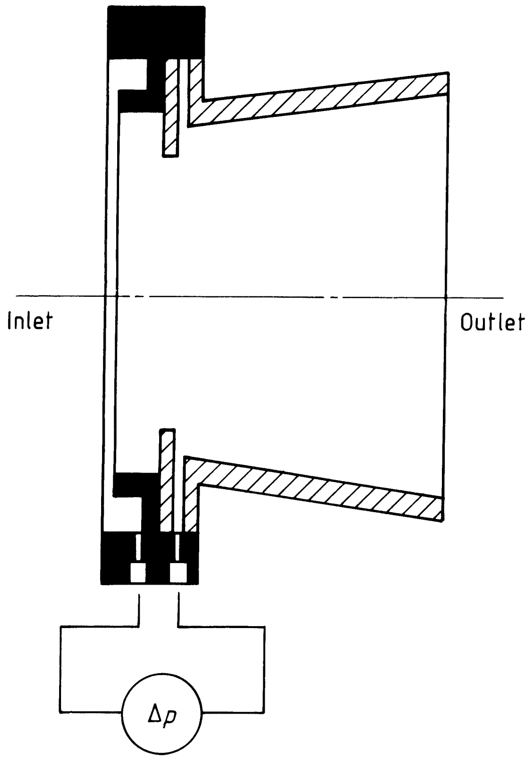


Figure 3.2.3 — Epiflo meter

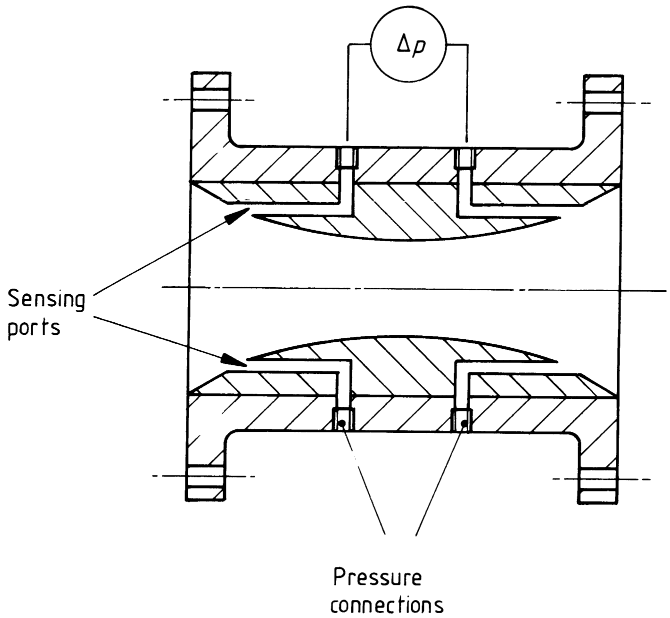


Figure 3.2.4 — One design of Gentile tube

3.2.3.2 ***Eccentric and segmental orifice plates***

These devices are mostly used to allow the free passage of solid particles or gas bubbles, which would otherwise tend to the trapped against the upstream face. The segmental orifice is a plate which is a segment of the pipe bore. The eccentric orifice has a circular hole which touches the pipe bore. For liquids containing gases the orifice is positioned at the top of the pipe and for gases containing liquids or liquids containing solids at the bottom of the pipe; see BS 1042-1.2. The segmental orifice has superior drainage properties to those of the eccentric orifice but is inferior in other respects such as coefficient data uncertainty.

3.2.3.3 ***Wedge meters***

The constriction is formed by a V-shaped wedge protruding into one side of the pipe as shown in Figure 3.2.5. Looking down the pipe the shape of the throat is a segment of a circle but unlike a segmental orifice there is no sharp edge. The device is robust and is suitable for clean or dirty fluids including those with solid suspensions. It is claimed to have a discharge coefficient characteristic which is flat even at pipe Reynolds numbers below 1 000, making the meter useful for the measurement of viscous fluids.

3.2.3.4 ***Orifice plates for low Reynolds numbers***

Various attempts have been made to modify the geometry of the orifice plate to obtain a constant discharge coefficient spanning the laminar transition and turbulent flow regimes in a pipe. In the most successful designs the sharp edge of the standard orifice plate is replaced by a more gradual entrance to the throat. This has the effect of obtaining a better balance between jet contraction effects and frictional effects at low Reynolds numbers. The two designs in general use are the quarter circle and conical entrance orifice plates.

The quarter circle orifice plate is shown in (a) of Figure 3.2.6. The circle radius specified in BS 1042-1.2 is a fraction of the orifice bore and depends on the β ratio. The upper limit of the pipe Reynolds number is 6×10^5 and the lower limit for small beta ratios is 5×10^2. The discharge coefficient is constant over this range but is a function of β. The uncertainty in the coefficient data given in the standard is 2 % to 2.5 % of rate depending on whether β is greater or less than 0.316.

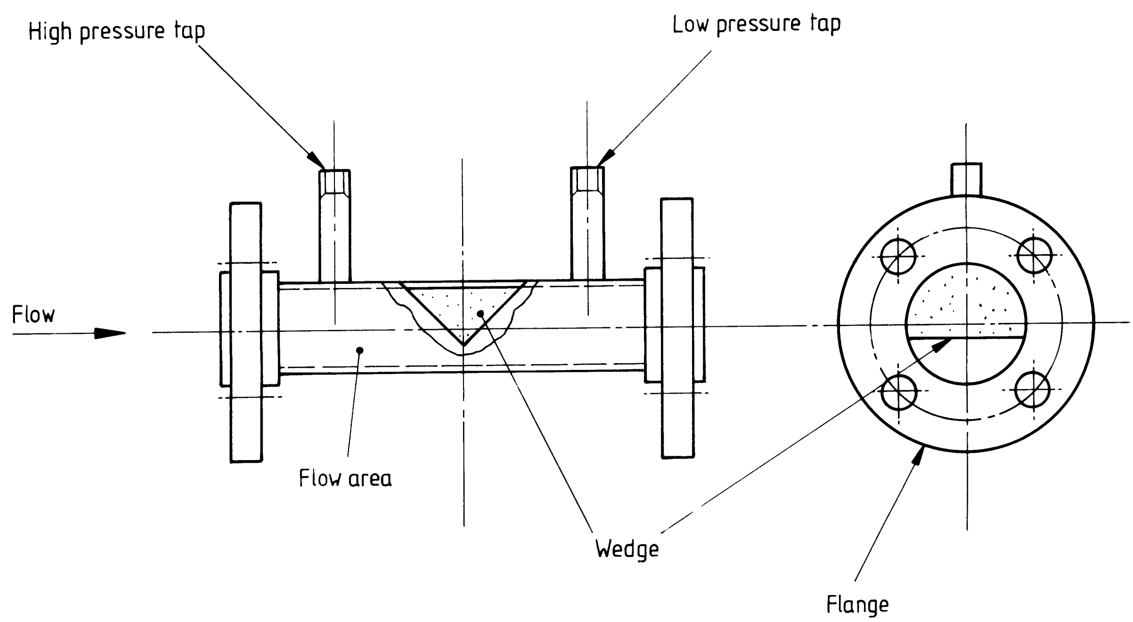
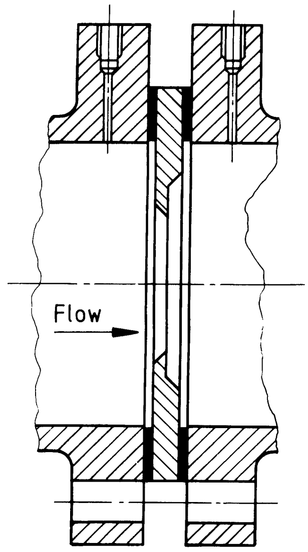
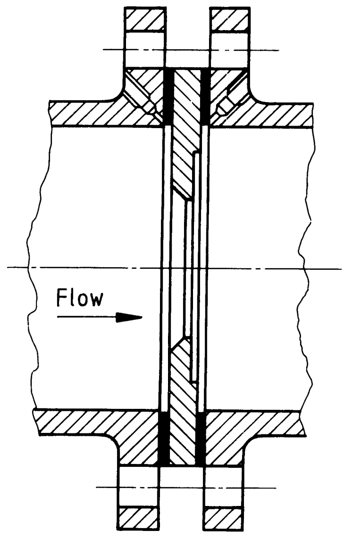


Figure 3.2.5 — Wedge meter



(a) Quarter-circle orifice plate



(b) Conical-entrance orifice plate

Figure 3.2.6 — Orifice plates

The conical entrance orifice plate is shown in (b) of Figure 3.2.6. The entrance is a 45° cone which intersects with a short cylindrical throat. The permissible axial length in accordance with BS 1042-1.2 may be less than the plate thickness, and a recess is then cut on the downstream face.

The plates are only used with small β ratios ($0.1 \leq \beta \leq 0.316$) but for these sizes the same discharge coefficient of 0.734 can be used in the pipe Reynolds number range $80 \leq Re_D \leq 6 \times 10^5$. The uncertainty in the coefficient data is 2 %. The conical entrance orifice plate can be used at lower pipe Reynolds numbers than the quarter circle plate but a smaller range of β ratios are permissible in accordance with BS 1042-1.2.

3.2.3.5 ***Integral orifice***

The integral orifice meter is a concentric orifice plate that is mounted inside or directly attached to the differential pressure transmitter. It extends the pipe size range of orifice meters from the recommended minimum of 50 mm down to 5 mm. The coefficient data is not as well developed as the larger conventional orifice meters and indications are that the uncertainty on the discharge coefficient is around 3 % of flow rate. The reason for this larger uncertainty is the range of β values available. The integral orifice can be manufactured with area ratios between 0.1 and 0.7. The Reynolds number constraint varies directly with the β ratio of the plate, the smaller the β ratio the lower the Reynolds number. This device is discussed further by Felton (1972).

3.2.3.6 ***Bypass devices***

When an external bypass tube is connected across an orifice plate, the bypass flow is a constant fraction of the total over a wide flow range. Several manufacturers have exploited this by placing a meter with either a linear or non-linear response in the bypass. The Rotary Shunt® meter, designed many years ago, and shown in Figure 3.2.7, is still used for liquids, gases and steam. Another example is the Litre Meter® which uses a Pelton wheel device in the bypass line. Other types of meters which have been used in the bypass line include variable area meters (see **3.2.4**) and thermal meters (see **3.9**). The bypass meter has the advantage that its overall cost, including the orifice, is less than that of an in-line linear flowmeter. It has however the disadvantage that in performance it is inferior to the full bore meter.

3.2.4 Variable area (VA) meters

3.2.4.1 ***General***

Two basic designs of VA meter have evolved. The more common is the type where pressure difference across a float is constant (e.g. Rotameters®) and the second type allows both pressure difference and area to change.

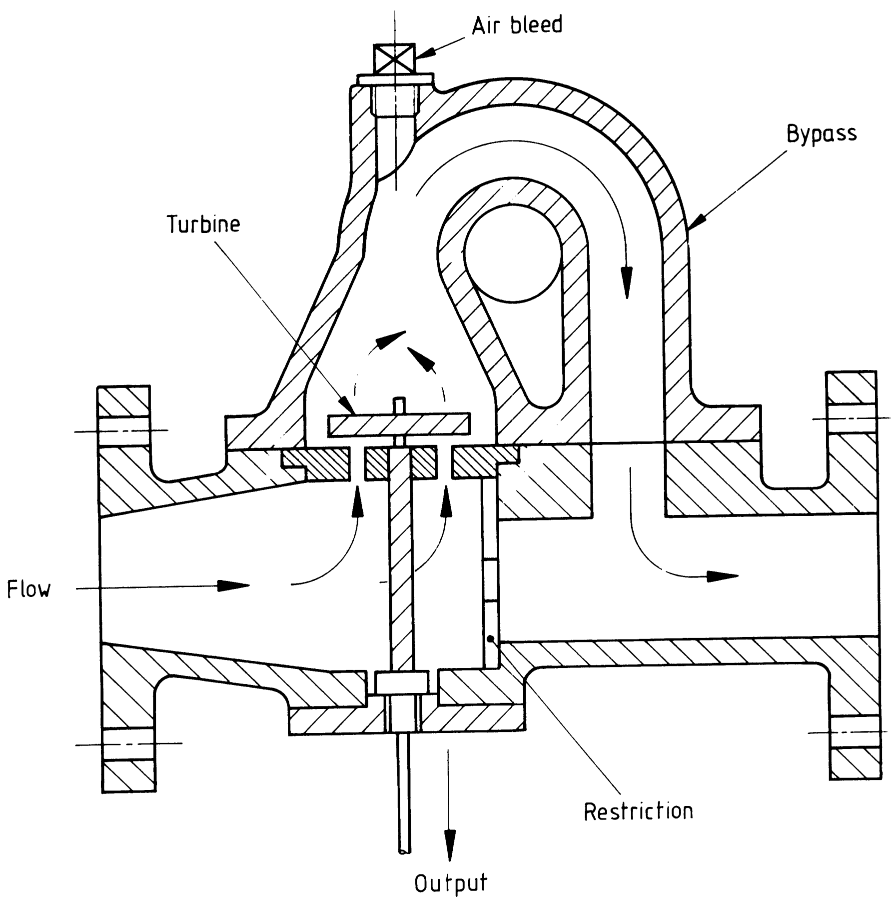


Figure 3.2.7 — Simplified arrangement of the Rotary Shunt® meter

3.2.4.2 ***Constant differential pressure***

In the simplest type of variable area meter, the body is a tapered transparent vertical tube with a printed or etched scale on plastic or glass. Inside the tube is a float of greater density than the fluid being metered. This is circular in shape, often with small grooves cut into the upper surface so that the float spins slowly. A typical design is shown in Figure 3.2.8. When there is no flow the float rests on the bottom seat. When flow commences, the float rises from the seat, maintaining a fixed pressure drop of equilibrium with gravity and buoyancy forces. To maintain a fixed pressure drop across the float as the flow increases, the float rises further thereby providing a wider annular area for the passage of fluid. Thus, at every position in the tube, the weight of the float, less its buoyancy in the fluid, is exactly balanced by the force of the fluid on the float. The height is then a direct function of flow rate and the value can be read from the marked scale.

When a meter is required for a viscous fluid, a special float with a sharp leading edge is used. Thin disc floats have been found to be relatively insensitive, whereas sphere floats are usually very sensitive to changes in viscosity. Sensitivity to fluid density changes can be reduced by selecting a float material which has a density much greater than that of the fluid.

Variable area meters are not normally regarded as high performance devices and the tapered transparent tube variety is usually selected for its cost effectiveness rather than performance. It is also a visual flow indicator. For such meters uncertainties of 2 % to 3 % of full scale would be typical. Versions manufactured to a greater precision (and thus more expensive) can give uncertainties around 0.5 % of full scale with individual calibration. A disadvantage of tapered tube meters with free floats is that they have to be mounted vertically.

Designs with metal tapered tubes are available and these generally have floats guided by an axial rod. Other designs use cylindrical tubes with out-flow ports progressively uncovered by a piston rising with increasing flow rate. All designs in which the differential pressure is constant across the float or piston have a range of about 10 : 1.

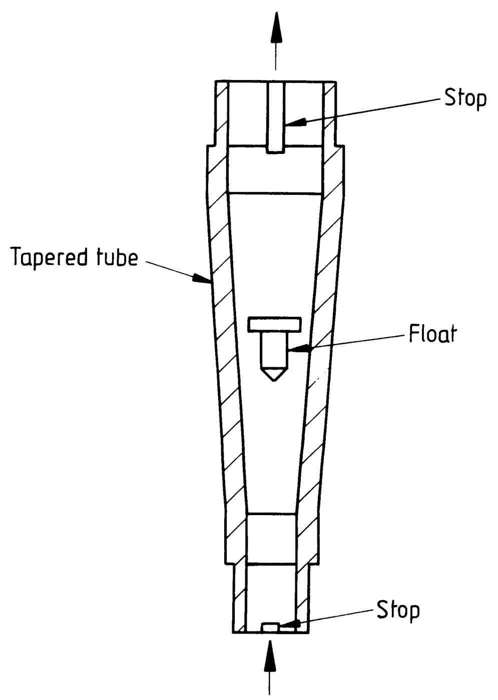


Figure 3.2.8 — Variable area flowmeter

3.2.4.3 ***Variable orifice***

An example of a design in which both differential pressure and flow area change with flow rate is the meter shown in Figure 3.2.9. The flow area changes as the shaped plug moves relative to the fixed orifice. As the plug movement is restrained by a spring, the differential pressure increases with flow rate. The differential pressure is the output signal and the plug profile can be designed to give a linear relationship over a very wide flow range. As a result of having moving parts and a spring, which are subject to wear, this device has the disadvantage of possible changes in its characteristics. This and other characteristics are discussed in Hayward (1976) or Turner (1972).

3.2.5 Insertion types

3.2.5.1 ***General***

Full bore flowmeters for larger pipe sizes can be very expensive and, if the optimum performance is not required, an insertion flowmeter device may be considered, particularly if low pressure loss is a requirement. Insertion devices are those which can be inserted into a pipe through a small branch, usually via a gland assembly. A valve may be incorporated on the pipe side of the gland to enable the insertion device to be installed without depressurizing the pipe.

The insertion device can usually measure single point velocities within the pipe or sometimes an averaged multipoint velocity. The total flow rate can then be obtained using velocity area techniques as described in **3.2.5.3**. All the devices described in this section involve the measurement or use of the difference between two pressures measured at tapping points in the device, although the insertion principle is also applicable to other types of device.

NOTE The main types of insertion device and the relevant clauses in which they are described are as follows:

a) differential pressure (pitot tubes) (**3.2.5**);
b) inferential (turbine) (**3.4.7**);
c) vortex (**3.5.5**);
d) electromagnetic (**3.6.6**);
e) thermal (**3.9**).

3.2.5.2 ***Pitot and pitot static tubes***

When the mouth of a pitot tube faces directly into an inviscid incompressible flow, the pressure inside the tube will be the stagnation pressure, p_o, where:

$$p_o = p + \tfrac{1}{2}\rho U^2 \qquad (3.2.1)$$

If the static pressure can be measured by means of a conveniently placed pressure tapping, then the local velocity can be determined from the difference between stagnation and static pressures:

$$U = C' \left\{\frac{2(p_o - p)}{\rho}\right\}^{½} \qquad (3.2.2)$$

where

C' is the flow coefficient which depends on the pitot tube design.

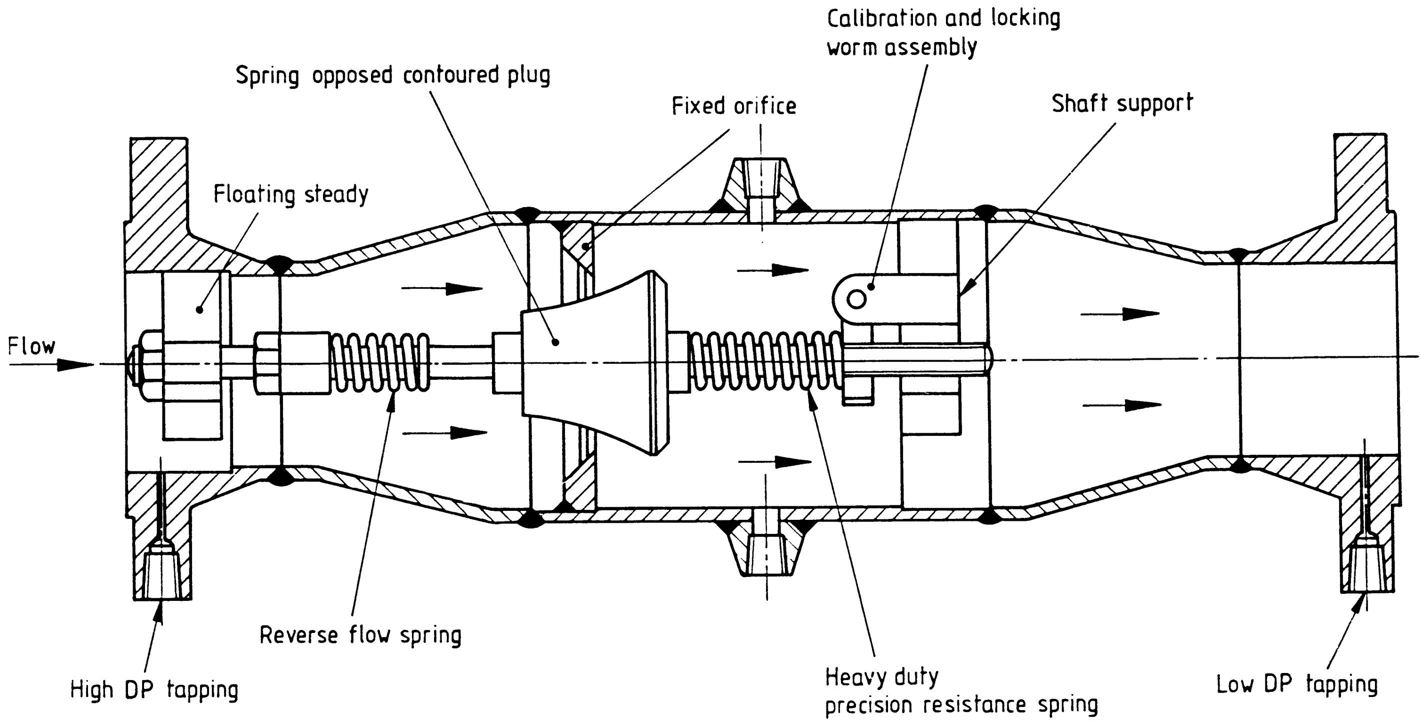
The static pressure tapping can be placed in the pipe wall in the same plane as the mouth of the pitot tube. Alternatively, the static pressure can be measured using a pitot-static combination probe as shown in Figure 3.2.10. The pitot-static probe consists of a pair of concentric tubes. The inner tube is the pitot whereas the static pressure tappings are in the wall of the outer tube. Connections are made to either side of a differential pressure sensor which then indicates the velocity head. Both pitot and pitot-static tubes can only measure the local velocity, but the bulk mean velocity in the pipeline will normally be required.

3.2.5.3 ***Velocity area integration***

The bulk mean velocity can be obtained by averaging velocities measured at several points selected according to the log-linear rule on one or more diameters. Details of this technique are described in **3.10.7**.

3.2.5.4 ***Three-quarter radius pitot***

If a pitot tube is located at a point 0.75 *r* from the pipe centre line the velocity measured will be approximately equal to the bulk mean value, provided the velocity profile is typical of fully developed turbulent flow. The performance will vary with Reynolds number and pipe roughness, and will be seriously affected if the location is too close to an upstream bend, valve or other fitting. Improved results are obtained if the probe is calibrated in situ.



NOTE DP is differential pressure.

Figure 3.2.9 — Variable area differential pressure meter

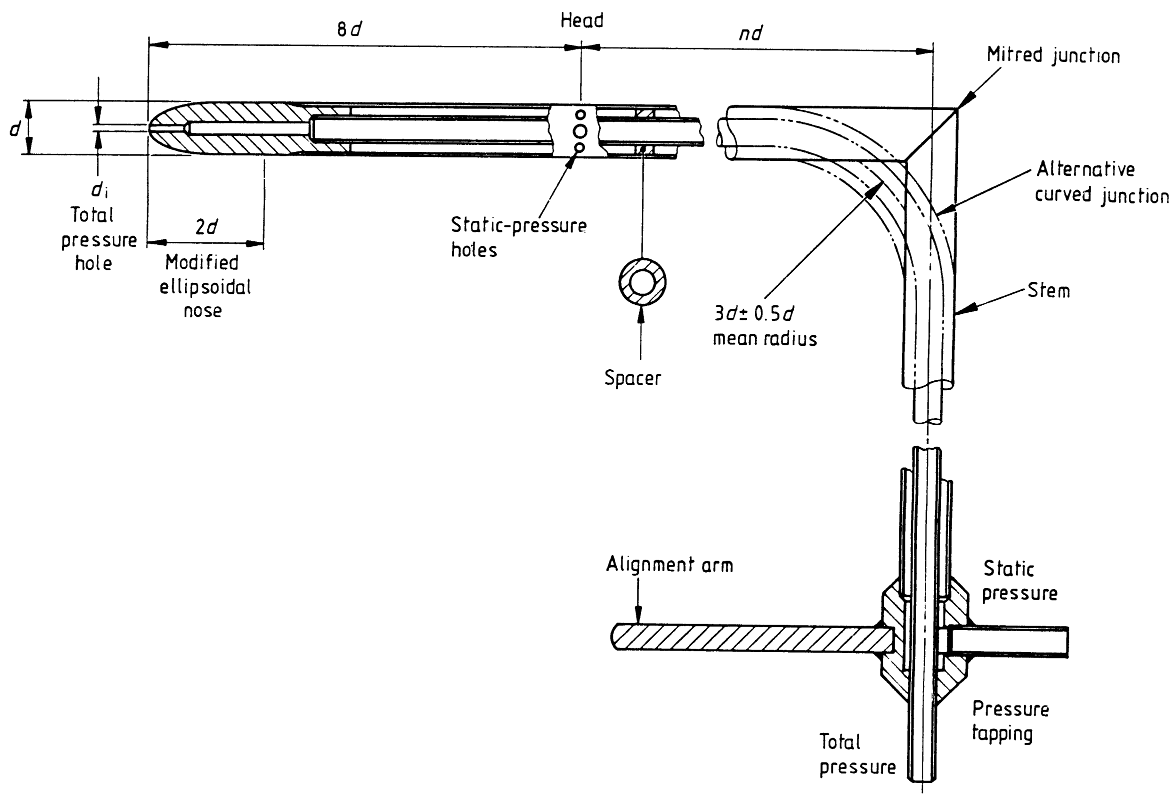


Figure 3.2.10 — NPL standard pitot-static tube

3.2.5.5 ***Averaging pitot tube***

This device, an example of which is shown in (a) of Figure 3.2.11, consists of a probe which spans the pipe. A number of forward facing holes are subject to slightly different stagnation pressures and the pressure inside the tube is close to the value corresponding to the bulk mean velocity. The low pressure tapping point is at the rear of the probe. This device is much more reliable than the single three-quarter radius pitot.

3.2.5.6 ***The Wilson flow grid***

This is a volume flow rate measuring device designed to give an enhanced pressure differential signal by accelerating the flow between an array of interconnecting closed-end pressure tubes which span the conduit.

Two designs of grid are available:

a) parallel array for use in rectangular conduits;

b) radial array for use in circular conduits.

These designs are illustrated in (b) and (c) of Figure 3.2.11 respectively. The differential pressure obtained across the external tappings is related to the average velocity and hence the volume flow rate in the conduit. It has been found that the signal obtained lies between 2.0 times and 2.8 times the mean upstream dynamic head and the loss/signal ratio lies between 0.075 and 0.145 dependent upon the design and size of the grid.

3.2.6 Inlet meters

3.2.6.1 *General*

When air is drawn into a pipe from a large open space free from wind or draughts it accelerates from rest to a velocity U and ideally, according to the Bernoulli equation, there will be a fall in static pressure equal to the kinetic pressure. In practice the shape of the inlet will affect the magnitude of the static pressure drop and the mass flow rate will be given by:

$$q_m = C\,A(2\rho\ \ \Delta p)^{1/2} \tag{3.2.3}$$

where

C is a discharge coefficient dependent on the inlet geometry.

3.2.6.2 *Borda inlet*

The air flow Borda inlet has two sets of tappings, the set nearer to the inlet for the differential pressure measurement Δp, and the second set for pressure measurement from which the density ρ can be calculated. The coefficient of discharge is of the order of 0.5, but the value depends on the ratio of wall thickness to outside diameter (see Figure 3.2.12). [See also Kinghorn and McHugh (1978)].

3.2.6.3 *Inlet meters for fan testing*

Three acceptable devices, namely the square edged orifice plate, the venturi nozzle and the conical inlet are specified in BS 848-1. For all three devices the mass flow rate is calculated from:

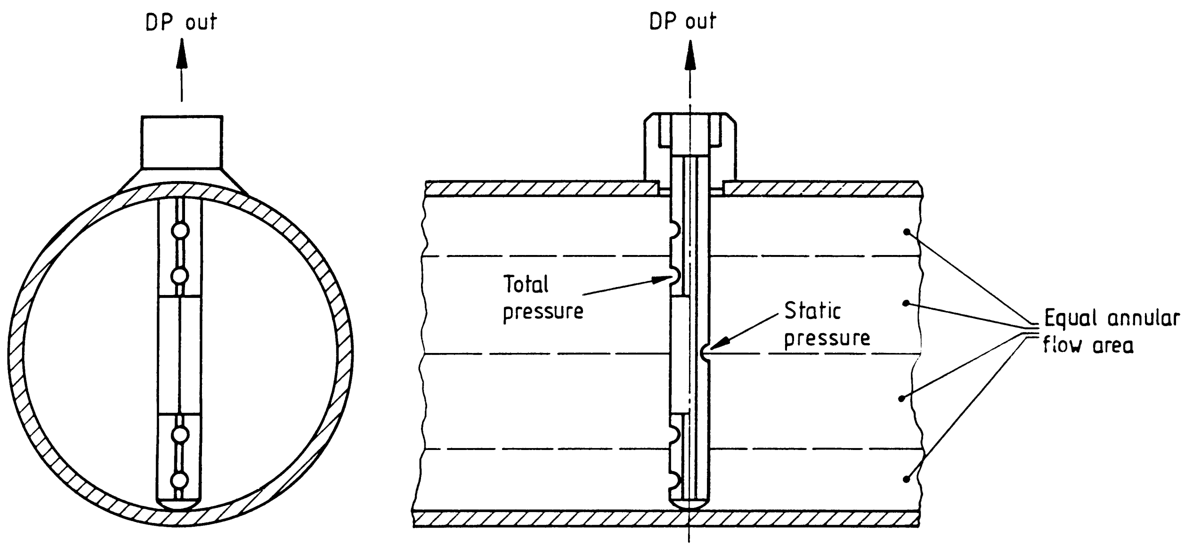
$$q_m = C\,A\,\epsilon(2\,\rho_a\,\Delta p)^{1/2} \tag{3.2.4}$$

where

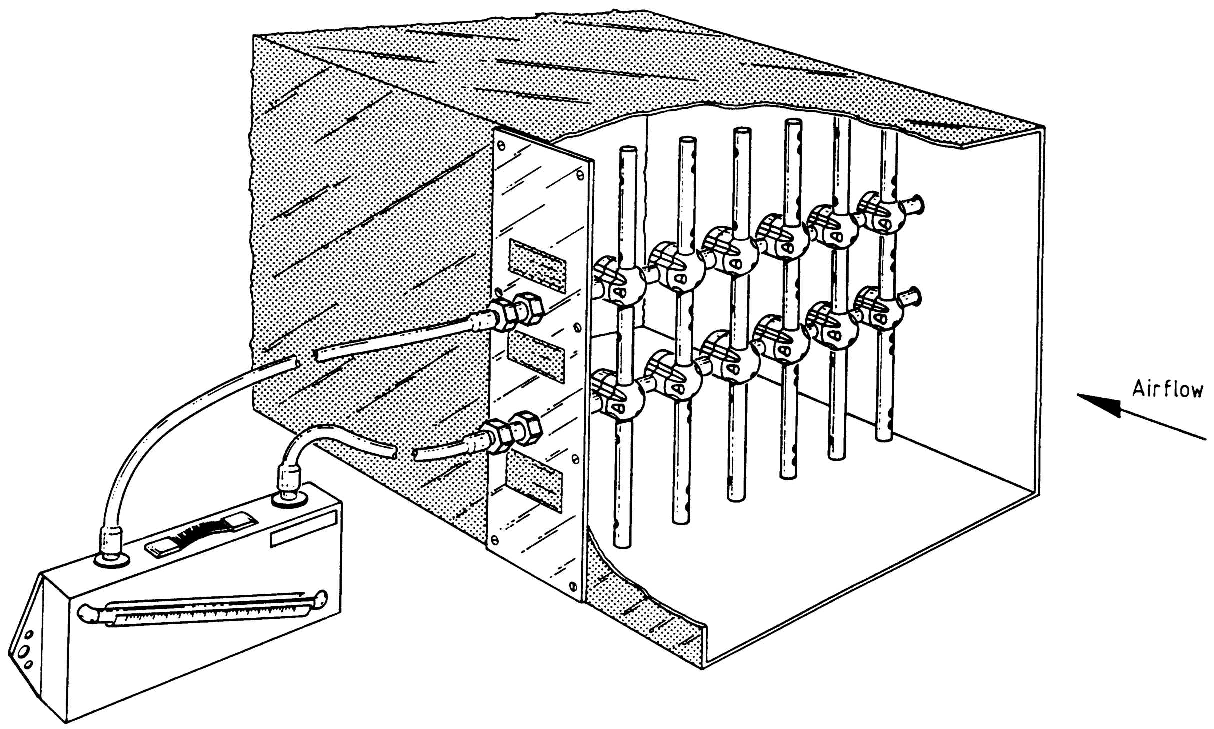
ρ_a is the ambient air density (in kg/m^3).

The orifice plate is set at the inlet end of the fan ducting and a downstream corner tapping is used to measure the pressure drop from the outside. The flow through the orifice plate is calculated in the normal way using the data given in BS 848-1 for an orifice with a beta ratio of zero. The data in BS 1042-1.2 is only applicable for β ratios greater than 0.2.

The venturi nozzle inlet profile and throat geometry specified in BS 848-1 is virtually identical to that specified for the BS 1042-1.1. In all three devices there are four equi-spaced tappings externally interconnected by a piezometer ring. The venturi nozzle inlet is the most difficult to manufacture and therefore the most expensive. The orifice inlet has a greater overall pressure loss for a given differential pressure than the other two inlets but has the advantage that plates of different beta ratio can be easily fitted to the same inlet ducting. The uncertainty in coefficient and expansibility data is similar for all three devices.

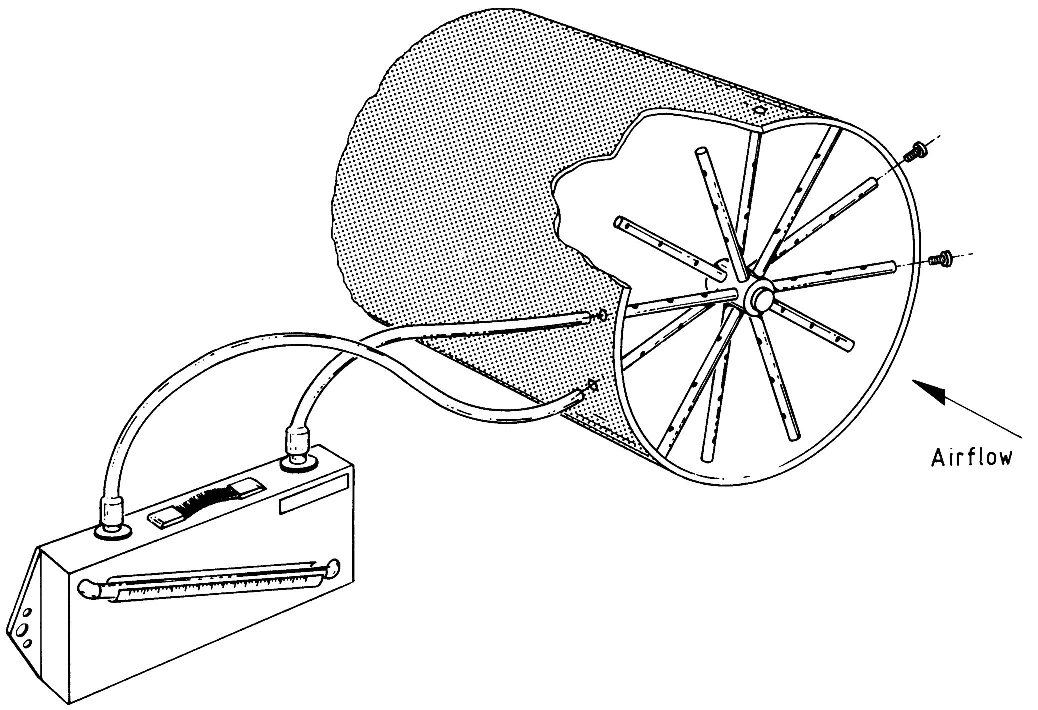


(a) Multi-port averaging pitot



(b) Wilson flow grid, parallel array

Figure 3.2.11 — Insertion type flowmeters



(c) Wilson flow grid, radial array

Figure 3.2.11 — Insertion type flowmeters *(concluded)*

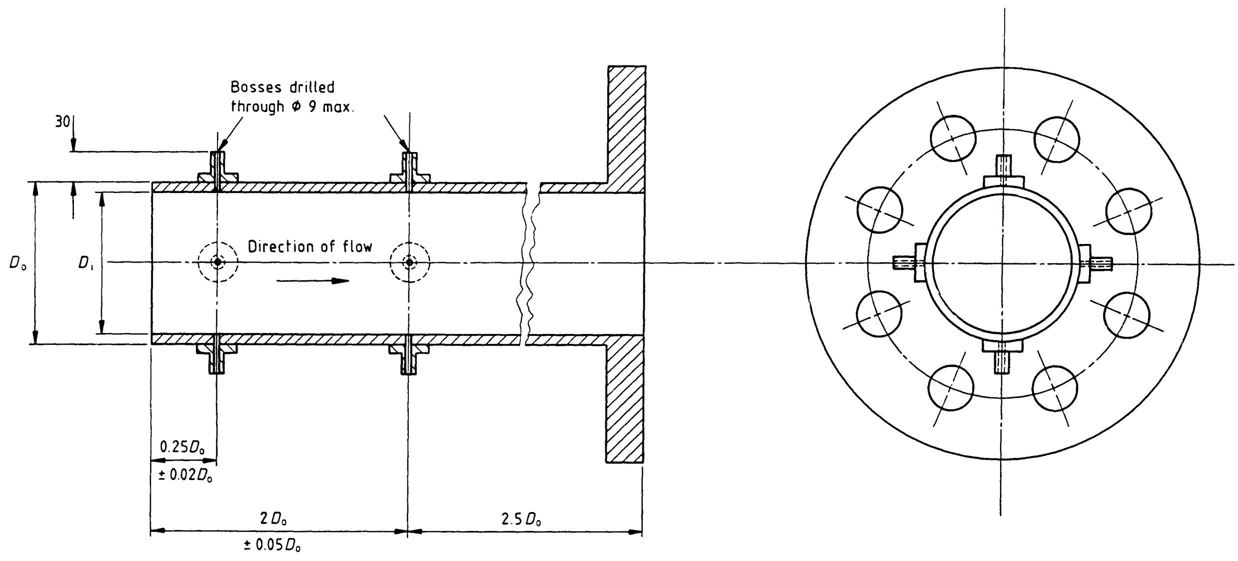


Figure 3.2.12 — Borda inlet

3.2.7 Miscellaneous types

3.2.7.1 *Sonic nozzle*

When the ratio of the pressure downstream of a convergent or a convergent-divergent nozzle to the upstream pressure is sufficiently low, the velocity in the throat is the local speed of sound and the nozzle is said to be choked. Under these critical flow conditions the ideal mass flow rate, assuming isentropic expansion of a compressible fluid (gas or vapour), is given by:

$$q_m = C A_t \ p_o C_* (RT_o)^{-1/2} \qquad (3.2.5)$$

where

- C is a discharge coefficient;
- C_* is the critical flow function dependent on the gas and on the initial pressure and temperature;
- A_t is the throat area (in m^2);
- T_o is the stagnation temperature (in K).

A basic design is shown in Figure 3.2.13 and is discussed in more detail by Hillbrath (1976) or Miller (1989). Data for the critical flow function are tabulated for various gases and superheated steam in Miller (1982). This reference also discussed the available discharge coefficient data for various designs of critical flow nozzles. The overall pressure ratio to ensure critical flow depends on the diffuser area ratio and the isentropic index of the gas but is typically around 0.9. An advantage of the sonic nozzle is that it has a constant coefficient of discharge and uncertainties of measurement less than 1 % of reading. A further advantage is that performance is entirely unaffected by downstream flow disturbances, including pulsations. Disadvantages include the significant pressure loss and the fact that flows through systems containing sonic nozzles can only be controlled on the upstream side.

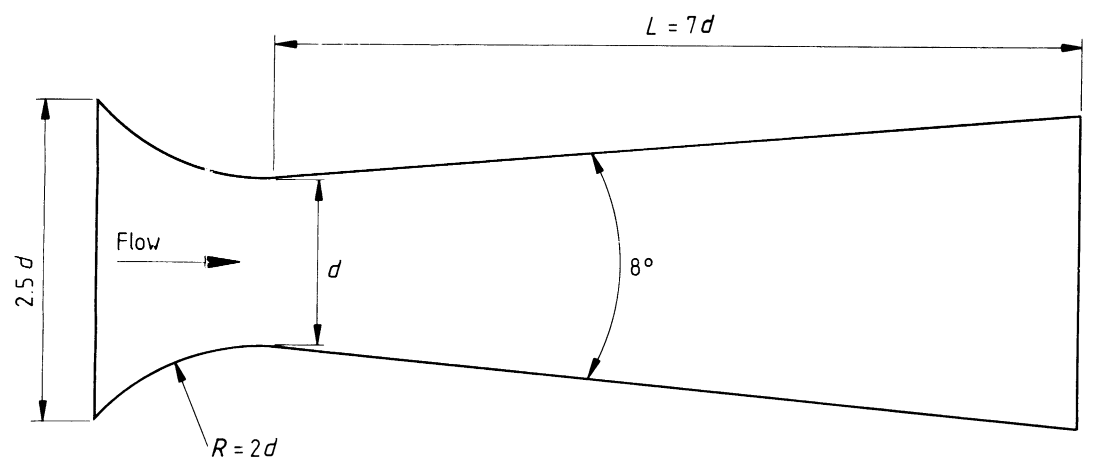


Figure 3.2.13 — Basic sonic flow nozzle

3.2.7.2 ***Elbow meter***

This meter makes use of the fact that there is a pressure difference between the inside and outside walls of a 90° bend proportional to $\frac{1}{2}\rho U^2$. Tappings are located in the plane of the bend on the 45° bisector as shown in Figure 3.2.14. Design and performance details can be found in Miller (1982) or the Shell Flowmeter Engineering Handbook (1986). Advantages are that the meter does not add to the system pressure loss assuming that the bend is necessary. A disadvantage is the small differential pressure signal, especially for gases.

3.2.7.3 ***Target meter***

This meter, also called the drag plate meter or drag disc, is shown in Figure 3.2.15. It operates on the principle that a measurement of force on a suspended body gives an output which is related to flow. Velocity changes around the body result in pressure changes. The drag force on the body is due to the differential pressure acting on the upstream and downstream surfaces. In turbulent flow, the force on the body, F_T (in Kg·m/s^2), is calculated from the equation:

$$F_T = C'' \rho A_b U^2 \qquad (3.2.6)$$

where:

C″ is the flow coefficient;

A_b is the area of the body (in m^2).

The output signal, i.e. the force on the body, is proportional to the square of the flow in the turbulent flow regime. Operation is generally not linear outside the turbulent flow regime. Thus the flow rate equation is:

$$q_m = C\,D\left\{\frac{\left(1-\beta_T^2\right)}{\beta_T}\,\epsilon\sqrt{\left\{\frac{\pi}{2}\rho\frac{F_T}{\{1-(1-\beta_T^2)^2\}}\right\}}\right. \qquad (3.2.7)$$

where

β_T is the diameter ratio (i.e. diameter of drag plate/D).

The advantages of the target meter compared with the basic concentric orifice meter are as follows:

a) it allows free passage of gas bubbles, liquid droplets or solid particles when present;

b) there are no pressure tappings to become blocked;

c) it is responsive to transient or fluctuating flow.

Disadvantages of the target meter compared with the basic concentric orifice meter are as follows:

1) like the orifice its non-linear response limits its range and pressure losses can be significant;

2) it is limited to small pipe sizes;

3) it has a fulcrum which is prone to damage.

3.2.7.4 ***Linear resistance (laminar) meters***

A characteristic of laminar or viscous flow is that the pressure drop along the flow duct is directly proportional to the fluid velocity, whereas in turbulent flow the pressure drop is proportional to velocity squared. Laminar flow is achieved by forcing the fluid through small diameter tubing for low flow levels or through narrow slots or honeycomb type material for higher flows, always keeping the Reynolds number below 2000. Pressure connections have to be made within the length of the element if a true linear relationship is required because there are turbulent flow entry and exit effects. Because the pressure response is linear, flow turndown can be as good as the discrimination of the differential pressure measurement. This means that 100:1 is normal and better than 1000:1 is possible. Calibration depends only on dynamic viscosity (a characteristic of the fluid being measured) while density and pressure have no effect, except to the maximum flow allowed.

The advantages of this type of meter are as follows:

a) linear response;

b) wide flow range;

c) relatively unaffected by pulsations;

d) bi-directional.

The disadvantages of this type of meter are as follows:

1) bulky for higher flows;
2) clean fluids important, gases should be reasonably dry;
3) affected by changes in viscosity, but this can be accounted for;
4) high pressure loss.

3.3 Group 3 meters: positive displacement (PD) types

3.3.1 General

The positive displacement meter operates by the successive mechanical division of the metered fluid into separate pockets. The number of pockets of known size which are passed indicates total volume and the frequency at which they pass gives flow rate. The positive displacement meter, (often simply called the PD meter), is therefore capable of indicating both quantity and rate of flow. Most meters in this group are driven by the flow. The exception is the metering pump which is powered externally.

Unlike other metering devices, PD meters can have the characteristics of both self-priming pump and prime mover and in some configurations it performs one or both of these functions in addition to its metering role. The cyclic volume of the PD meter is a function of the swept volume of the measuring chamber or chambers, i.e. the volume being swept by rotation or reciprocation. It is essentially a total quantity device and is usually unsuitable for instantaneous flow rate measurement due to intrarotational non-linearity, i.e. its volume/cycle relationship is usually sinusoidal, unless the flow rate is determined over a long period of time. While the principle of operation of the PD meter is simple, many of the designs are highly ingenious and depend upon precision in both manufacture and assembly.

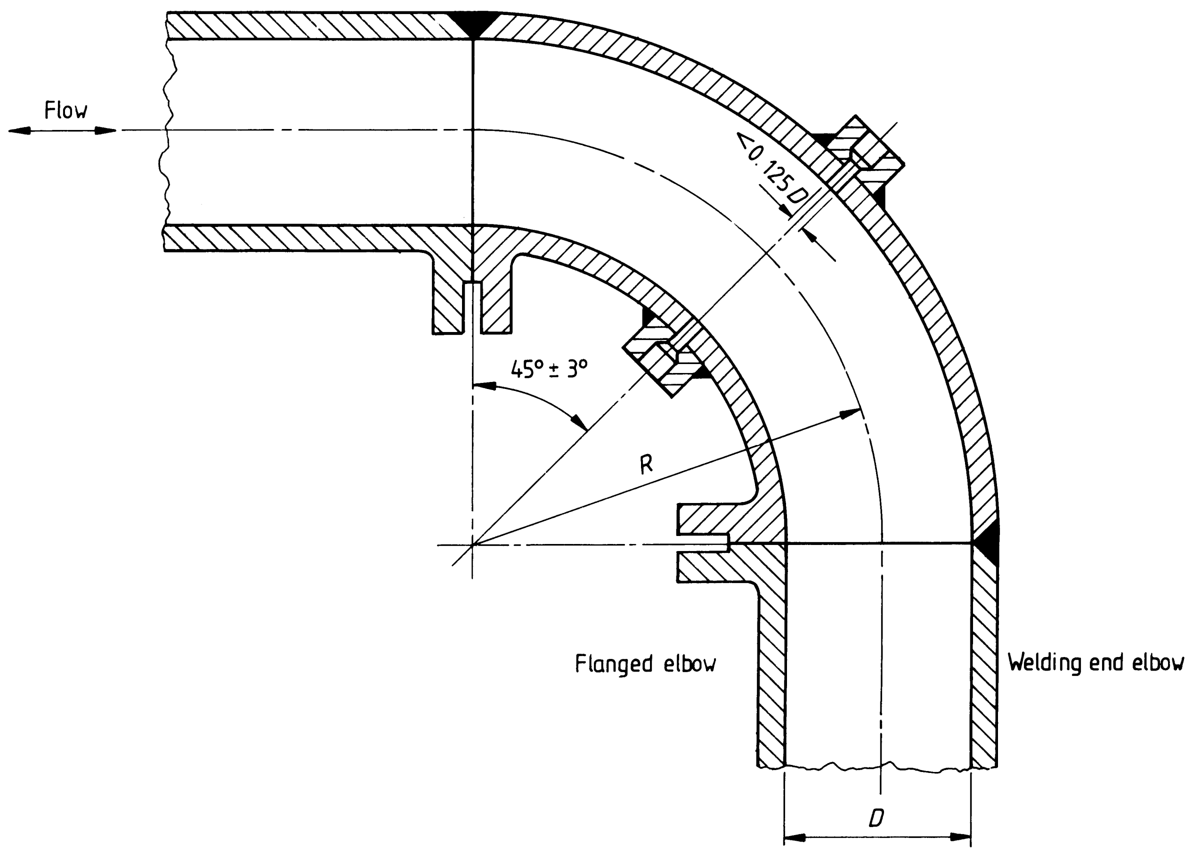


Figure 3.2.14 — Elbow meter

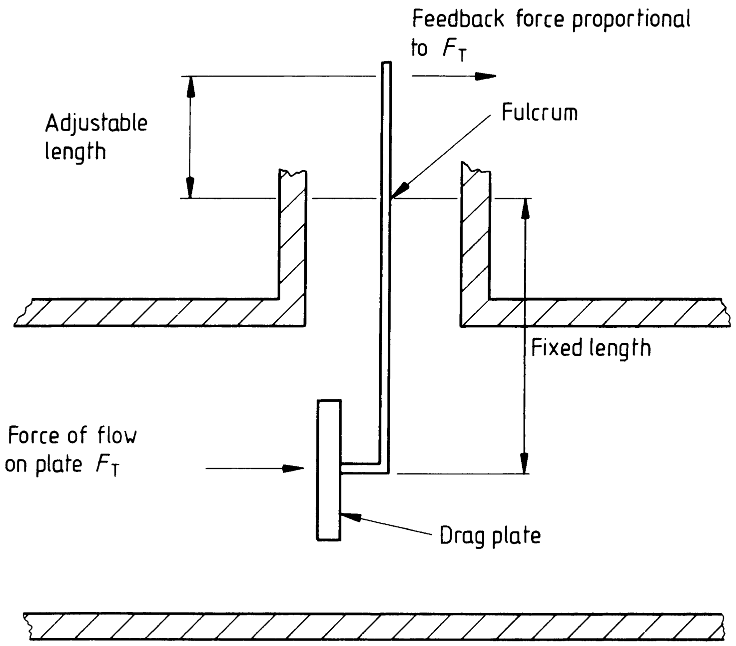


Figure 3.2.15 — Target meter

For legal metrology applications with hydrocarbons, oils, gases and water, the volume registers and metering chambers are sealed to prevent tampering and fraud. Such meters are subject to type approval by the relevant authority.

3.3.2 Basic characteristics and types

PD meters are one of the oldest groups of flowmeters and consequently are well tried and trusted with defined applications guidelines and known characteristics. Some types of displacement flowmeters have measurement uncertainties that are among the lowest of any flowmeter currently available. Many designs are manufactured to close tolerances to ensure that leakage past or through the metering element does not degrade performance. A recent paper by Baker and Morris (1985) discusses the many designs available and presents a theoretical analysis of the more important parameters affecting performance.

One of the more unusual characteristics of this class of meter is that as viscosity increases, performance improves. This is because the metering element of leakage is reduced, due to increased fluid resistance. It is the reason why PD meters find very widespread use in the metering of viscous fluids, particularly hydrocarbons (see Hendrix 1982). They also do not suffer from the effects of inlet flow variations and unlike most other types of flowmeter are not significantly affected by either inlet swirl or velocity profile distortion. However, the precise tolerances of manufacture are also a limitation when they are used on dirty process fluids. Any abrasive fluid action, will cause wear on critical components and for this reason they are generally for use with clean fluids only.

The group can be subdivided into four main classes as follows:

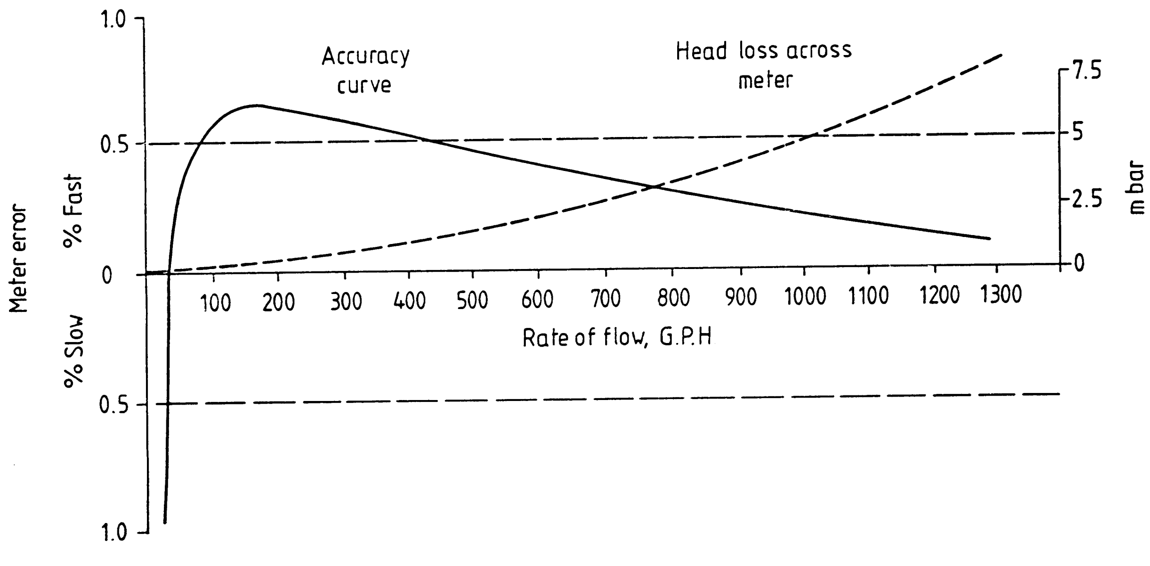
a) reciprocating motion (single and multiple piston);

b) rotating motion (vane and gear types);

c) oscillating motion (semi-rotary meters);

d) nutating motion (disc meters).

Although the means for separating and counting the fluid pockets are many and varied, this group of meters possess similar basic characteristics. The performance is usually stated in terms of meter error against flow rate. Figure 3.3.1 shows data for a 25 mm bore rotary piston meter. At low flows the meter has to overcome frictional resistance before motion commences and at low flows leakage could be significant. As flow increases, less slip occurs and performance improves. Some designs of vane meters are capable of metering uncertainties of 0.1 % of reading and calibration limitations prevent a full assessment of the lowest uncertainty being realized. The headloss curve in Figure 3.3.1 follows the classical shape, increasing with the square of the flow. Lubricating properties of fluids are a factor in the choice of PD meters. In certain applications component wear can be accelerated by the pressure difference across the metering element and this produces uneven loading. The effect of an increase in viscosity is to reduce slip and increase the rangeability of meters. At high viscosity however the pressure drop increases and the maximum flow is often lower than that for fluids such as water.



NOTE W.G. is water gauge (pressure), G.P.H. is gallons per hour.

Figure 3.3.1 — Basic positive displacement meter performance for a 25 mm rotary piston type

Since meter linearity at low flows is impaired by the mechanical friction associated with gear trains and other drag producing components, some suppliers fit shaft encoders to enable the meter to resolve smaller volumes of fluid with reduced frictional loading. Such developments have shown that some forms of meter are capable of repeatabilities in excess of ± 0.005 % of reading, leading to their adoption as international transfer standards.

3.3.3 Liquid displacement types

3.3.3.1 *Reciprocating piston types*

The reciprocating piston meter is analogous to the reciprocating piston engine. The pistons are arranged in line or, more commonly, radially (with three to five pistons), drive a common crank. The crank synchronises the movement of the pistons and the rotary or slide valves, which allow fluid to fill or exhaust from the cylinders. In some designs, ports in the cylinder wall are used instead of valves. These ports are covered and uncovered by the movement of the pistons.

One design of piston meter which uses ports in the cylinder walls is shown in Figure 3.3.2. The principle is that fluid from the inlet enters the central portion of the meter and passes to the cylinder behind one of the four pistons, depending on which port is open. A groove in each of the pistons allows flow from an adjacent cylinder to pass to the outlet, the route available depending on the positions of the pistons. A description of the sequence of movements is given in Figure 3.3.2.

The volume measured in one cycle is the product of the piston stroke, cylinder area, and the number of pistons. This volume can be adjusted in some designs by altering the stroke of the pistons by altering the position of the step K. Otherwise, the volume indicated is adjusted during calibration in the readout mechanism driven from the crank. Piston sealing is achieved by fine clearances or by elastomer seals; however the need to reduce frictional forces and keep a good seal requires compromise in all designs.

This type of meter is capable of a high level of performance with good reliability in clean, low viscosity fluids. Its expected uncertainty of 0.1 % over a 10 : 1 flow range makes it popular for fiscal duties at lower flow rates. One of the most common applications is in petrol dispensing.

Many variants are available, but for very low flow rates, the pistons and cylinders are replaced by bellows or diaphragms where the frictional forces will be lower and the piston seal removed.

3.3.3.2 *Sliding vane meter*

The sliding vane meter typically comprises a cylindrical rotor mounted within a profiled body. The rotor carries vanes arranged in cruciform manner which contact the body wall and are free to slide within slots machined along the axis of the rotor. The operation of a sliding vane meter is shown in Figure 3.3.3. In this meter the fluid enters through an inlet manifold (5) and causes the rotor (2) to revolve by exerting pressure on the vanes (3). The proximity of the rotor and vanes to the casing (1) forms a seal, while the body profile controls the movement of the vane assemblies. The radius of the measuring crescent is constant so that the fluid trapped between the inlet and outlet porting is maintaining at constant volume. An output shaft is typically connected to the rotor to drive the meter volume register.

NOTE The numbers in brackets to those given in Figure 3.3.3.

The theory of the sliding vane can be found in Hahn (1968).

This type of meter is widely used as a reference meter and transfer standard. An uncertainty of 0.05 % of reading over a 10 : 1 flow rate range is not uncommon for a high quality sliding vane meter. Due to vane contact with the measuring chamber wall and consequent wear, this type of meter is sometimes de-rated, in flow rate terms, for use with dry abrasive fluids. A variant of the basic meter type, usually called a rotary vane meter, employs a cam mounted on the rotor shaft to control the position of the vanes. Uncertainty is typically 0.5 % of reading and better under favourable conditions.

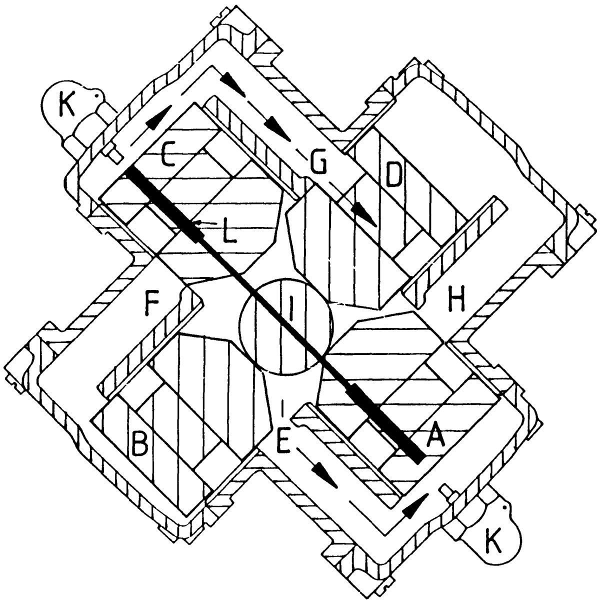
3.3.3.3 *Oval gear meter*

There are many types of gear meter of which the oval gear type is one. The basic design consists of two meshed, oval gear rotors which are forced to contra-rotate by fluid pressure. The close fit between the rotors and the measuring chamber traps discrete volumes of fluid which are continuously discharged through the outlet port. Swept volume is that between the rotor and the chamber wall. Uncertainty is usually in the order of 0.5 % of reading.

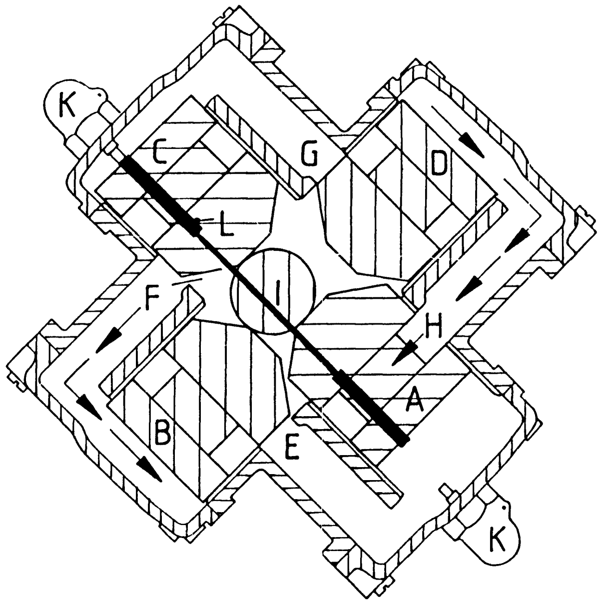
3.3.3.4 *Helical displacement meter*

Inter-meshing, helically fluted rotors trap discrete volumes of fluid against the measuring chamber wall. The rotors are controlled by timing gears to prevent metal to metal contact. The meter is particularly suitable for handling non-lubricating fluids.

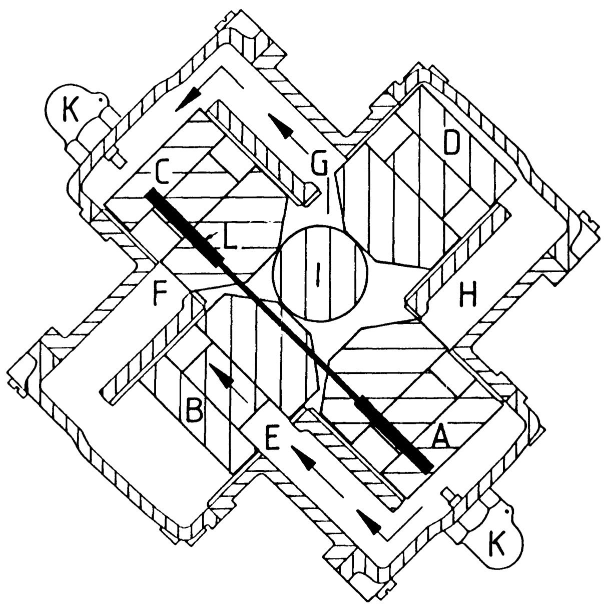
The geometry of the meter is illustrated by (a) of Figure 3.3.4. In a variant of the helical displacement meter, flow takes place along the axes of two contra-rotating helical screws, effectively a fluid conveyor, (see (b) of Figure 3.3.4). Uncertainty is typically of the order of 0.5 % of reading or better, depending on the fluid being metered.



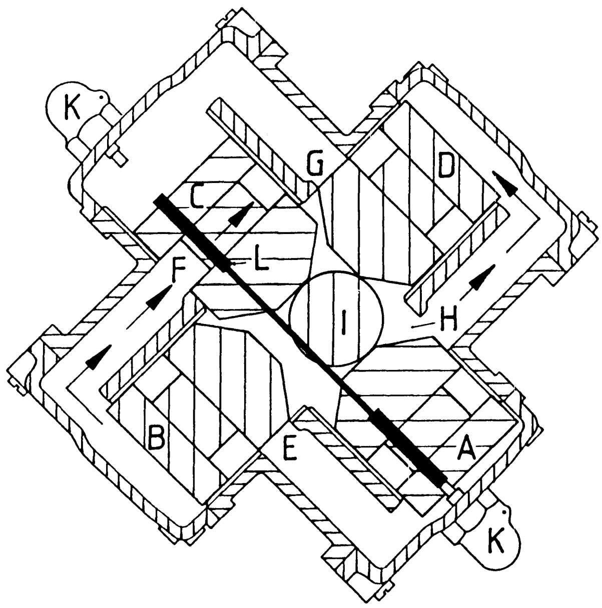
(a) Position 1
The central portion of the meter is continuously fed with liquid from the inlet pipe. Piston B has travelled outward thus admitting the liquid through the port E to the head of piston A. The opposing piston C is ported to outlet through G and is thus forced outwards by the differential pressure across it, drawing piston A inwards via the connecting rod L.



(b) Position 2
As piston A moves inward it allows flow out through H, reducing the pressure in the cylinder behind piston D and hence that piston moves outwards. The movement of piston C has opened port F, allowing the inlet pressure to force piston B inwards.



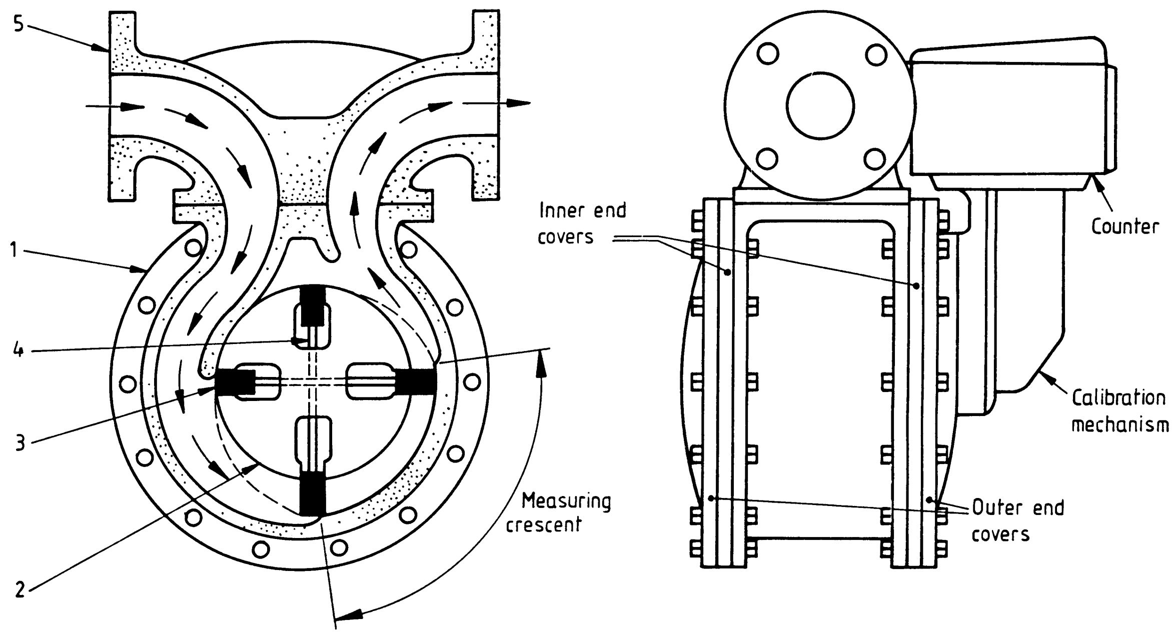
(c) Position 3
Piston B has reached the inward extreme of its travel thus allowing piston A to discharge the liquid through E into the common outlet chamber and thence to the outlet elbow.



(d) Position 4
Piston A has completely discharged its measured volume of liquid and is ready to repeat the cycle of operations.

NOTE I is the common crank.

Figure 3.3.2 — Typical cruciform reciprocating piston meter



Key
1 Casing
2 Rotor
3 Vanes
4 Vane coupling rod
5 Inlet manifold

Figure 3.3.3 — Sliding vane displacement meter

3.3.3.5 ***Bi- and tri-rotor meters***

Bi- and tri-rotor meters are similar in operation to both the oval gear meter and the helical meter. Two or three synchronized rotors revolve within a measuring chamber trapping discrete volumes of fluid between the rotors and the chamber wall (see Baker and Morris 1985). Each rotor shaft carries a timing gear and each of the bladed displacement rotors moves alternately through the measuring chamber half-cylinder bores. The single blocking rotor rotates to produce a continuous capillary seal between the upstream and downstream fluid. The blocking rotor is geared to revolve at half the speed of the displacement rotor.

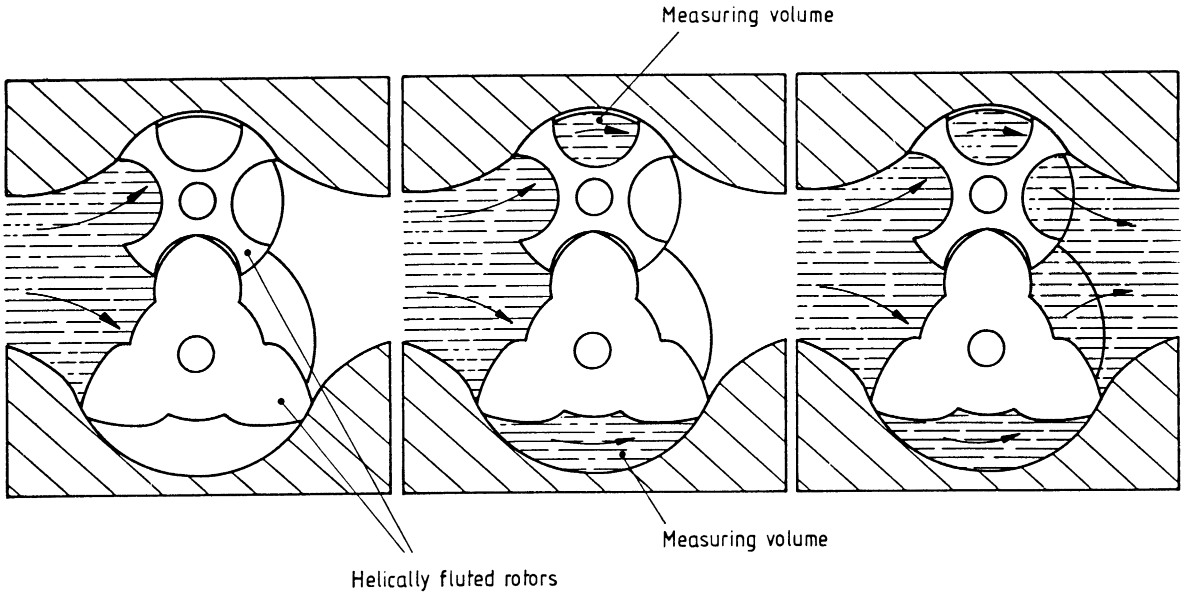
3.3.3.6 ***Rotary piston meter***

This is one of the most widely used positive displacement meters and is variously known as the rotary, semi-rotary or oscillating piston meter. The meter piston is constrained by the chamber wall, the barrier plate and the central boss so that it moves in a rotary or oscillatory motion. The operation of the meter through one cycle is illustrated by (a) to (d) of Figure 3.3.5 and by the corresponding items (a) to (d) as follows.

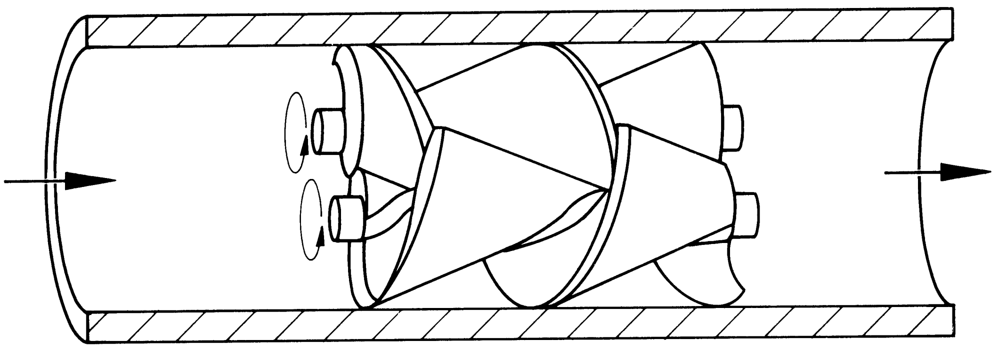
a) At the beginning of the cycle the inlet port in the base of the working chamber is open to the inside wall of the piston and in-flowing water causes the piston to start its semi-rotary oscillatory movement sliding upon the division shutter. Simultaneously exhaust water in the remaining part of the piston is being expelled through the outlet port in the top of the working chamber. The water outside the piston is neutral water (i.e. neither in-flowing or exhaust water).

b) The piston has moved round a quarter of its path and the in-flowing water continues filling the area inside the piston and commences to fill the area outside the piston. The neutral water of (a) is now exhaust water being expelled through the outlet port.

c) The piston has now moved round half of its path. In-flowing water is shown on the inlet side of the chamber. Neutral water inside the piston is cut off from both ports and the exhaust water continues to be passed through the outlet port.



(a) Rotary helical design



(b) Screw helical design

Figure 3.3.4 — Helical displacement meters

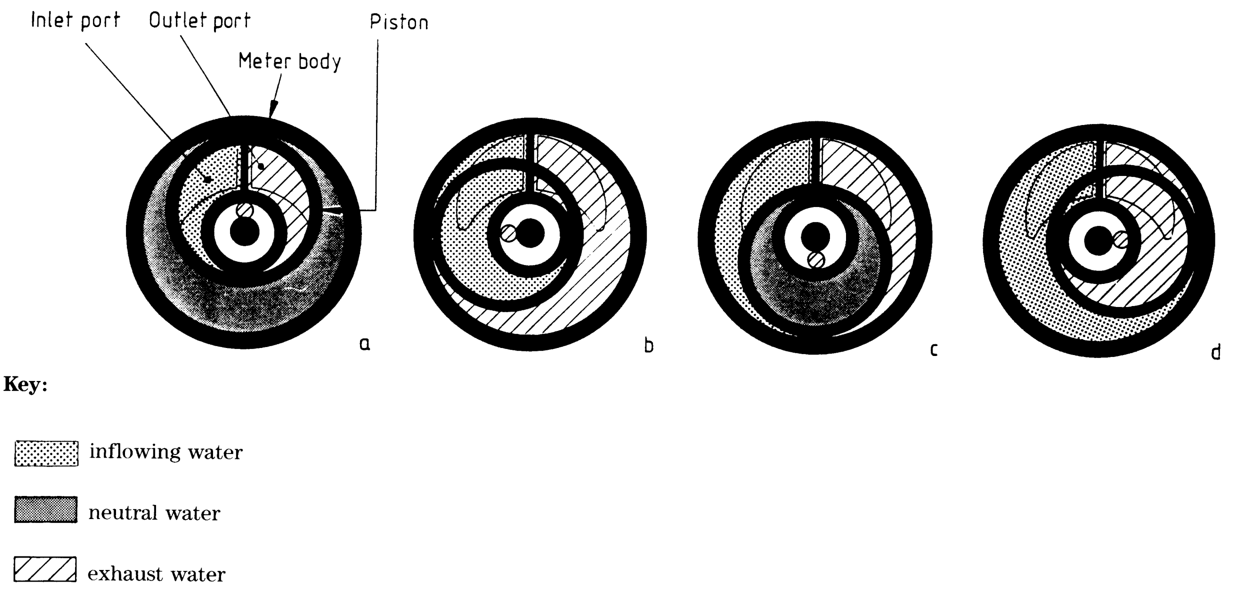


Figure 3.3.5 — Rotary piston meter

d) With three quarters of the cycle completed, the piston is just starting to open to the inlet port for the beginning of another cycle. The neutral water of (c) within the remaining part of the piston has now become exhaust water and the in-flowing water in the chamber will soon become neutral water as in (a).

At their most precise, rotary piston meters have an uncertainty of between 0.2 % and 0.5 % of reading (depending on the medium, the measuring range, the material of construction and the calibration regulations) over a flow rate range of at least 10 : 1. The reproducibility is typically ± 0.5 %.

The rotary piston meter is widely used to meter cold potable water in the water supply industry (see BS 5728). Flow rate ranges up to 266 : 1 are specified for an uncertainty of 5 % of reading at low flow rates and 2 % at higher flow rates.

3.3.3.7 ***Nutating disc meter***

The flat measuring element performs a nutating (wobbling) motion within the measuring chamber. A typical nutating disc meter is illustrated by Figure 3.3.6.

In this meter, a disc mounted within the casing is constrained from rotation by a radial partition attached to the measuring chamber wall, but it is free to swivel about its vertical axis. Incoming fluid alternatively fills above and below the disc, the pressure differential causing the disc to rock or nutate. The disc is mounted on a central sphere which carries a pin to translate the disc movement into a rotary motion to drive the meter register. The nutating disc meter has fewer working parts than most comparable meters but must still be protected by filtration. Uncertainty is typically 1 % of rate over 10 : 1 flow rate range.

3.3.4 Liquid metering pumps

By definition, liquid metering pumps perform the functions of both meter and pump. They require an external source of power, typically an electric or pneumatic motor. The main types are those which operate in a similar manner to the reciprocating piston meter and those which make use of peristaltic action. Piston metering pumps may be single or double acting and may be ganged together to give the required capacity. The capacity can be varied by adjusting the piston stroke and the flow rate by varying speed.

The peristaltic metering pump operates by continuously squeezing a plastic or elastomeric tube. Its operation is illustrated in Figure 3.3.7. An elastic tube is clipped to a multi-curve track, the central curve of which is concentric with a rotor carrying a number of rollers. The rollers pass over the tube squashing it against the track at the point of contact. As the roller rotates it pushes the trapped fluid ahead of the squashed section while the restitution of the tube behind the roller creates a pressure reduction, so drawing in more fluid to be trapped by the next roller. Flow rate is proportional to the size of the tube bore and the speed of the rotor. Further details can be found in Woodcraft (1973). The peristaltic metering pump is suitable for both liquids and gases subject to tube compatibility. Both devices described have virtually no viscosity limitation, they will pump almost any liquid which will flow. Uncertainty is normally of the order of 1 % of flow rate. Various types of both positive displacement meters and turbine devices are sometimes used, without volume registers, as torque generators to drive additive injectors.

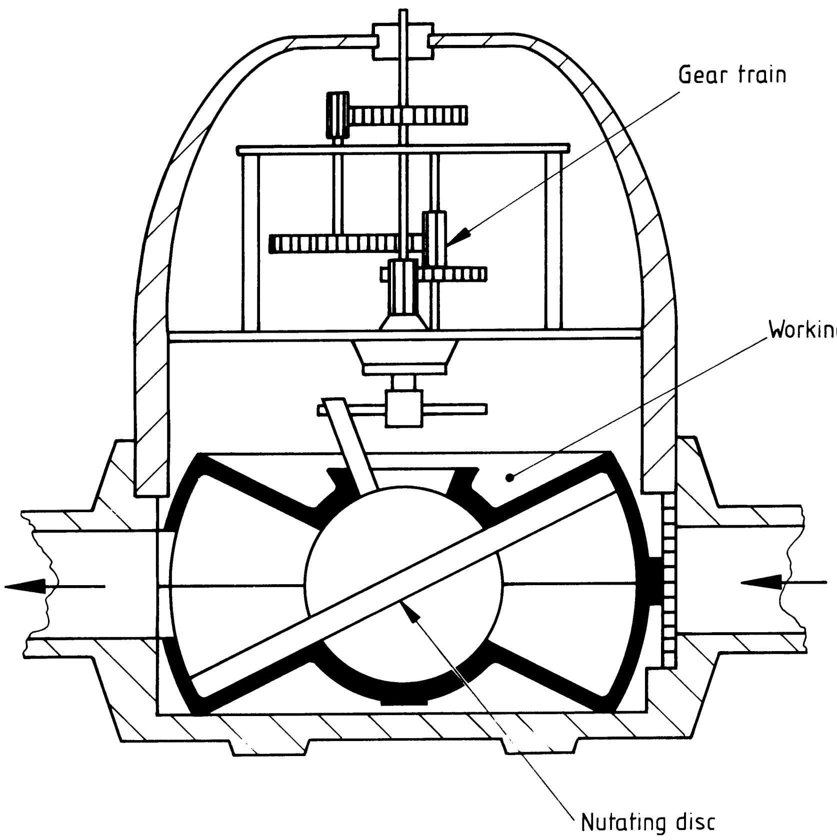


Figure 3.3.6 — Nutating disc meter

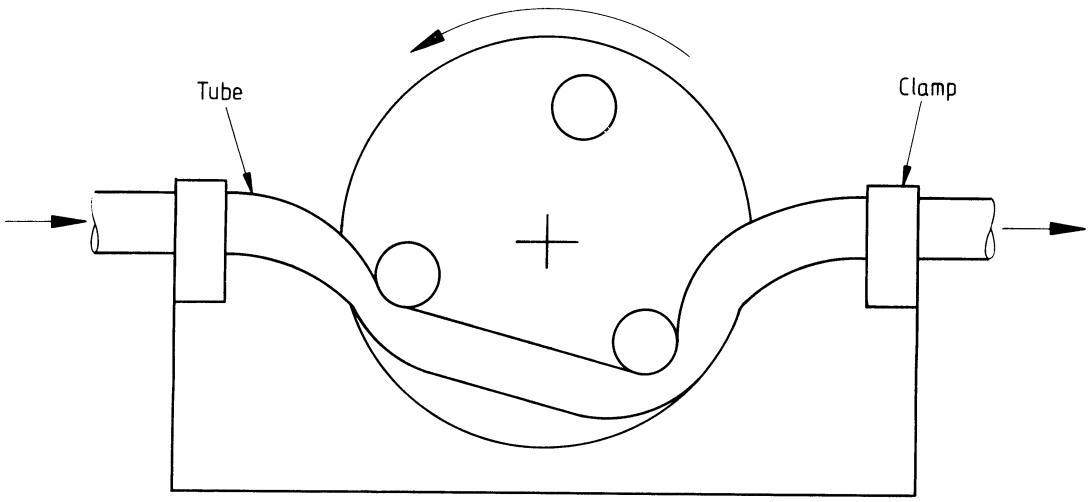


Figure 3.3.7 — Metering pump

3.3.5 Gas displacement meters

3.3.5.1 ***General***

For many liquid metering applications, particularly the metering of water, the simplifying assumption is made that the fluid is incompressible. Equally, the coefficient of cubical expansion of the liquid is often ignored or, at best, treated as a second order effect. In gas metering neither the effects of compressibility or of temperature can be disregarded. Gases are highly compressible, particularly at low pressures, and have high thermal expansion coefficients. For these reasons it is usual to quote the capacities of gas meters at specified temperature and pressure conditions.

A further important difference between positive displacement liquid and gas meters is the permissible mechanical and fluid friction that can be tolerated and the usually low output torque of the metering element. Due to the relatively low mass and hence low kinetic energy of a gas stream, the meter must have low frictional resistance and the output torque available to drive ancillary devices is severely limited.

3.3.5.2 ***Diaphragm meter***

The diaphragm dry gas or bellows meter consists of four chambers, two of which are enclosed by bellows. The porting of the chambers, which are analogous to pistons, is controlled by a double slide valve. The complete cycle of operation is illustrated by Figure 3.3.8. Each chamber is successively ported to the inlet and then discharged by the movement of the slide valves. A mechanical linkage connected to the diaphragms actuates the volume mechanism. An uncertainty over a 20 : 1 flow rate range of 1 % of rate can be achieved at ambient conditions. Further details on gas meters can be found in BS 4161 and BS 6400.

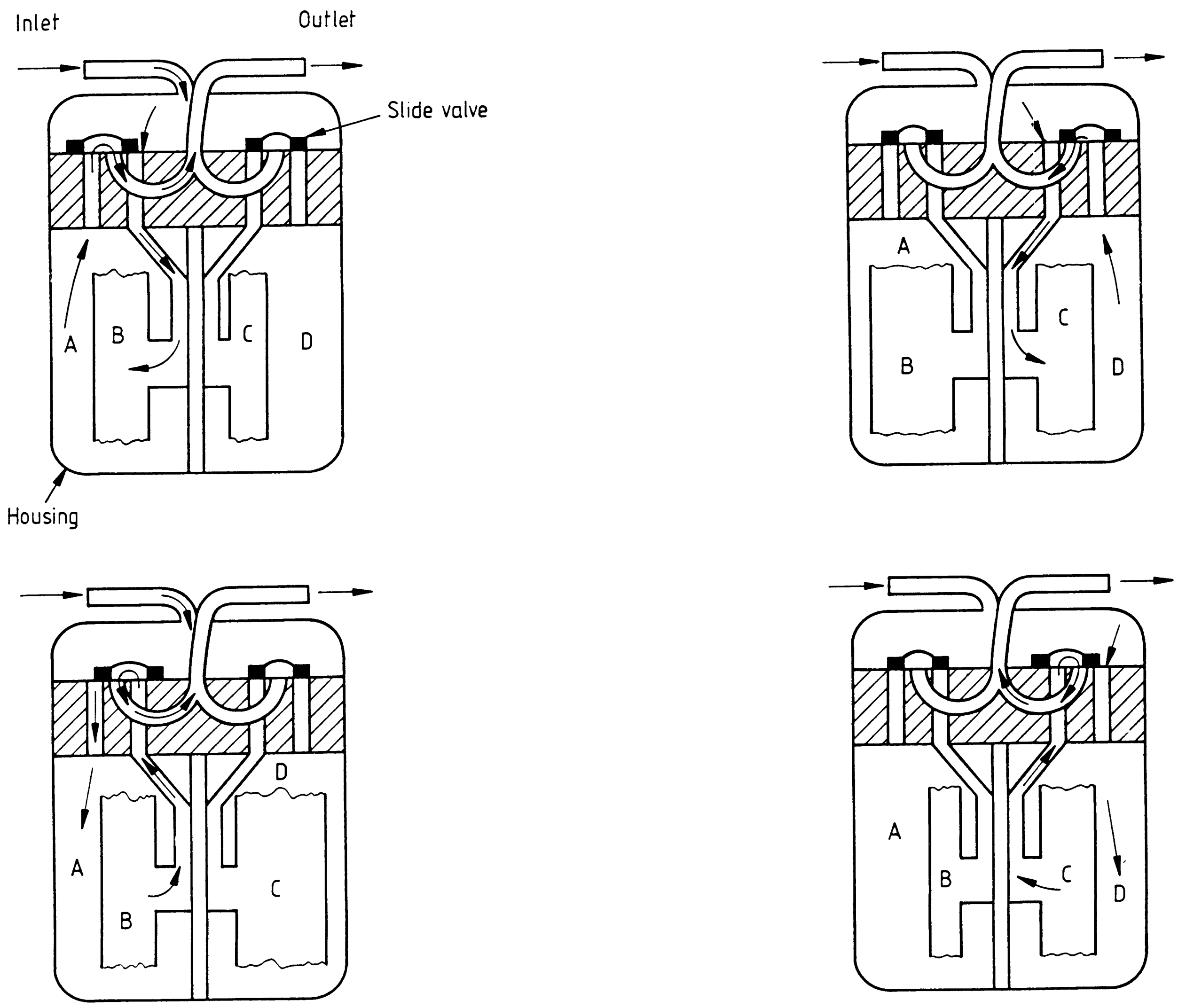


Figure 3.3.8 — Operation of a gas diaphragm meter

3.3.5.3 ***CVM (Constant Volume Meter)***

The CVM shown in Figure 3.3.9, is a proprietory gas meter capable of higher flow rates and performance than the bellows or diaphragm meter. It comprises an annular measuring chamber, four rotating vanes and a rotating gate or rotary valve. Gas enters the meter through the inlet port and its pressure causes the vane assembly to rotate. Timing gears connect the vane assembly to the gate which revolves and successively ports each pocket of trapped gas to the meter outlet. This meter has a quoted uncertainty of 0.5 % of rate over 10 : 1 flow rate range.

3.3.5.4 ***Roots meter®***

The Roots meter® is a proprietory device very similar to the oval gear meter. Two lobed contra-rotating rotors are mounted within the measuring chamber. As the lower rotor turns in a counter-clockwise direction, gas enters the space between the rotor and the chamber wall. When the rotor has reached the horizontal position, a discrete volume of gas is trapped between the rotor and the chamber wall. As the rotor continues to turn the trapped gas is ported to the meter outlet. The upper rotor simultaneously performs a similar cycle and the process is repeated four times for each complete revolution of the motor shafts.

Uncertainty of the order of 0.5 % of rate is obtainable over a 20 : 1 flow rate range. A disadvantage of this meter is that it introduces significant pressure pulses into the flowstream. Devices for pressure and/or temperature compensation are available.

3.3.5.5 ***Wet gas meters***

The wet gas meter consists of a compartmented drum mounted in a water bath. The drum is free to rotate about its axis and the water, maintained at a level just above the drum centreline, acts as a gas seal. The meter is illustrated by Figure 3.3.10. Gas enters at the centreline into a compartment of the drum and as the compartment fills the drum is caused to rotate. The filled compartment is sealed by the water. As the drum rotates, the filled compartments are successively ported to the meter outlet, the gas being displaced by water. Oil is sometimes used in place of water to avoid changes in gas humidity.

The meter requires skilled operation and can produce measurement uncertainty of about 0.25 % of rate. It requires carefully controlled conditions for successful operation and is rarely used outside flow measurement laboratories and hence is more of a reference type of meter.

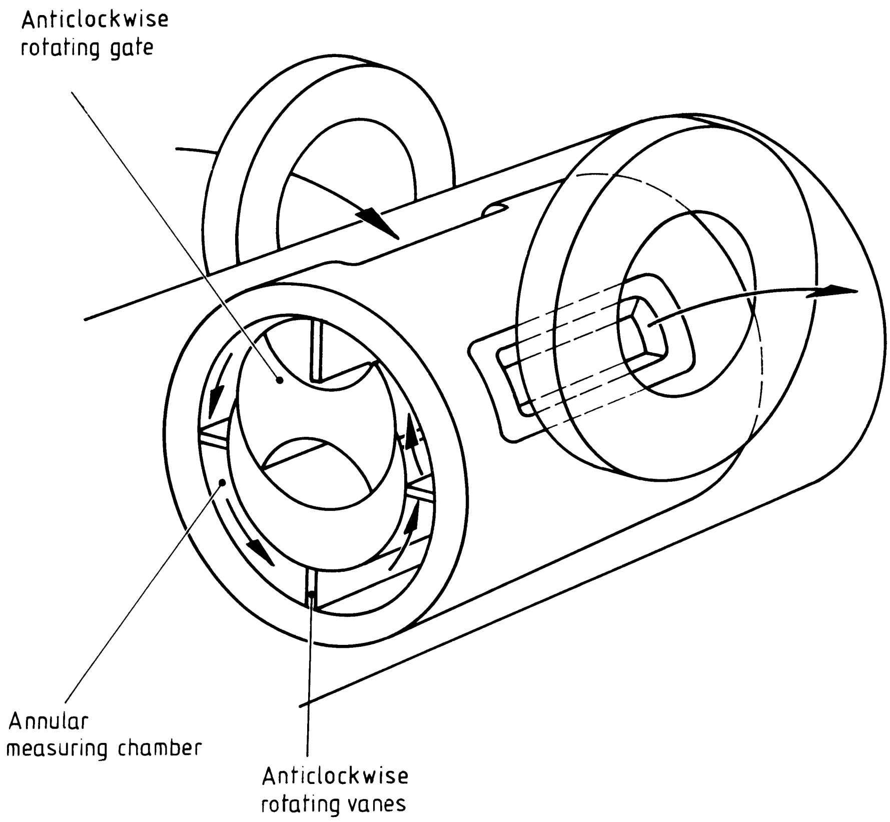


Figure 3.3.9 — Rotary CVM gas meter

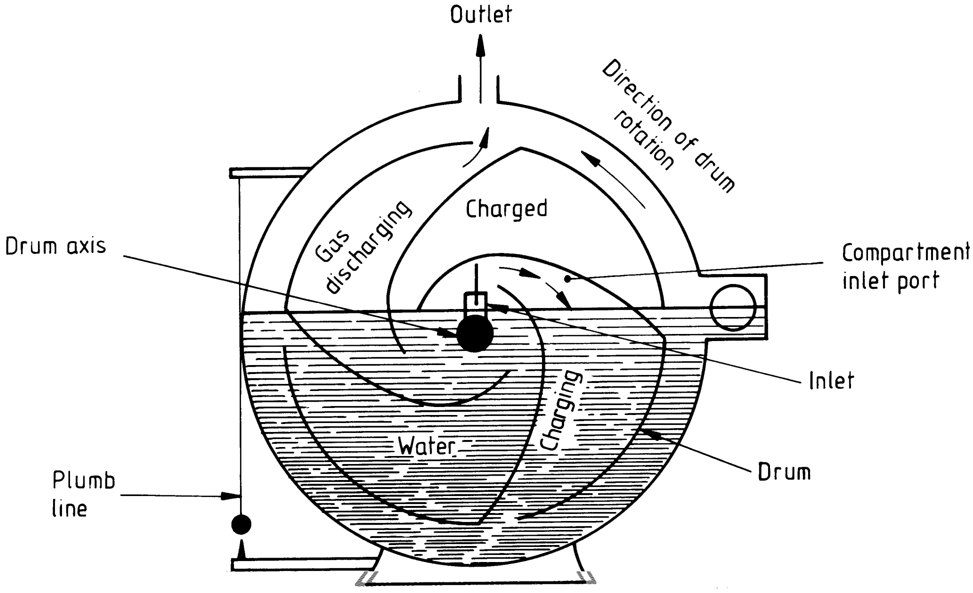


Figure 3.3.10 — Wet gas displacement meter

3.3.5.6 ***Multi-rotor meters***

A number of non-proprietory, multi-rotor meters are available which have similarities both with the Roots® and CVM devices and with the multi-rotor meters used for liquid applications. Temperature and/or pressure compensation devices may be used, powered by long-life batteries, so maintaining the self-contained advantage. Vertical, top inlet installation is sometimes recommended since the rotor action provides a degree of self-cleaning.

3.3.6 Materials of construction

A range of materials is used for PD meters to encompass a very wide range of fluids. Mild steel, carbon steel, stainless steel, bronze and aluminium are all found as body materials. The choice and thickness of body material will dictate the maximum operating pressure and temperature and most suppliers of PD meters keep extensive databanks of successful applications. Aluminium, ebonite, steel alloys, graphite fibres, hard rubbers and proprietary materials have all been used for the metering element. Other materials employed include brass, plastics, hastelloy and titanium composites. The material choice allows acids, alkalis, solvents, organic chemicals, food stuffs, hydrocarbons, most gases, etc. to be metered with one type of meter from the group. Material selection therefore should be performed in close consultation with the supplier, particularly when aggressive or non-lubricating fluids are being metered.

3.3.7 Advantages and disadvantages of PD meters

The advantages of PD meters over other groups of flowmeter are as follows:

a) low uncertainty and good reproducibility;

b) reliability is good;

c) relatively insensitive to upstream flow conditions;

d) simple principle of operation;

e) will meter a wide range of liquids and gases;

f) excellent for totalizing in remote locations;

g) some designs can be self-powered;

h) most general application industrial designs are rugged.

The disadvantages of PD meters over other groups of flowmeter are as follows:

1) suitable over limited pressure and temperature range;
2) meters are much larger than some equivalent flow rate meters;
3) can be damaged by particles in the flow, filtration is often needed;
4) relatively expensive;
5) headloss can be high;
6) usually for uni-directional flow only;
7) introduce pulsations into the flow;
8) flow will be interrupted by seizure of meter.

3.4 Group 4 meters: rotary turbine type meters

3.4.1 General

This group of meters contains a very wide range of designs all operating on the same basic principle. A rotating component (wheel, vane, rotor or helical runner) is made to rotate by the fluid flow. This is used as a measure of the flow rate through the device.

3.4.2 Axial turbine meters

3.4.2.1 *Basic design and construction*

A rotor, with its axis of rotation on the axis of the pipe, is fitted with narrow blades set at an angle to the flow along the axis. The flow causes the rotor to rotate at a speed proportional to the flow rate of the fluid being metered. The speed of the rotor is sensed by a pick-off on the outside of the meter body. The shape and design of the blades and bearing vary considerably between manufacturer and the basic performance can also vary greatly. The whole rotor and bearing assembly is mounted centrally within the body by upstream and downstream hangers, which are also claimed to act as flow straighteners. The basic components are shown in Figure 3.4.1. The end connections may be flanged as shown or threaded. The material used is generally stainless steel with the bearings being made from stellite or tungsten carbide (journal designs) or stainless steel (ball bearing designs). The rotor blades are generally made from ferrite steels to generate pulses of sufficient strength for detection. Each time a blade passes the pick-off a pulse is generated. The output signal is therefore a pulse train, each pulse corresponding to a discrete volume of fluid. Totalization of the pulses give the volume passed and the pulse frequency gives the flow rate.

The design of gas meters is somewhat different from that shown in Figure 3.4.1. Traditionally gas meters have much larger centre bodies than liquid meters with numerous short blades positioned close to the wall. Gas densities can be several orders of magnitude lower than liquid densities and to ensure there is sufficient driving torque to overcome the drag component, the velocity at the rotor is increased. The general philosophy adopted is to accelerate the gas past the blades to ensure high torque at all points along the operating curve.

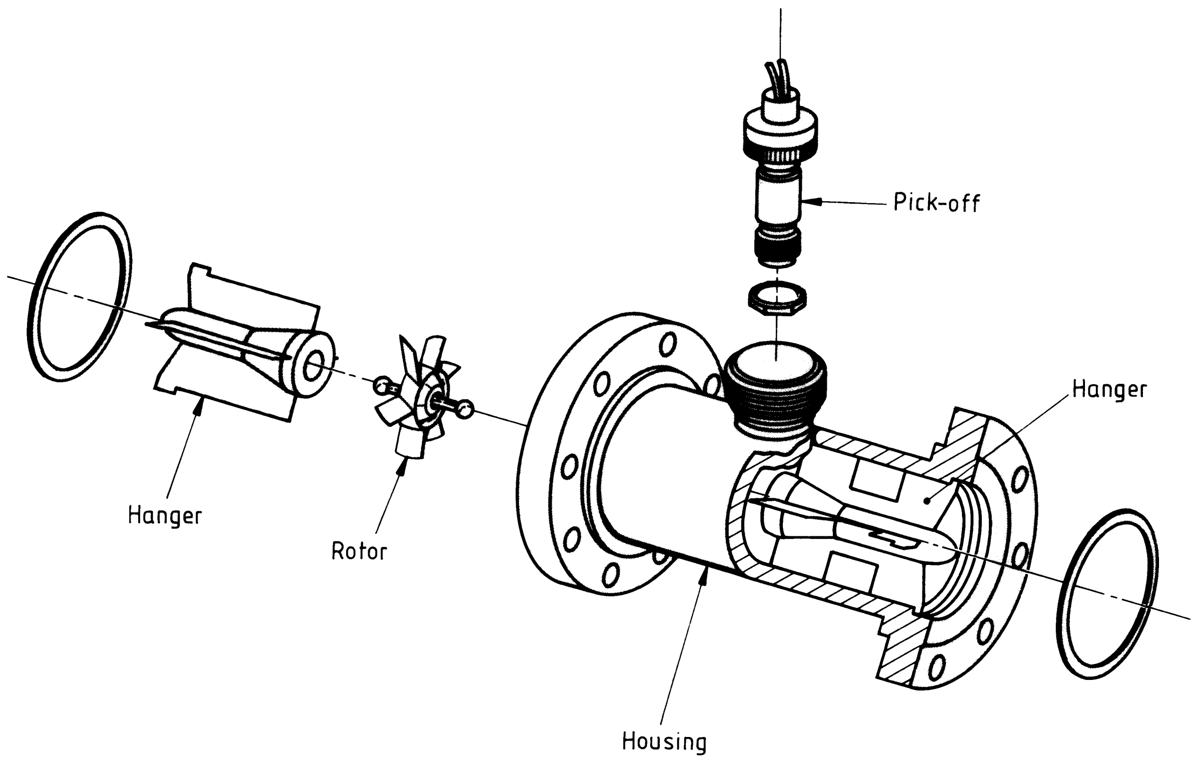


Figure 3.4.1 — Basic elements of turbine flowmeter

3.4.2.2 ***Basic operating characteristics***

When the turbine meter is running at constant flow rate the driving torque generated by impact on the blades exactly balances the resisting forces from bearing friction, viscous drag and magnetic drag. The actual behaviour is a complex function of many variables. The most important of these are as follows:

a) temperature, pressure and viscosity of the fluid;

b) lubricating qualities of the fluid;

c) mechanical wear of the bearings;

d) conditional and dimensional changes of the blades;

e) changes in inlet velocity profile and/or swirl;

f) pressure drop through the meter.

Because the output is dependent on all these factors, the highest performance is obtained by proving or calibrating under actual operating conditions. All turbine meters require calibration to establish the base meter factor curve since our present theoretical understanding is insufficient to enable a calculation to be used to estimate it. The uncertainty of the calibration facility is therefore very important since turbine meters have low inherent uncertainty. The performance of the meter includes the random and systematic components of error (see Appendix B) of the facility and these can be readily identified by a good quality turbine meter. If the total uncertainty of the calibration rig can be kept below 0.05 %, then the turbine can be calibrated to an uncertainty only fractionally worse than this. These aspects are discussed further in section 6.

Typical characteristics for a turbine meter operating in a low viscosity fluid are shown in Figure 3.4.2. This shows the change in meter factor (the pulse output per unit volume), the pressure drop, the output frequency and the output voltage from the coil as a function of the flow rate through the device. The relationship between the meter factor and the flow rate can be split into two main sections. The linear portion, generally the upper three quarters of the operating range, is to a large extent influenced by the fluid viscosity, meter size and design. The meter should always be operated predominately in this region, where a mean meter factor can be used with little source of error. In the non-linear region, the flow profile, bearing and other retarding effects become more pronounced. The slope of the curve becomes steeper and meter linearity becomes very poor. The repeatability of the meter is however unaffected in this region. At very low flow rates the repeatability becomes poor as retarding forces begin to overcome hydrodynamic driving forces. Eventually the meter ceases to respond below a certain minimum flow and output stops. At the other end of the performance curve, provided there is sufficient static pressure inside the meter body to suppress cavitation, then the meter can be run considerably over a maximum rated throughput for short periods without affecting the bearings greatly. Prolonged high speed usage should be avoided as both bearing life and meter accuracy will suffer.

The pressure drop is proportional to the square of the flow rate. Typical values for well designed meters lie between 20 kPa to 70 kPa (0.2 bar to 0.7 bar) at maximum flow.

The ability to respond to transient flow is a valuable characteristic. A turbine can respond to a step change in flow within 5 ms to 10 ms, while even the larger meters (> 0.1 m bore) respond in 20 ms. Generally speaking the low inertia straight blade designs achieve the more rapid response and this can also be achieved on the larger meters by fabrication of hollow rotors.

A well designed, dynamically balanced meter can have an uncertainty of 0.1 % of reading but the average industrial meter is between 0.25 % and 0.5 % of reading over flow ranges of approximately 10 : 1. The overall precision, repeatability and range varies greatly between manufacturers and the prospective user has much scope in matching the meter to the required specification. The uncertainty of smaller meters is inferior to that stated. These (6 mm to 15 mm diameter) have uncertainties between 0.5 % and 1.0 % of reading over 5 : 1 flow ranges. Repeatability is not dependent on size, most being in the range ± 0.02 % to ± 0.05 % of reading. The latest twin rotor designs have certified repeatabilities of better than ± 0.01 % under controlled conditions.

The magnitude of the output signal varies with design of meter but is usually between 10 mV and 1 V. The frequency depends on meter size, the number and pitch of the blades and the flow rate. The normal range however varies between 5 Hz and 5 kHz. The higher the frequency the greater the resolution and the higher the potential accuracy. Care has to be taken to avoid electrical interference which may cause, as with all pulse type flowmeters, an increased number of pulses to be registered.

3.4.2.3 ***Simple theory***

The most simple theory assumes frictionless, one dimensional flow past one dimensional blades with no rotor retarding torques. The rotational speed, f (in Hz), is simply related to the flow velocity in the pipe by the equation:

$$f = \frac{N\,U \tan\alpha}{2\pi r_t} \qquad (3.4.1)$$

where

N is the number of blades;

r_t is the radius of blades (in mm);

α is the angle at which the blades are set (in degrees).

The meter factor, K_m, which is usually defined as the frequency divided by the velocity is then:

$$K_m = \frac{fN}{u} \frac{\tan\alpha}{2\pi r_t} \qquad (3.4.2)$$

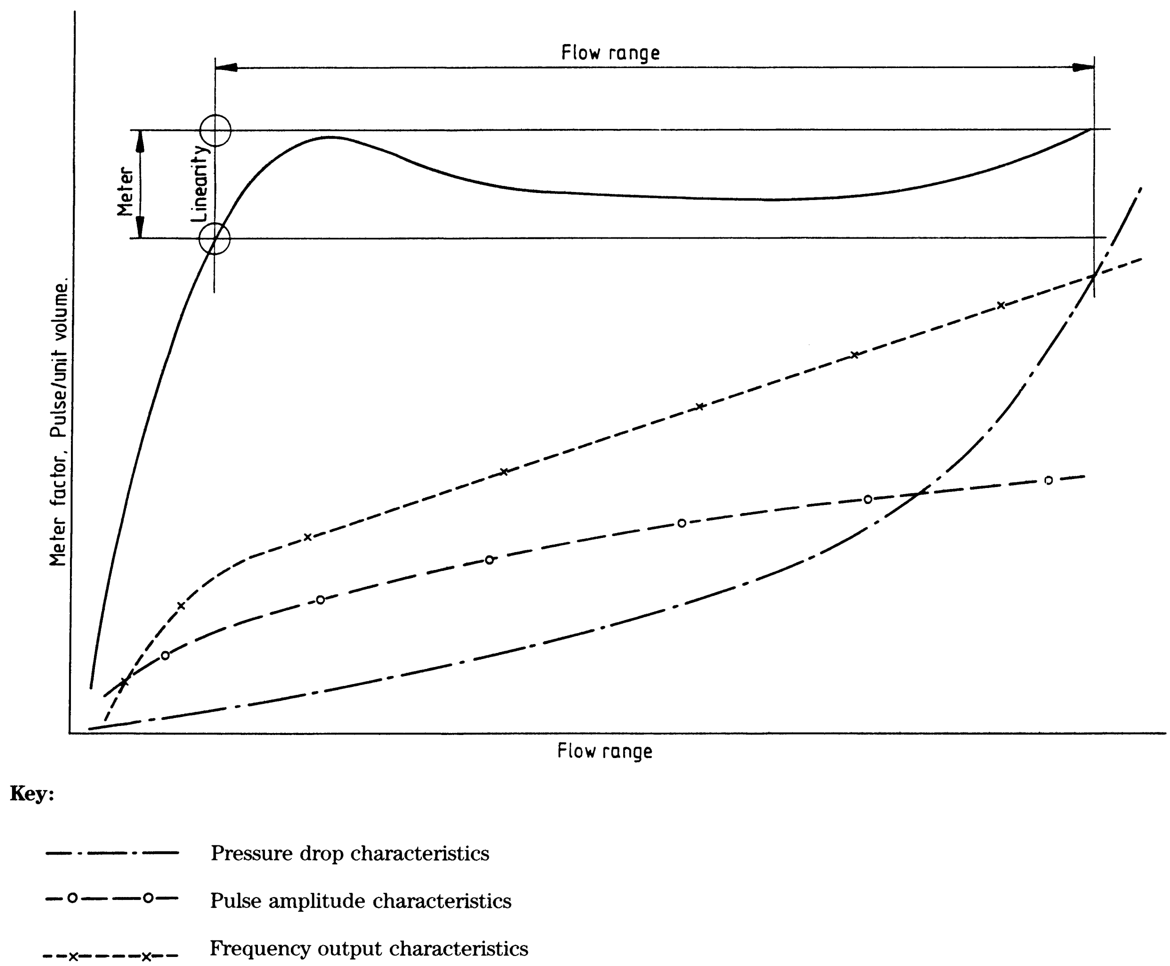


Figure 3.4.2 — Turbine flowmeter characteristics

Turbine meters are manufactured with both helical (where the blade angle increases steadily from blade hub to tip) and straight (constant angle blades). The above expressions are true for helical rotors at any radial position but for straight bladed meters are only true at one radius, that where the retarding and driving forces exactly balance. On either side of this position, variations in blade velocity with distance from hub means that angles of incidence develop between the velocity vectors and the blade angle. Closer to the tip the incidence is negative because of low velocity and near the hub the incidence is positive because of high velocity. In simple terms this means part of the blade is acting as a turbine and part as a pump. The meter integrates any profile variations and gives an output proportional to the average value. The angles of incidence on helical meters are much lower than for straight meters and this may partly explain their improved linearity in viscous fluids. The performance curve is a complex function of flow profile, blade shape and fluid properties, and full theoretical analyses are given in Tan and Hutton (1971) or Furness (1982).

3.4.2.4 ***Advantages and disadvantages***

The main advantages of the modern rotary turbine meter are as follows:

a) high frequency output and hence high resolution;

b) good accuracy and repeatability;

c) linear calibration over a wide linear range;

d) digital output, convenient for totalizing and rate indication;

e) low to medium purchase costs;

f) applicable over wide temperature and pressure ranges.

From this list it would appear that all the features of the ideal flowmeter are present. Like all flowmeters there are disadvantages and these are as follows:

1) high maintenance costs;

2) bearing friction changes with time possible affecting accuracy;

3) sensitive to swirl;

4) sensitive to fluid viscosity;

5) gasmeters are sensitive to density effects;

6) fluid must be single phase to obtain good performance;

7) may be affected by pulsating flows.

The reliability of the meter calibration depends on bearing friction remaining constant. This means that wear or clogging will cause shifts in characteristics. For the highest performance for the lowest uncertainty, regular checking against a primary standard is necessary. Also, like many flowmeters, it is sensitive to swirl in the pipe, the effect of which is quite pronounced. Installation guidelines are discussed in **4.4.5**.

Turbine meters are sensitive to Reynolds number and require careful calibration if used on viscous fluids. Helically bladed meters are less sensitive than straight bladed designs and should be chosen if a range of liquids of different viscosities is being metered. These effects are discussed in more detail for the two designs in **4.4.3**.

3.4.3 Helix type or Woltmann meters

3.4.3.1 *Basic design and construction*

This group of meters is similar in design to the axial turbine meter described in **3.4.2** but with a rotor fitted with a number of broad vanes forming a multi-threaded helix. The rotor axis can be either horizontal or vertical. The main difference between the helix type meter and an axial turbine type meter is the provision in the former of an output gear train which transmits the rotary motion of the rotor to the mechanical indicating device or counter. There is more friction than in an axial turbine type meter because of the gear train and counter. A typical design is shown in Figure 3.4.3.

The speed of the rotor is proportional to the mean velocity of the flow and depends on the angle of inclination of the rotor vanes. Adjustment of the meter can be effected by deflecting the incoming fluid with a hinged blade fitted to one of the upstream straightening vanes. This can either increase or decrease the rotor speed to change the shape of the error curve. The advantage of a vertical rotor is that the upthrust of the fluid tends to balance, to some extent, the downthrust of the rotor weight.

NOTE Recent meter developments have resulted, for cheapness, simplicity and ease of replacement, in the use of one size of metering element fitted in a range of casing diameters. In the extreme the diameter over the rotor of the metering element may amount to no more than half of the internal diameter of the casing to which it is fitted. Such methods of construction have created a variant meter type, which may be called a partial diameter helix or Woltmann meter, which is extremely sensitive to flow velocity profile distortion.

3.4.3.2 *Performance characteristics*

Mechanical helix type or Woltmann meters tend to be used almost exclusively for the metering of water; hence their characteristics comply with the requirements of BS 5728. In general, class B meters are the best available in this type though class C may be achievable in some cases. The head loss of a mechanical helix or Woltmann type meter is typically less than 0.3 bar at maximum flow rate.

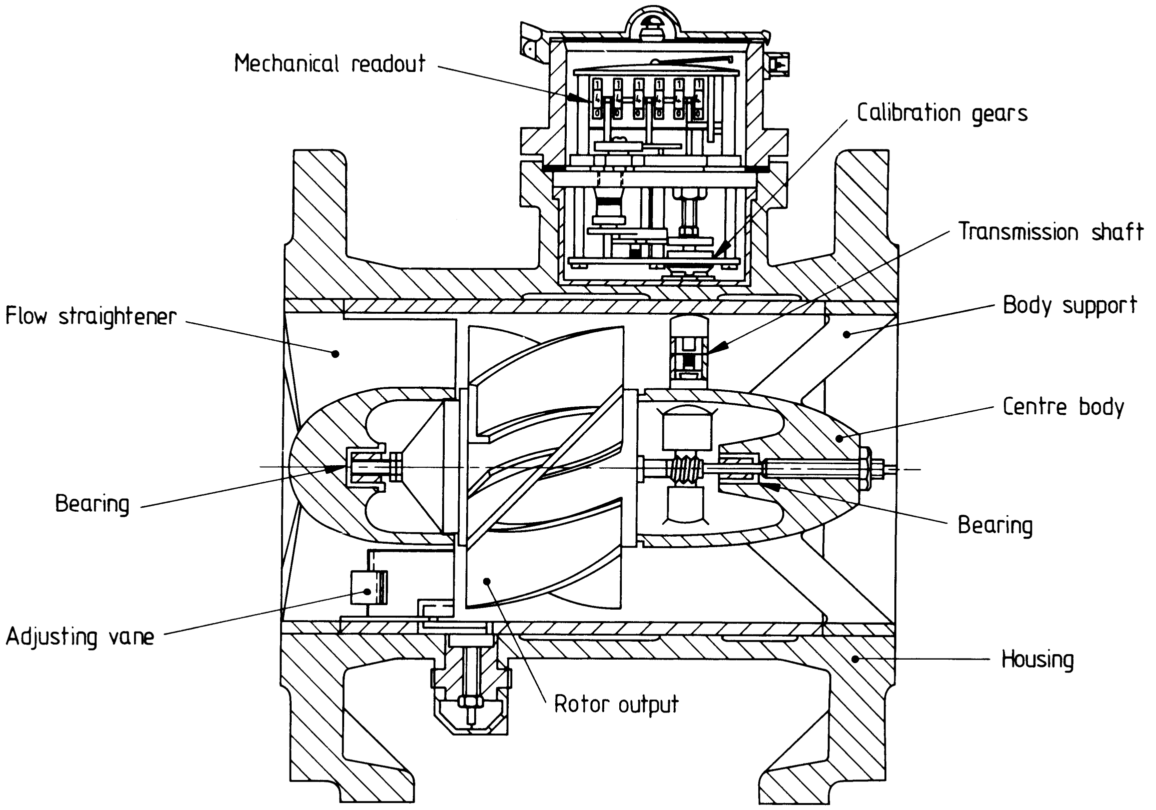


Figure 3.4.3 — Typical helix type or Woltmann meter

3.4.3.3 ***Materials of construction***

With a broad size range for this type of meter, the meter casing may be bronze or plastic in the smaller sizes, but is nearly always cast iron for sizes above approximately 75 mm. The internals of the meter are almost always plastics, and this includes the materials of the gear train and register.

3.4.3.4 ***Advantages and disadvantages***

Helix meters are relatively cheap, reliable, of simple construction, and of acceptable accuracy for the water industry; they need no source of external power and their quality is assured by the water meter regulations. Like all intrusive types of meter, head loss is a disadvantage, though it is less than for some other mechanical type meters. Undoubtedly the major disadvantage of this meter type is its sensitivity to flow disturbances up or downstream of the meter, in particular to swirling flow.

3.4.4 Jet (or vane) type mechanical inferential meters

3.4.4.1 ***Basic design and construction***

In this form of meter construction the flow is formed into one or more jets which impinge more or less tangentially (depending on the type) on to the periphery of a bladed rotor.

The impact of the jet(s) serves to rotate the rotor and operates, through gearing, the indicating device of the meter which registers total volume flow. A typical design is shown in Figure 3.4.4. A single jet meter passes the total flow through one jet which strikes the rotor at one point on its periphery. A multi-jet meter embodies means for dividing the total flow into a number of jets spaced around the periphery of the rotor.

Both single and multi-jet meters are used in large quantities in the water supply industry (though not so much in the UK) and are constructed to comply with the requirements of BS 5728.

Single jet meters usually occupy the smaller end of the meter size range, whilst multi-jet meters are intermediate between them and the larger helix or Woltmann type meters.

3.4.4.2 ***Performance characteristics***

The characteristic curves of jet type meters comply with to the classification requirements of BS 5728 (see Figure 3.4.5 for typical example). Single and multi-jet type meters having a wider flow rate range than class B of the standard, although not uncommon, tend to be special meters.

The head loss of jet type meters is generally 1 bar at the meter's maximum flow rate.

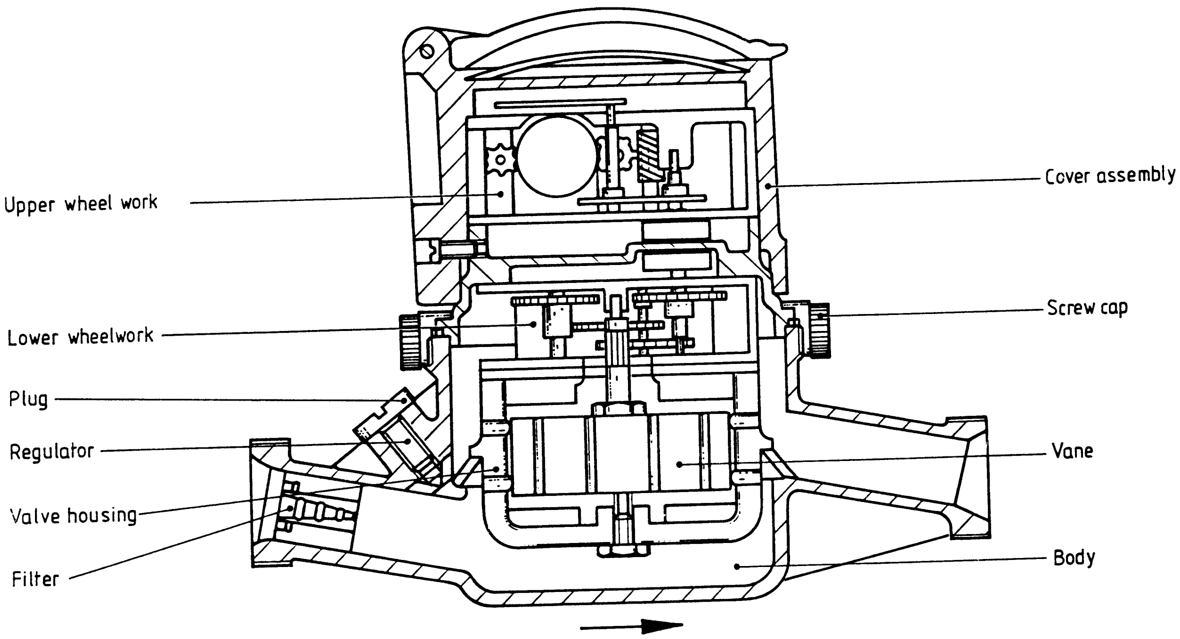


Figure 3.4.4 — Jet (or vane) type mechanical meter

3.4.4.3 ***Materials of construction of jet type mechanical inferential meters***

Both single and multi-jet meters occupy the lower end of the meter size range, and hence tend to have bodies of bronze or other non-ferrous metals or plastics. The rotors too are usually of plastics, and in the case of the multi-jet meter, to minimize end thrust, the rotor may be constructed of plastics of a density similar to that of water. The meter internals, including the gear trains and register, are nowadays commonly of plastics.

3.4.4.4 ***Advantages and disadvantages***

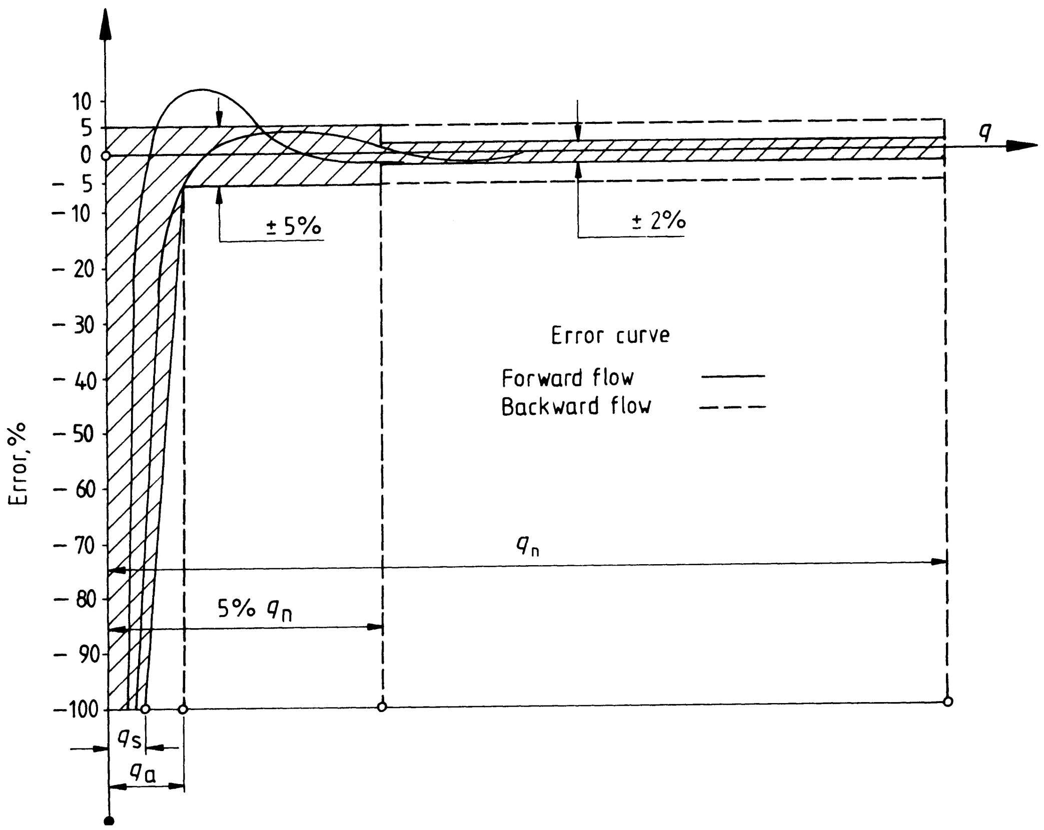
Jet type meters, through being made in very large numbers, are relatively cheaply priced; they are reliable, durable, and need no additional electrical power. They are less sensitive to the effects of dirt in the water than volumetric meters, and the single jet meter in particular, can be constructed to be very compact. The head loss is higher than that of the helix type meter, and its sensitivity to disturbed flow conditions is very variable, some makes of meter being relatively insensitive, and others being highly sensitive.

3.4.5 Semi-axial type turbine meters

Various designs of meter, sometimes called propeller meters, exist in which the axis of rotation of the turbine rotor lies at an angle to the flow axis.

One design, a propeller type inferential meter, is shown in Figure 3.4.6. The shaft in this design rotates on ball bearings, either sealed or lubricated by the process fluid, and the rotation of the turbine rotor is transmitted to the counter through a magnetic pick-off. The size range is usually from 25 mm to 100 mm. The best uncertainty claimed is 1 % of full scale.

Repeatability is ± 1 % and linearity is ± 2 %, both of full scale.



Key
q is the flow rate
q_n is the nominal flow range
q_s is the stalling flow upper limit
q_a is the minimum flow within permitted tolerance limits

Figure 3.4.5 — Performance characteristics for vane type meter

3.4.6 Miniature jet type meters

This design of meter is identical in principle to the single jet type mechanical inferential meter; it is sometimes called a Pelton wheel meter. Intended for the measurement of small quantities of liquid, the miniature rotor revolves, customarily on jewelled bearings, and its rotation is transmitted to the counter through a magnetic or optical pick-off.

The shaped inlet passage converts the low velocity incoming fluid to a higher velocity single jet which impinges tangentially on the bladed rotor (see Figure 3.4.7). Repeatability of ± 0.1 % and a linearity of ± 1 % of full scale deflection are typical for this type of meter. Flow rates as low as 0.008 L/min are possible and 15 L/min is probably the largest flow rate that this type of meter will handle.

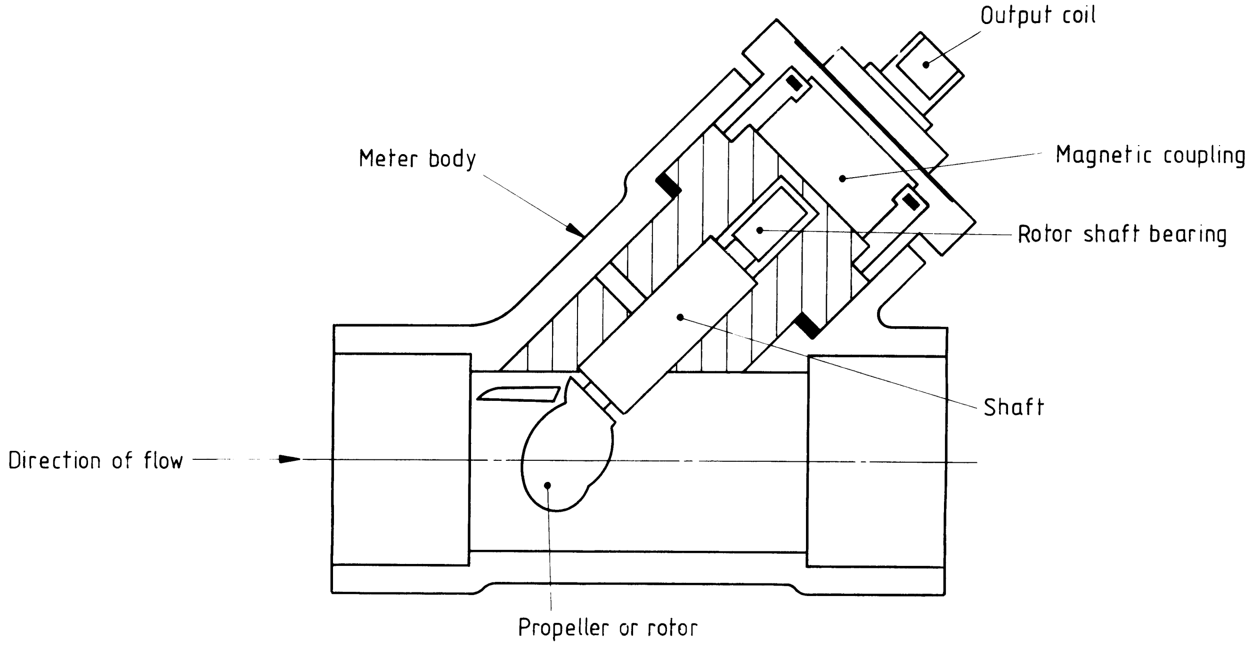


Figure 3.4.6 — Propeller type meter

3.4.7 Inferential insertion meters

3.4.7.1 *Design of insertion meters*

Small turbine probes mounted on the end of a strut are a very cost effective way of measuring local velocity in large bore pipes. The position of the probe is critical since the velocity may vary across the pipe. If the velocity profile is known, the total volume flow can be related to the measured local velocity. The meters use the same principle of operation as full bore turbine meters and in some cases have comparable performance. However, the actual performance is governed to a large extent by positioning and Reynolds number effects. The use of compensating electronics and flow computers (see **5.5.6**) may improve performance significantly. The meters need swirl-free flow to give accurate velocity determination.

3.4.7.2 *Hydraulic considerations*

For fully developed turbulent flow the relation between the local velocity, v (in m/s), and the centreline velocity, u_c (in m/s), is approximately given by the following equation:

$$v = u_c \left(1 - \frac{y}{r}\right)^{\frac{1}{n}} \quad (3.4.3)$$

where

n is an exponent that varies between 6 to 10 depending on the Reynolds number;

y is any radial pipe position.

Equation 3.4.3 states that the flow profile becomes flatter as flow velocity increases. The continuity equation states that the mean axial fluid velocity is given by:

$$U = \frac{2}{a^2}\int v \, \mathrm{d}r \quad (3.4.4)$$

where

a is the pipe area.

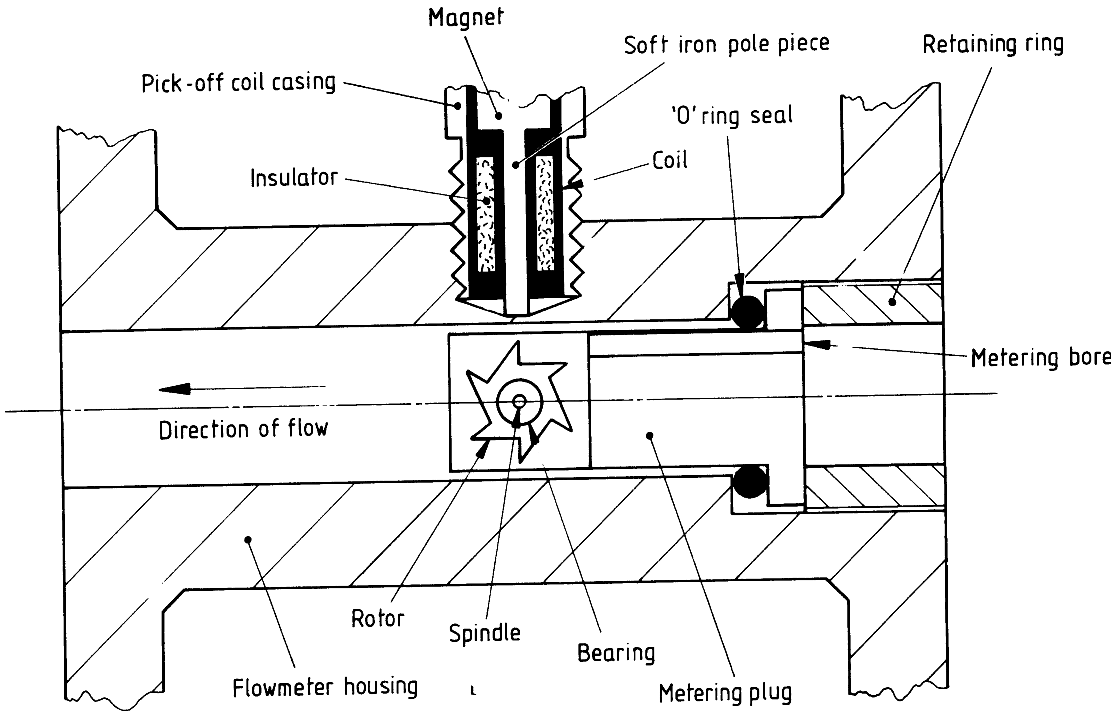


Figure 3.4.7 — Pelton wheel inferential flowmeter

Substituting and integrating gives:

$$U = u_c \left(\frac{2n^2}{(2n + 1)(n + 1)}\right) \qquad (3.4.5)$$

Thus, from a knowledge of the Reynolds number and by measuring the flow on the centreline with the insertion meter, the mean axial fluid velocity can be found. The total volume flow is then found by multiplying the mean velocity by the flow area. The significance of the derived expression is that it will determine the linearity of the meter. A 1 % change in the value of the expression in the parentheses of equation 3.4.5 will mean linearity changes by 1 %. A similar analysis can be performed for critical positioning, which is the location in the pipe where the measured velocity is equal to the mean velocity. Critically positioned meters exhibit better linearity in turbulent flow and it is worth spending time to calculate the optimum position (see Spitzer 1984) but this approach is only valid where the pipe diameter is about 10 times greater than the diameter of the insertion meter.

3.4.7.3 ***Advantages, disadvantages and materials of construction***

The important point about all insertion meters is their very low pressure loss. When pumping power or delivery head is limited they are an alternative to full bore meters. Blade angles do need to be considered as this affects selection. The bearings could be subject to heavy loading unless the velocity of the flow is restricted. As velocity increases, blade angle is reduced to restrict bearing load and thereby give a useful working life.

Typical bearings are ball races or jewelled designs depending on application. Other materials of construction are similar to full bore turbine meters, with stainless steel being most commonly used.

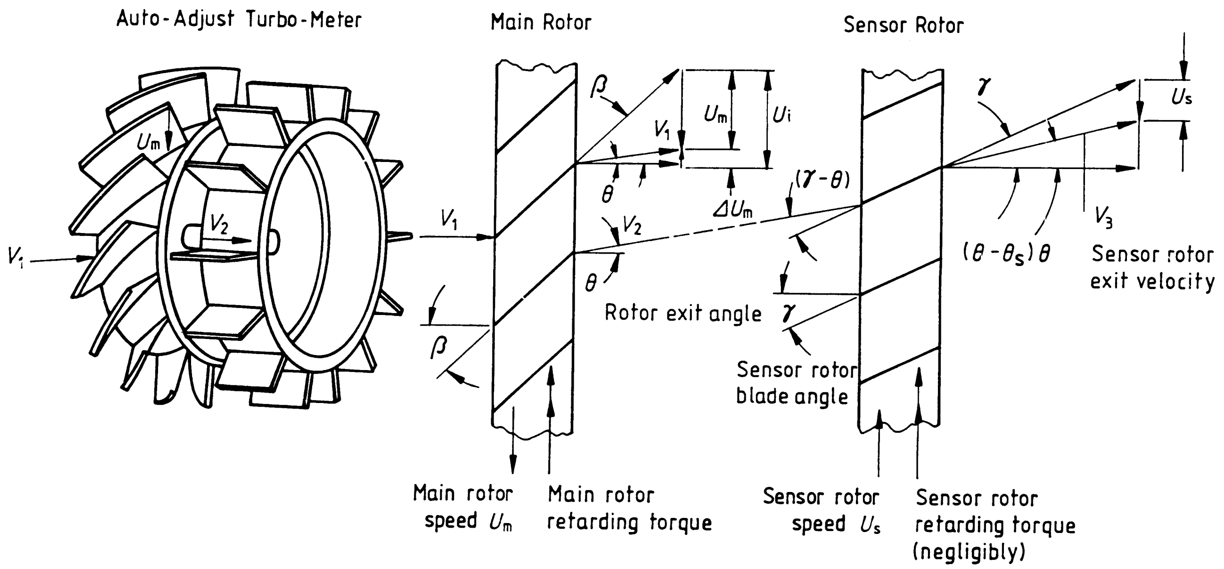
3.4.8 Special designs

3.4.8.1 ***Twin rotor meters***

Twin rotor designs have been produced in recent years. These rotors compensate for changes in fluid velocity and generally exhibit much wider rangeability than conventional meters.

In one design the meter internals have an upstream indicating rotor and a downstream slave rotor positioned some distance from the first rotor. The slave and central shaft run on one set of bearings while the indicating rotor rides on a second separate set of bearings attached to the central shaft. This means that relative motion between indicating turbine and its bearings remains close to zero. This plus the use of radio frequency (RF) pick-offs (see **3.4.9.2**), results in drag-free metering and a significant increase in range results.

In another design, shown in Figure 3.4.8, the rotors are no longer separated but are very close together (Figure 3.4.8) with the sensing rotor downstream of the main rotor. High performance is obtained by the sensing rotor detecting small deviations in exit angle of fluid leaving the main rotor. The sensing rotor has a blade angle considerably smaller than that of the main rotor but larger than the exit angle. It therefore rotates in the same direction as the main rotor but at a lower speed. When the speed of the sensor rotor is subtracted electronically from that of the main rotor, the difference depends only on the blade angles of the two rotors. The changes in the difference in the two rotor speeds are then an indication of the changes in the meter characteristics (see Figure 3.4.8).



NOTE The defined auto-adjust turbo-meter accuracy, α, is given by the following equation:

$$\alpha = \frac{U_m - U_s}{U_i} = \left(\frac{U_m}{U_i}\right) - \left(\frac{U_s}{U_i}\right)$$

$$= \left(1 - \frac{\text{Tan }\theta}{\text{Tan }\beta}\right) - \left(\frac{\text{Tan }\gamma}{\text{Tan }\beta} - \frac{\text{Tan }\theta}{\text{Tan }\beta}\right)$$

$$= \left(1 - \frac{\text{Tan }\gamma}{\text{Tan }\beta}\right) = \text{constant}$$

Figure 3.4.8 — Twin rotor turbine flowmeter

3.4.8.2 *Bearingless meters*

One useful adaptation of the turbine is the Hoverflo® . This is also a double rotor meter but with the rotor elements at opposite ends of a central shaft which is normal to the flow. Each rotor takes approximately half of the flow. When fluid passes through the device, both rotary and supportive forces are generated. The rotor therefore floats with no surface contact thus eliminating any need for bearings. The meter, shown in Figure 3.4.9 will work in both horizontal and vertical flows. It cannot match conventional turbines for linearity or rangeability but does possess high repeatability. This can be used with linearizing electronics to improve rangeability in difficult applications.

3.4.8.3 ***Shrouded rotors***

Output frequency (hence meter resolution) can be increased on the larger meters by the use of shroud rings. These enable round numbers of pulses per barrel to be achieved when used in petroleum applications through the use of nickel or iron rivets in the outer ring. These generate pulses in the same way as the blades and can give up to ten times the resolution of simple blade counting. By positioning multiple pick-offs on the meter, pulse integrity can also be verified.

3.4.9 Pick-off design and rotor speed sensing

3.4.9.1 ***Magnetic types***

The voltage and frequency output depend on both meter and pick-off design. Two basic types of pick-off are available, magnetic and radio frequency modulated carrier. In the magnetic designs, the coil may be mounted in the pick-off (reluctance type) or magnetic materials are used in the blades (inductive type). Another variant of the inductive design is the use of small magnets embedded in the blades themselves. The magnetic properties of the circuit are changed by the presence of the blade and an a.c. output results. The magnitude of the signal varies between manufacturers but is usually in the range 10 mV r.m.s. to 1 V r.m.s. In the reluctance design the coil is fine copper wire wrapped around the magnet. This has a resistance of about 2 500 ohms and produces an output of 30 mV at the lowest flow. In the inductive design a coil is wound around an iron slug and each time the blade passes the pick-off a current is induced in the coil. The frequency decreases with increasing meter size and also drops as flow rate decreases. The lowest frequencies are therefore obtained on large meters (> 300 mm bore) running close to the rated minimum flow. Pulse rates can be increased however by using the shrouded rotors described in **3.4.8.3**. The higher the frequency, the greater the resolution. Magnetic pick-offs of both types produce a magnetic drag on the rotor. This can become appreciable at low flow rates especially on small meters.

3.4.9.2 ***RF type pick-off***

Magnetic drag can be eliminated through the use of the RF carrier pick-off. The coil in the pick-off is part of an oscillating circuit operating around 50 kHz. The passage of blades through the coil field changes the amplitude of the oscillator output signal. A typical design is shown in Figure 3.4.10. This type of sensor is suggested when low density or low velocity measurements are to be made. Magnetic methods are more common simply because they are cheaper to implement.

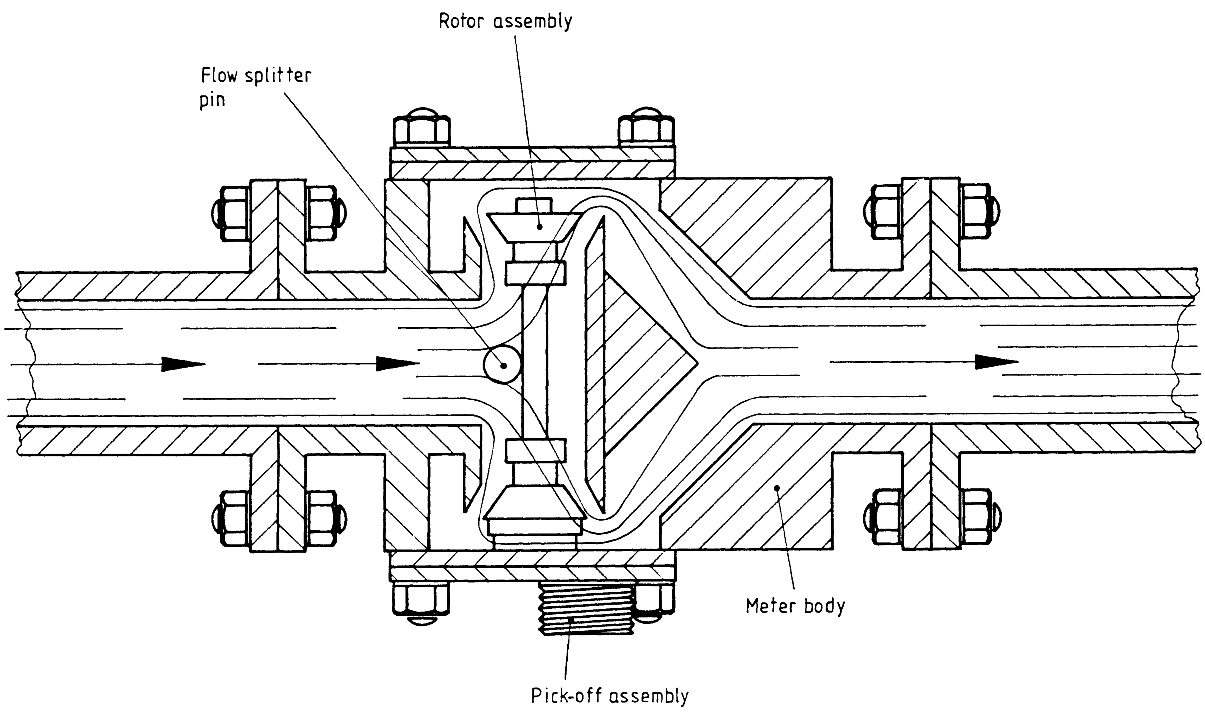


Figure 3.4.9 — Bearingless turbine type meter

3.4.9.3 ***Optical sensors***

These are intrinsically safe and have no retarding effects on the rotor. The light generated by a photo-diode is periodically interrupted by the presence of blades. The pick-off is therefore an optical switch. The disadvantages of the technique is that transparent sections are required within the meter to transmit and receive the light and fluid turbidity may degrade the output signal significantly. Few meters are available fitted with these devices but the interest in them is growing and new designs are likely.

3.5 Group 5 meters: fluid oscillatory types

3.5.1 General

Oscillatory meters are a group of flowmeters employing fluid phenomena to infer flow rate. Some of these meters are applicable to fluids independent of the fluid state, i.e. the output does not vary between liquids and gases. They represent a solid state approach to flow measurement and are beginning to gain industrial acceptance in a wide range of applications.

3.5.2 Vortex shedding meters

3.5.2.1 ***Simple theory and principles of operation***

When a fluid flows past a fixed solid body supported diametrically across a pipe, vortices can be shed alternately from the two sides at a frequency which closely follows a linear relationship with fluid velocity. Vortex shedding commences in the case of a circular cylinder when the body Reynolds number (Re_b) is approximately 50. Below this value of Re_b the vortices are either stationary immediately downstream of the cylinder, or, at still lower values of Re_b they are non-existent (see Figure 3.5.1). For accurate flow measurement by this technique the following typical conditions need to be met.

a) The pipe Reynolds number should lie between 3×10^4 and 5×10^6.

b) The ratio of body width to body height should ideally lie within the limits of 0.2 and 0.35 if unmodulated vortex shedding frequencies are essential for the electronic circuitry to work efficiently. Slender bodies are used in some designs in order to reduce head loss, but the circuitry has then to cope with both frequency and amplitude modulation of the signals from the vortex sensor. This situation arises because single vortices are no longer shed over the entire length of the body.

c) The flow profile should be fully developed and symmetrical and should be free from pulsations in critical frequency bands.

d) The pressure drop across the bluff body should be significantly less than that at which cavitation or gas liberation occurs.

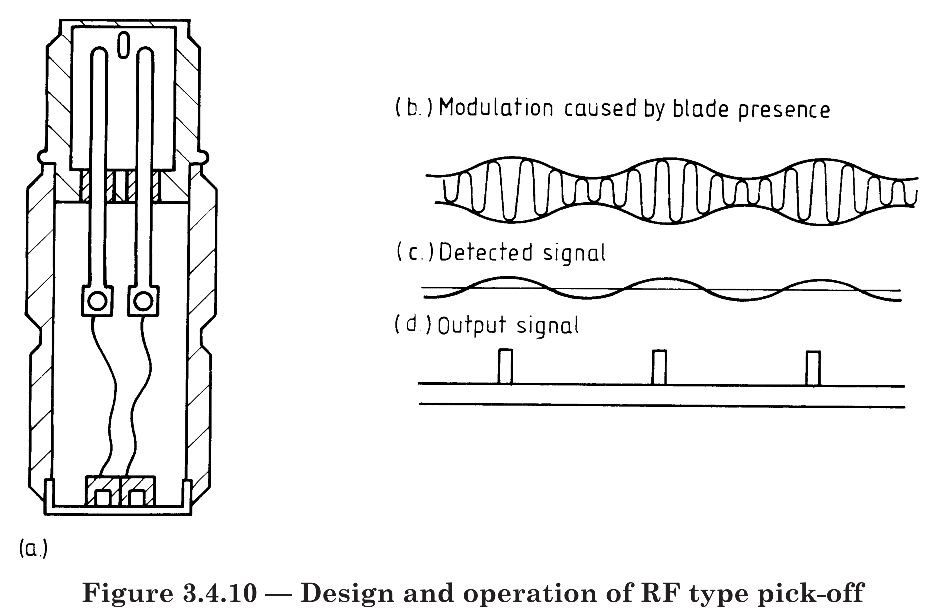
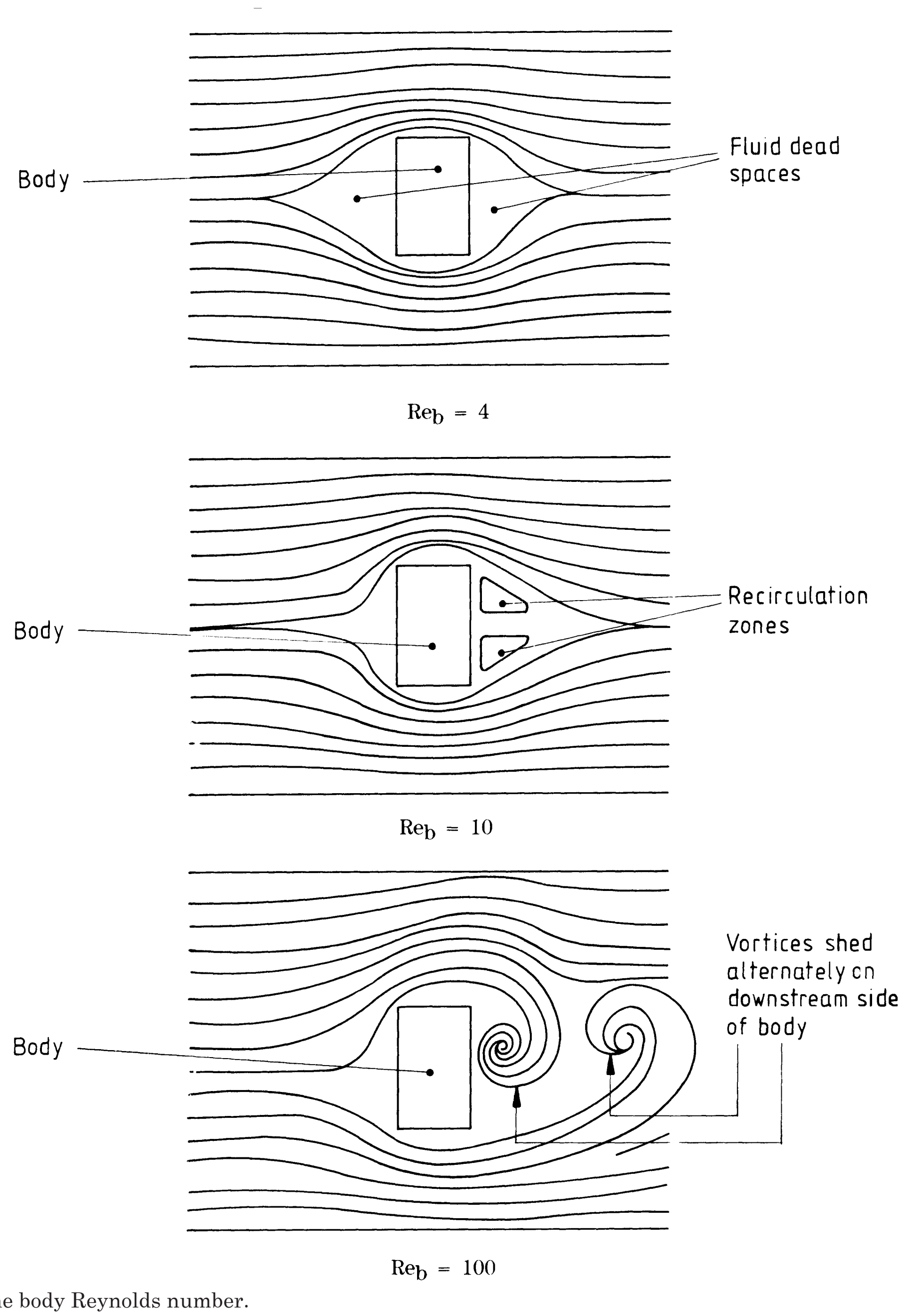


Figure 3.4.10 — Design and operation of RF type pick-off



NOTE Re_b is the body Reynolds number.

Figure 3.5.1 — Phenomenon of vortex shedding

The theory of vortex shedding is mathematically imprecise but can be explained qualitatively. Fluid forced to flow past the side of the bluff body develops a steep velocity profile. The fluid close to the surface of the body experiences drag whilst that at a distance is accelerating due to an area reduction arising from the body blockage. This velocity profile imparts a rotational motion to the fluid and creates a spinning free vortex at the point of separation from the downstream edge or surface of the bluff body.

A qualitative explanation for the phenomenon of alternate shedding is more difficult but experiments have been devised to show that there is a fluid feedback mechanism which exists at the immediate rear of the bluff body. This decelerates the flow past the opposite side until the original vortex is swept downstream. For satisfactory operation, the axial length of the bluff body has to be precisely normal to the axis of the flow stream, i.e. the bluff body should not be sloping backwards or forwards and the flow profile in the plane of the body length has to be symmetrical. When these and other manufacturer conditions are met, there is the following very close approximation to a linear relationship between mean pipe flow velocity, U (in m/s) and shedding frequency, f (in H_z).

$$U = \mathrm{K} f \qquad (3.5.1)$$

where

K is a constant for all fluids and for a given design of meter.

The volume flow rate q_v in a pipe can be computed from the equation:

$$q_v = AU = A\mathrm{K} f \qquad (3.5.2)$$

where

A is the area of the meter bore.

Equation 3.5.1 is derived from the following general relationship between fluid velocity and frequency shedding.

$$f = S\frac{U'}{d} \qquad (3.5.3)$$

where

S is the dimensionless Strouhal number;

d is the width of the bluff body (in m);

U' is the fluid velocity passing along the side of the bluff body (in m/s).

For an ideal linear flowmeter S should remain constant over the whole flow range and (regardless of Re_b), equation 3.5.3 indicates that a vortex meter is a linear device whose calibration is independent of the fluid composition and its physical parameters. Because U' the fluid velocity past the side of the bluff body for a given rate of pipe flow, is dependent upon the blockage ratio as determined by the bluff body width, the frequency of shedding can be made insensitive to changes in this width. This is because an increase in width should reduce the shedding frequency, but this is compensated by an increase in U' due to the higher blockage effect. When the body width is approximately one third of the meter bore the compensation is nearly complete and a symmetrical change in body width typically causes a 0.4 % change in meter factor. The optimum ratio of body width to meter bore varies slightly with the body shape. The basic flow characteristics of vortex meters have been investigated by Caspersen (1977), Zanker and Cousins (1977) and Inkley et al (1980).

3.5.2.2 ***Basic design and construction***

Vortex meters consist of a bluff body within a housing to generate the vortices, a vortex sensing method and electronic circuitry for conditioning the output signals. There are many commercial meter designs available, all having different specifications and performances, e.g. some designs are suitable only for liquids, others only for gases or steam, whilst some can measure all fluids. Each manufacturer has developed a different body shape empirically and some of the designs are the subject of patent protection. Typical designs are illustrated in Figure 3.5.2. Recent developments have shown that stronger and more regular shedding can be obtained by using two bodies with an optimum axial spacing. The design of a good bluff body is a compromise between minimum pressure loss, a constancy of Strouhal number over a wide flow range, strong shedding capabilities, regular two dimensional shedding and low cost.

3.5.2.3 ***Vortex sensors***

The vortex sensors can be located within the bluff body, downstream of it or in the new designs outside of the pipe. External sensors can generally claim the advantage of offering simple replacement or servicing procedures without removing the meter from the line.

Figure 3.5.3 illustrates some of the commercially available sensor designs which may be classified into four groups as follows:

a) thermal;

b) pressure;

c) strain;

d) ultrasonic.

Thermal sensors are normally heated thermistors insulated from the meter components and the fluid by a thin glass coating. The heated thermistors are subject to a cooling effect which is a function of flow velocity past their surfaces. This, in turn, alters their resistance values and provides the raw electrical output signal. By having the two thermistors in a push-pull arrangement, the effect of common mode hydrodynamic noise can be eliminated. They can be positioned either in the face of the bluff body or mounted internally. In both cases the thermistors sense the oscillating flow. A third arrangement is to bring two ducts from sensitive locations on each side of the bluff body or from the meter body, to an external sensor housing.

Thermal sensors have the advantage of being relatively insensitive to vibration, but their time constant can be a limiting factor at high shedding frequencies. They are also susceptible to failure by damage or erosion of the glass coating.

Pressure sensors measure the pressure difference across the bluff body or between sensitive locations in the main meter body housing. The sensing is carried out by diaphragms whose response results in either a change of capacitance or a change in a force on a piezoelectric cantilever arm. Alternatively, the pressure difference can be sensed by a reluctance type pickup. The oscillating ball sensor is intended for the measurement of pure clean liquids, especially the cryogenic variety. The presence of scaling deposits or other solid material will hamper the movement of the ball. The oscillating disc is intended for high temperature applications, for example, steam flow measurement.

Strain sensors measure the force exerted by flowing vortices on an elastically mounted fin attached to the rear of the bluff body or on a second downstream body. The force is converted into an electrical signal by means of a piezoelectric strain sensor. In some modern designs two piezoelectric sensors are mounted outside the flow. One senses the bluff body movement while the second measures any meter housing vibration which could degrade signal to noise ratio. Such a compensation technique produces enhanced signals.

Ultrasonic sensing is carried out by directing an ultrasonic beam across the downstream fluid flow to a receiving sensor. The vortices amplitude modulate the ultrasonic beam in a gas stream by virtue of the density gradients, whilst liquids phase modulate by virtue of velocity components in the vortex.

3.5.2.4 *Performance characteristics*

A typical specification for a commercial vortex shedding flowmeter is as follows:

Accuracy (% of rate):	
Digital output:	± 0.75 % calibrated for liquid ± 1.5 % uncalibrated for liquid ± 1.25 % calibrated for gas and steam ± 1.5 % uncalibrated for gas and steam
Analogue output:	Add 0.15 % to figures for digital output
Repeatability (% of rate):	± 0.15 % to ± 0.25 % depending on design
Flow range	Variously quoted 10 : 1 to 50 : 1, depending on application (see note)
Minimum pipe *Re*:	3×10^4, but down to 10^4 if reduced accuracy is acceptable
Maximum pipe *Re*:	Limited by cavitation, high frequency loss in sensor or compressibility, but usually 5×10^6

NOTE The quoted specification for the dynamic range may be unrealistic in a practical application, not because the meter is incapable of meeting its claims, but because the top end of the range corresponds to fluid velocities which are unacceptable to the user.

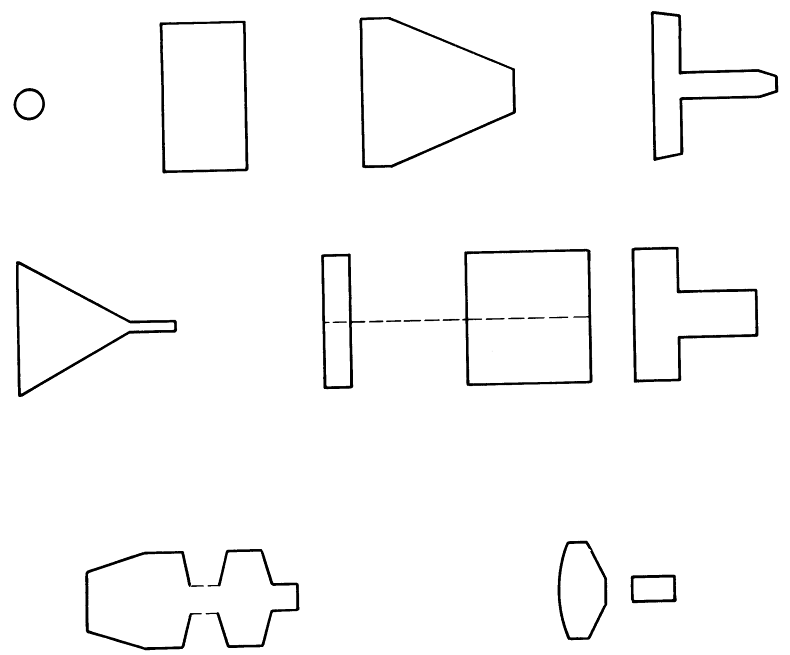


Figure 3.5.2 — Plan view of typical bluff body shapes

3.5.2.5 ***Advantages and disadvantages***

The main advantages of the vortex shedding meter are as follows:

a) relatively low installed cost with simple installation;

b) good long term stability of output;

c) performance relatively unaffected by viscosity, density, pressure and temperature;

d) suitable for liquids and gases;

e) analogue or frequency output;

f) wide turndown with good linearity.

The main disadvantages of the vortex shedding meters are as follows:

g) sensitive to high level of vibration (but newer models are less sensitive);

h) serious errors can be caused by swirl;

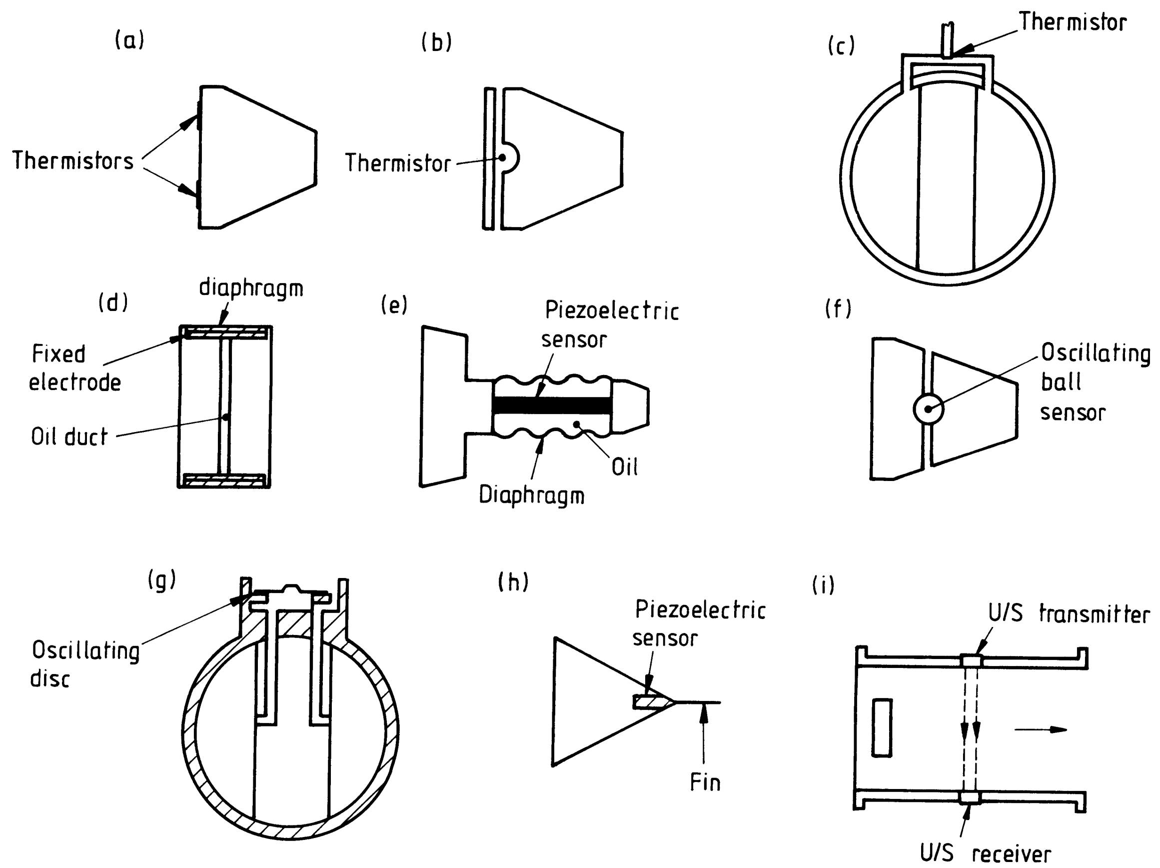
i) limited size range (typically 12 mm to 200 mm);

j) limited pulse resolution;

k) pulse train suffers from frequency and amplitude modulation;

l) has a pressure drop of approximately two velocity heads;

m) limited pressure and temperature range.



NOTE Items (a) to (c), (d) to (h) and (i) are respectively thermal, pressure and ultrasonic vortex sensing designs.

Figure 3.5.3 — Vortex sensing designs

3.5.3 Fluidic oscillators

One type of commercial fluidic flowmeter is illustrated in Figure 3.5.4. It depends for its operation on the Coanda effect exhibited by a jet of fluid having a tendency to attach itself to a solid surface. The qualititative explanation for this attachment is similar to that given for vortex shedding. The drag effect of fluid layers close to the stationary wall imparts a velocity gradient which directs the jet towards the surface of the wall. The oscillatory effect is achieved by a feedback mechanism. The fluid stream passes through special porting in the meter body designed to develop a slightly higher pressure at a point where an auxiliary jet can be ducted off and fed back in a direction at normal incidence to the incoming fluid. The hydrodynamic action which follows, switches the main jet to the alternate wall at which point the sequence is repeated, resulting in the jet switching periodically from one stable position to the other. The switching frequency is a linear function of fluid velocity and is dependent upon the meter geometry and the dynamic characteristics of the fluid in the auxiliary duct.

A fluidic flowmeter has a performance consistent with that of a vortex shedding meter. However it can operate linearly down to a lower Reynolds number, i.e. approximately 2×10^3.

3.5.4 Special designs

One type of flowmeter, developed in 1965 and bearing the trade name Swirlmeter® (see Figure 3.5.5), generates a strong fluid instability in a controlled manner, from which the flow rate is inferred. The inflowing fluid has a swirl imparted to it by means of fixed helical blades and then undergoes acceleration by means of a venturi throat, followed by deceleration in an expanding cone. This conditioning generates a hydrodynamic instability which takes the form of a precessing vortex whose precession frequency is a linear function of fluid flow.

The frequency measurement is made with a thermistor sensor similar to that used in vortex meters. For some applications a piezo sensor is used. In either case a pulse rate scaler can be used to covert the signal into integral engineering units. The performance is similar to a vortex shedding meter but its application is normally limited to gas flow measurement on account of its high headloss (approximately ten velocity heads or about five times the loss of a vortex meter). The linearity is approximately ± 0.75 % of Reynolds number rate, its repeatability ± 0.2 % of rate and the minimum is 10^4.

Apart from the limitations already referred to and the problem of obtaining mechanical similarity in production, the advantages and disadvantages of the swirlmeter are similar to those listed for the vortex shedding meters. One additional advantage of the swirlmeter is its relative insensitivity to swirl or upstream profile disturbances but it is sensitive to flow pulsations.

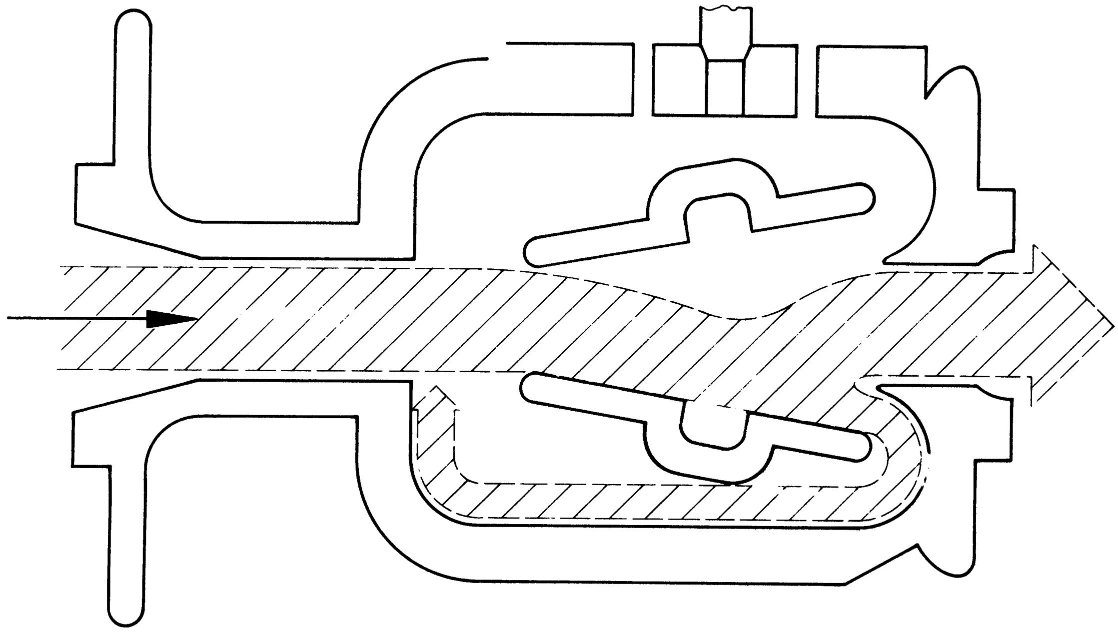


Figure 3.5.4 — Fluidic oscillating flowmeter

3.5.5 Insertion vortex meters

3.5.5.1 *Design*

The insertion meter follows the same operating principles as the vortex shedding pipe meter but has differences in design and performance. A small assembly consisting of a bluff body, outer casing and sensor is fixed to a supporting strut. This allows the meter to be supported in a chosen location within a large diameter pipe. The insertion meter measures the velocity of the fluid at its point of location and as discussed in **3.2.5** this is not necessarily representative of the average pipe velocity. Also, the presence of the insertion meter and its support strut has a blockage effect on the fluid flow, so it cannot be assumed that the flow velocity through the meter is the same as that which existed at the metering point before the meter was inserted. The effect tends to increase the fluid velocity through the meter above the free flow value.

The bluff body has to be supported in a housing to maintain strong regular shedding action. A bluff body without such a housing, necessary to maintain two dimensional shedding, is unsatisfactory.

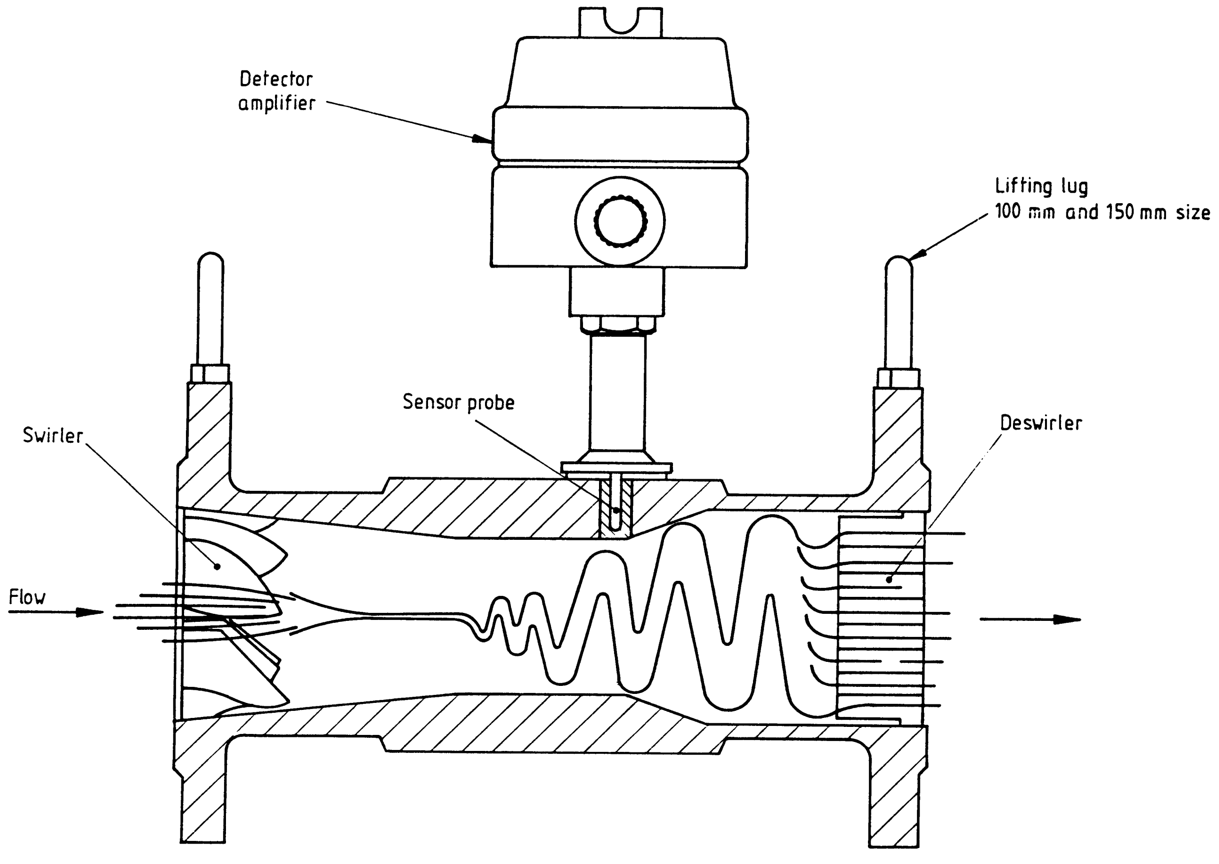


Figure 3.5.5 — Swirlmeter®

3.5.5.2 ***Advantages and disadvantages***

The advantage is primarily one of cost and very low head loss. The disadvantages of the insertion vortex meter are as follows:

a) The meter needs to be calibrated for accurate measurement as it is sensitive to velocity profile changes and a blockage effect.

b) Insertion meters, small enough to pass through an isolating valve, have design limitations imposed on them which make them potentially less accurate than a full size meter designed for installation in a pipe line.

As a result of these disadvantages, the uncertainty of an insertion vortex meter is probably not better than 5 % of flow rate but with a good symmetrical fluid velocity profile, and a selected location in the stream where velocity profile changes have minimum effect, an uncertainty of 2 % of rate might be achieved after calibration.

The main advantage is the low cost of installing this type of meter in large bore pipes (> 0.5 m).

3.6 Group 6 meters: electromagnetic types

3.6.1 General

When a fluid moves in a magnetic field an e.m.f. is generated in accordance with Faraday's law (see Figure 3.6.1). If the field is perpendicular to an electrically-insulated pipe, which contains the moving fluid, and if the electrical conductivity of the fluid is not too low, a voltage may be measured between two electrodes on the pipe wall. This voltage is proportional to the magnetic field strength, the average velocity of the fluid, and the distance between the electrodes. Thus the velocity and hence the flow rate of the fluid may be measured.

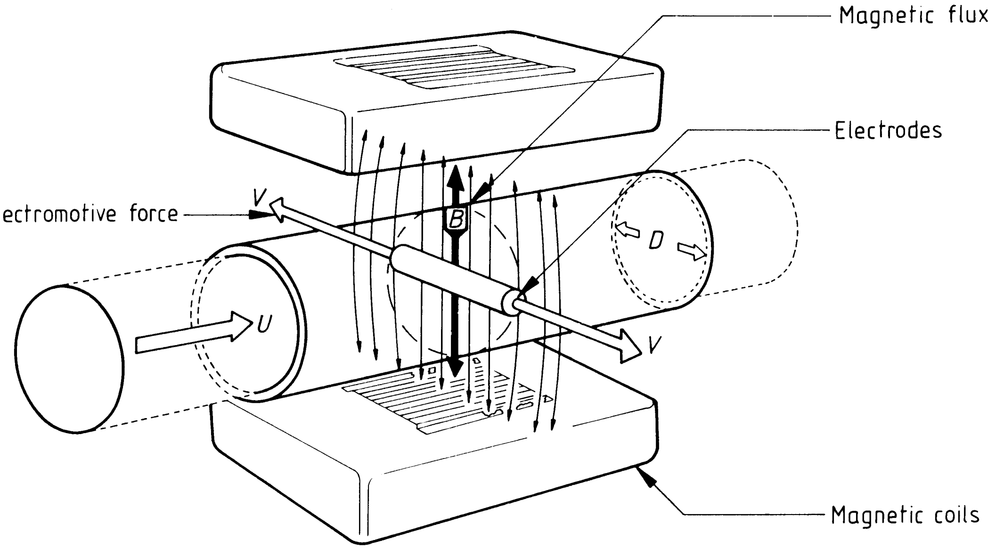
Flowmeters based on this effect are called electromagnetic flowmeters (sometimes magnetic flowmeters or just magmeters) and were the first practical form of flowmeter to be developed which did not present any obstruction to the fluid flowing through the meter. The only head loss is due to the length of meter tube. A further very advantageous feature is that they do not have any moving parts.

3.6.2 Electromagnetic flowmeters

3.6.2.1 *Basic description*

The electromagnetic flowmeter consists of a primary device through which the process fluid flows, and of a secondary device which converts the low level signal generated by the primary device into a suitable standardized signal for acceptance by industrial instrumentation (see, for example, BS 5863). The system produces an output signal proportional to volume flow rate (or average pipe velocity). Its application is generally limited only by the requirement that the metered fluid shall be electrically conductive and non-magnetic.

The primary and the secondary devices can be combined in a single assembly.



Key:

B is the magnetic flux density

D is the inside diameter of meter tube

V is the flow signal (e.m.f.)

U is the mean axial fluid velocity

Figure 3.6.1 — Principle of an electromagnetic flowmeter

3.6.2.2 *Primary devices*

The primary device of an electromagnetic flowmeter consists of the coils, the yoke of ferromagnetic material, the meter tube through which the fluid flows and the electrodes. The primary device may also contain circuitry for deriving the reference signal.

Figure 3.6.2 shows an exploded view of an industrial primary device. The coils and the yoke are arranged to produce a magnetic field. The meter tube is of a non-magnetic material such as plastics, aluminium, brass or non-magnetic stainless steel. An insulating lining is used with metallic tubes to prevent the metal tube from short-circuiting the electrode signal. The lining may be of glass, elastomer, plastics, ceramic, etc. The materials used for the lining and the electrodes are chosen to be compatible with the fluid to be metered.

Other specific designs can also be available, for example a cast steel case with the coils insulated inside the case and liners fitted internal to this. Flanges are usually provided to connect the primary device to the plant pipework, although flangeless meters are available in smaller sizes.

The coils producing the magnetic field may be energized from the normal single-phase supply, or by some other supply. The coil assembly is mounted either externally or encapsulated within the pipe. In the latter case, the pipe is made of magnetic material.

A pulsed d.c. meter is one in which the field windings of the primary device are energized from a constant voltage or current source and employs an output signal sampling technique which rapidly differentiates between the pure flow signal and any other spurious signals which may be present.

Usually the bore of the meter tube will be the same as that of the adjacent pipework. If in this case the axial velocity corresponding to the maximum flow rate is less than that recommended by the manufacturers, a primary device with a smaller bore should be used. A primary device with a bore smaller than that of the adjacent pipework may also be used for other reasons, e.g. to reduce cost or in the interest of rationalization.

3.6.2.3 ***Secondary devices***

Secondary devices are required to carry out the following processes.

a) Amplify and process the electrode and reference signals to obtain a signal proportional to flow.

b) Eliminate, as far as possible, spurious e.m.f.s, including common mode and quadrature signals and signals arising from electrochemical effects and disturbances at electrodes.

c) Provide means of compensating for supply voltage and frequency variations where necessary.

d) Provide means of compensating or minimizing magnetic field strength variation in the primary device. This is important since it directly affects repeatability of the voltage at the measurement electrodes.

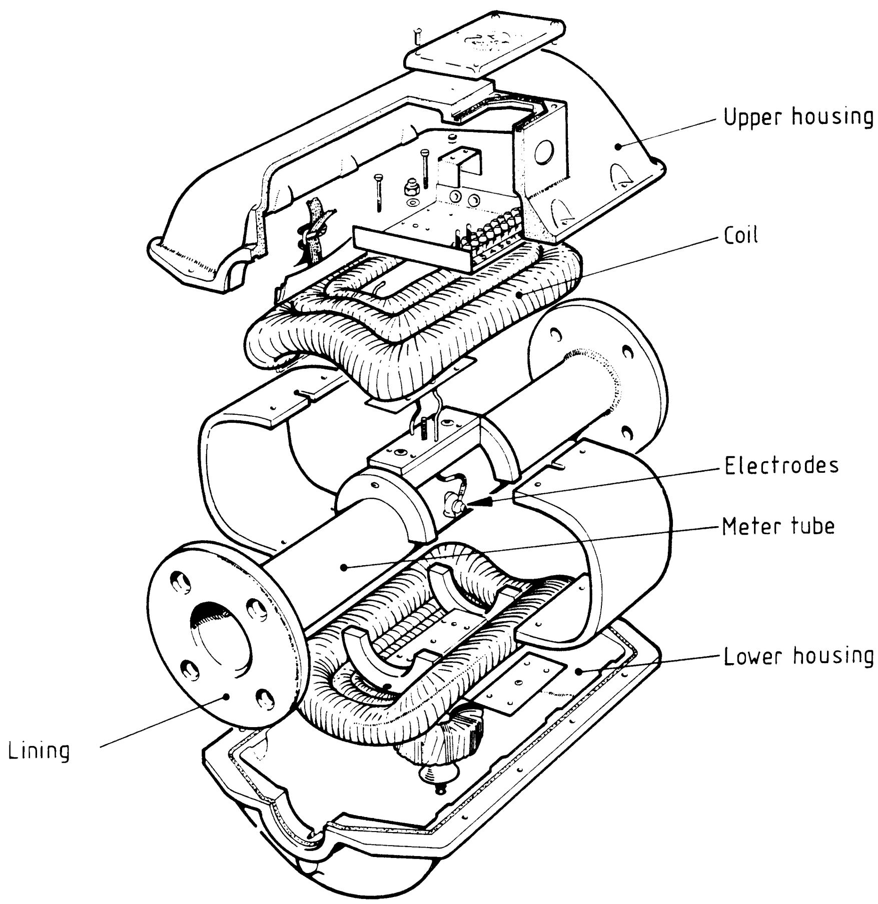


Figure 3.6.2 — Exploded view of the primary device of an electromagnetic flowmeter

Compensation is achieved by using the following means.

1) A gain-compensated amplifier in which the gain is proportional to the supply frequency and inversely proportional to the supply voltage.

2) A system in which the output is proportional to the ratio of the flow component signal and a reference signal derived from the field current. At a given flow rate both signals may vary with supply voltage and frequency but their ratio will remain constant.

3) A system where the field current is stabilized.

An industrial electromagnetic flowmeter can be either a d.c. system or an a.c. system.

For a.c. systems with unregulated coil current, the secondary device measures the ratio of *V*/*B* (see **3.6.3**). Voltages, other than the flow signal (*V*), may be picked up by electrode leads. These voltages may be generated by the varying flux intersecting a loop composed of the electrode leads, the electrodes, and the fluid connecting the electrodes (transformer effect). Such a voltage will be approximately 90° out of phase with the flow signal. That portion which is 90° out of phase is called quadrature. The remainder is the in-phase component. The in-phase component is zeroed at no flow during initial installation unless the flowmeters have a device which provides this function automatically.

If the coil current is regulated, the magnetic field is considered to be constant and it is only necessary to measure the electrode signal. If the coil current is not regulated, then, in order to compensate for variations in the magnetic field, the secondary device may use a reference signal obtained from the primary element. This reference signal may be derived from the supply voltage, the supply current, the flux density in the iron or the flux density in the air gap.

In a pulsed d.c. system, under ideal or reference conditions, the peak-to-peak value of the electrode signals, ($V_p + V_n$) is proportional to the flow velocity in the pipeline and V_p is also equal to V_n [see Figure 3.6.3(a)].

In a practical situation, if the zero or no flow signal is offset in the positive direction by an amount V_e, then the positive signal is ($V_p + V_e$) and the negative signal is ($V_n - V_e$) [Figure 3.6.3(b)].

Hence the overall value of the electrode signal is $V_p + V_n$ and the offset zero is eliminated. The same applies if the offset is in the negative direction. The comprehensive system thus eliminates zero errors automatically at all times and zero adjustment is not usually required either at start-up/commissioning or at any time during subsequent operation.

The introduction of microprocessors to handle the signal processing has given rise to a number of advantages including the following.

a) The elimination of all adjustable potentiometers and other adjustable electromechanical components which are most frequently the cause of system failure or malfunctioning.

b) The ability to include various diagnostic and self-checking routines as well as to transmit the measurement signal in digital form.

c) The ability to display in digital form such information as flow rate, in either engineering units or as a percentage of the upper range or the totalized flow.

d) The ability to provide an analogue signal for process control as well as a pulse output scaled to suit specific applications or to function as a batching counter.

3.6.2.4 ***System output***

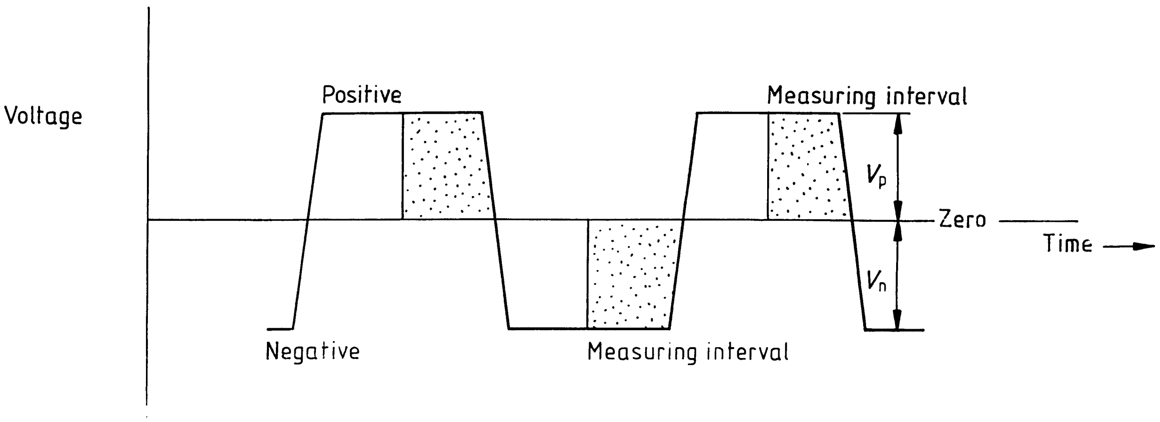
The system output can be one or more of the following:

a) analogue direct current in accordance with BS 5863-1;

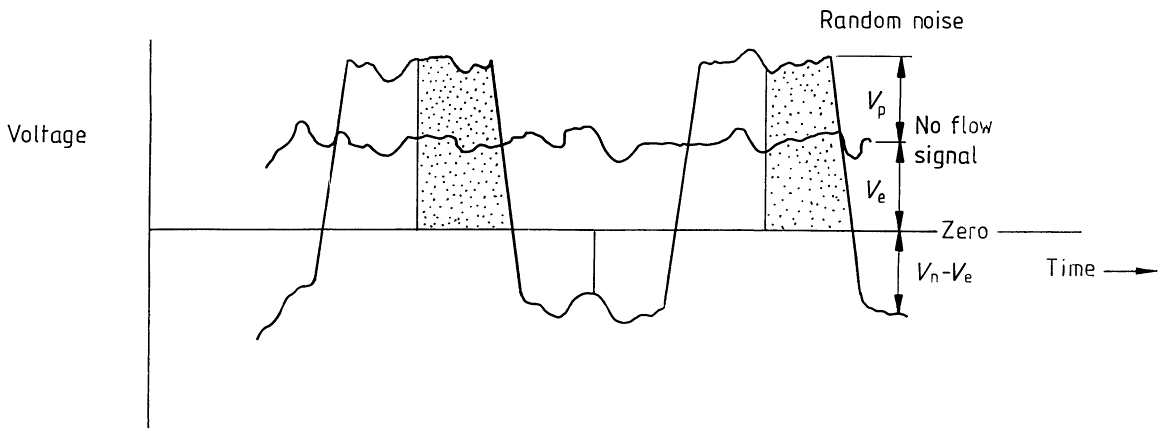
b) analogue direct voltage in accordance with BS 5863-2;

c) a frequency output in the form of scaled or unscaled pulses;

d) digital.



(a) Ideal conditions



(b) Practical conditions

Key:

V_p is the value of the positive part of the peak to peak signal;

V_n is the value of the negative part of the peak to peak signal;

V_e is the zero offset value.

Figure 3.6.3 — Principle of pulsed d.c. (bipolar) system

3.6.3 Basic theory

In accordance with the Faraday law of induction, the strength of the induced voltages is given by the following simplified expressions:

$$V = kBL_e U \qquad (3.6.1)$$

where

k is a constant.

The volume flow rate in the case of a circular pipe is:

$$q_v = \frac{\pi D^2}{4} U \qquad (3.6.2)$$

Which combined with equation 3.6.1 gives

$$q_v = \frac{\pi D^2 V}{4kL_e B}\text{, or} \qquad (3.6.3)$$

$$q_v = K \frac{V}{B} \tag{3.6.4}$$

Equation 3.6.4 may be interpreted in various ways to produce a calibration factor which in practice is usually determined by wet calibration.

3.6.4 Effect of velocity distribution

Ideally, the magnetic field would be so arranged that the calibration factor is always the same, irrespective of the flow pattern. Though this can be done in flowmeters with special electrode arrangements, it cannot be achieved if small electrodes are used. In practice, when a flow velocity profile which is significantly different from that in the original calibration is presented to the electrode plane, an electromagnetic flowmeter may exhibit a shift in calibration. The arrangement of pipe fittings upstream of the primary device is one of the factors which can contribute to the creation of a particular velocity profile.

Precise data on the effects of flow disturbances is not always available but for most electromagnetic flowmeters it is recommended that any source of flow disturbance such as a bend should be at least ten pipe diameters upstream of the electrode plane if the calibration factor is not to be altered by more than 1 %. When the distance is unavoidably less than this, the manufacturer's advice should be sought.

Swirling flow can also alter the calibration factor because, although flow components perpendicular to the pipe axis cannot contribute to the flow rate, they may contribute to the signal. Furthermore, the amount and distribution of swirl arising from various upstream pipe configurations, such as several bends in different planes, is difficult to predict from the geometry of the pipework.

When swirling flow may be suspected, it is good practice to insert a swirl reducer at a suitable distance upstream of the primary device.

3.6.5 Variations in design

3.6.5.1 *Large contacting electrodes*

Electromagnetic flowmeters with large electrodes (e.g. square or circular shaped electrodes subtending 20° at the tube axis) are sometimes constructed. These reduce velocity profile effects due to pipe fittings. They also reduce the source impedance of the meter, easing the problem of measuring flow of liquids with conductivities approaching that of pure water. Variations in the distributions of contact impedance over the electrode/liquid interface can, however, cause a sensitivity uncertainty of a few percent and transformer effect signals larger than usual causing greater drifting of zero. Choice of materials for the electrodes plus regular and careful cleaning are needed if these problems are to be avoided. Further details on performance aspects can be found in Al-Khazraji and Baker (1979).

3.6.5.2 *Contactless electrodes*

It is not necessary for the electrodes to make direct contact with the liquid. Electrodes are sometimes embedded in the insulating material of the liner. They make electrical contact with the liquid by capacitance coupling. The thickness of the insulating material between the electrodes and liquid, together with the area of the electrodes, should be such that the impedance at the operating frequency is not too high for precise measurement of the flow signal. Contactless electrodes are less likely to cause leakage of the liquid or to react chemically with it. When their dimensions are comparable with the tube diameter, velocity profile effects are greatly reduced.

3.6.5.3 *Compact or short tube designs*

Economics in design and construction have recently led to the appearance of compact designs in the marketplace. These are often flangeless designs, a typical example being shown in Figure 3.6.4. This figure also shows the typical saving in length this new design of meter offers. By the use of d.c. excitation, operating a lower magnetic field strength, the size of the coils can be greatly reduced. If meters are shorter than around two pipe diameters, the electrical and magnetic properties of the pipes attached to the meter can affect the sensitivity. With metal pipes the conductivity causes partial shorting of the flow induced e.m.f. to a degree which is variable due to the changing character of the contact impedance between them and the liquid. This can affect the accuracy by 1 % with tube lengths of 1.5 diameters. However, the limiting effect in short tube meters is the reduction in sensitivity caused by the reduced magnetic field strength of the smaller coil and the smaller electrode dimensions.

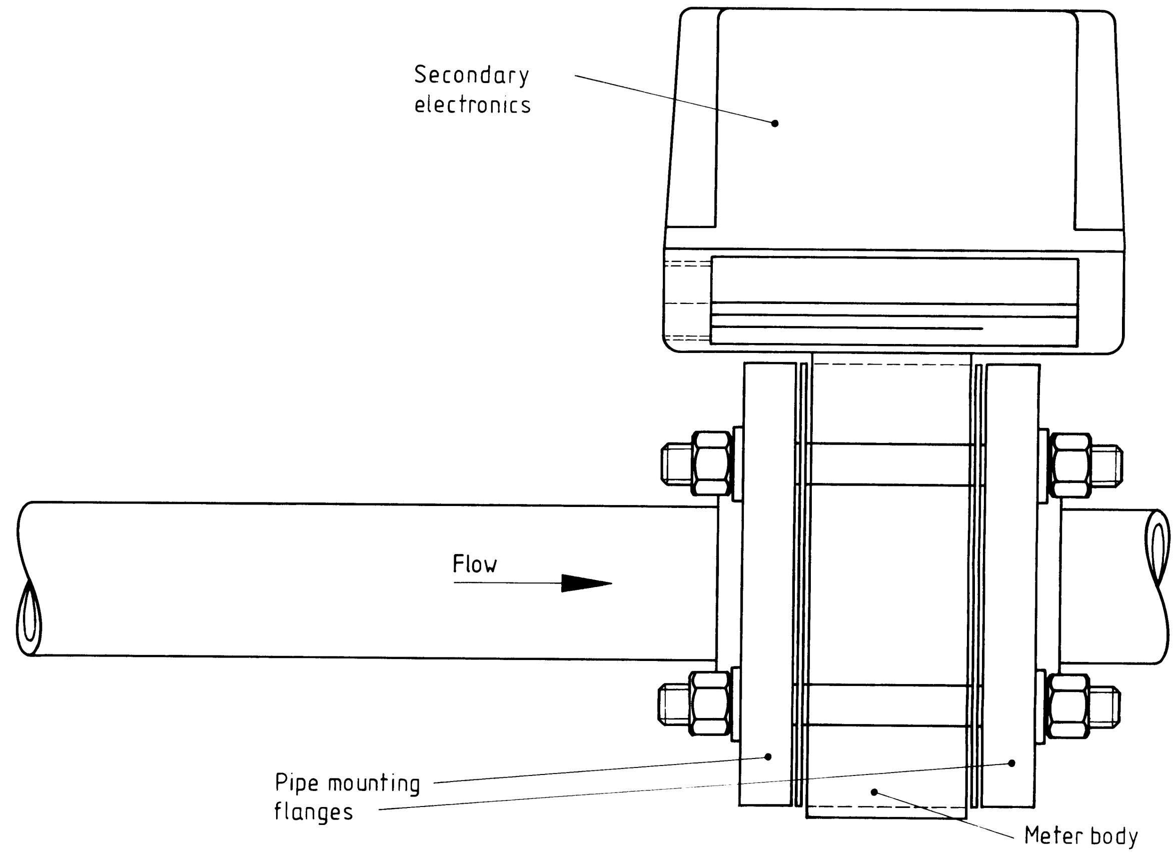


Figure 3.6.4 — Modern compact electromagnetic flowmeter

3.6.6 Electromagnetic velocity probes

There are basically two types of electromagnetic velocity probes, as follows.

a) An inside-out version of the conventional electromagnetic meter, as shown schematically in Figure 3.6.5. The electrodes are situated on the outside of the body in contact with the liquid. The coil is embedded in an insulating body. The probe axis has to be aligned with the direction of the local flow velocity (the z direction in Figure 3.6.5) and the flow induced potential is measured across the electrodes in the usual way. The basic equation is modified slightly to give the measured potential difference, V' (in V)

$$V' = \mathrm{K}\, v\, B_0 d^*$$

where

d^* is the probe diameter;

B_0 is the flux at some reference position (in T);

v is the local velocity (in m/s);

K is a constant which depends on the magnetic field shape and the velocity distribution in the boundary layer.

The boundary layer velocity distribution is a function of the Reynolds number (with d^* the characteristic length) so V', the measured potential difference, may not be a linear function of v. The dimensions of the probe should be small compared with the radial distance in the undisturbed flow over which v changes appreciably.

b) A mini version of the conventional full-bore electromagnetic meter on a stem. The sensor body provides both an orifice within which the electrodes are set and the location of a coil which provides the flux field within the orifice. The velocity of flow through this sampling orifice is measured as for conventional electromagnetic meters. Installation within the pipe is by means of an extension strut to which the sensor is attached.

These probes are sometimes inserted in tubes to measure the total flow rate through the tube. The probe axis then coincides with the tube axis and the probe diameter need no longer be small compared to the tube diameter.

3.6.7 Performance characteristics

The performance of electromagnetic meters as with other types of flowmeter can vary widely. Uncertainty can be expressed as either a percentage of reading or a percentage of full scale, with most being in the range 0.5 % of flow rate to 1 % full scale. Some d.c. type meters are similar in performance to the a.c. types but generally they have a well defined zero point as discussed and superior signal conditioning. This has meant that the new meters with microprocessor control have uncertainty statements better than 0.5 % of reading.

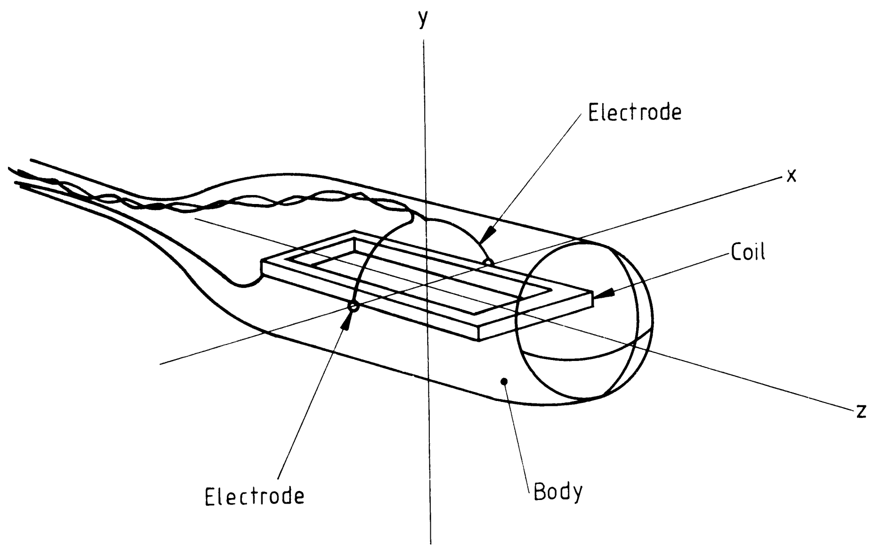


Figure 3.6.5 — Electromagnetic velocity probe

It is important to study published specifications of electromagnetic flowmeters carefully. Some suppliers quote an upper range velocity with an associated turndown whereas others quote a user selectable range of velocities without a turndown. It is important to note that if a low value for the maximum velocity is chosen the turndown of the meter is reduced.

Care should also be taken when selecting electromagnetic meters for high velocity applications. The choice of liner material requires particular attention if the line velocity is above 5 m/s.

3.7 Group 7 meters: ultrasonic types

3.7.1 General

Ultrasonic meters are relatively new to industrial flow measurement, and although they have still to establish their applications niche they are showing considerable promise. Some designs are true non-invasive meters, with the facility of being clamped-on devices, while others have ultrasonic transducers in direct contact with the fluid.

A wide variety of flowmeters have been designed employing ultrasonics, i.e. acoustic waves with frequencies above the audible range. The most commonly used flowmetering methods use time of flight (otherwise known as transit time) and Doppler techniques. Other applications of ultrasonics to flow measurement include the measurement of the bending of the ultrasonic beam caused by flow, the detection of vortices in vortex-shedding flowmeters and as a method of detecting disturbances in a correlation flowmeter.

Ultrasonic waves travel in a medium with a speed of sound relative to the medium. The frequency and wave length of the ultrasonic wave are related by the following equation:

$$c = f\lambda \qquad (3.7.1)$$

where

c is the velocity of sound in the medium (in m/s);

f is the frequency (in Hz);

λ is the wavelength (in m).

In liquids and gases, the only waves which propagate are longitudinal (compression) waves. The motion of individual particles in the fluid is in the same direction as the direction of wave propagation. In solids, the ultrasound may be transmitted as either a longitudinal wave or a transverse (shear) wave in which the motion of individual particles is orthogonal to the direction of propagation. In thin plates or pipe walls modes of vibration may be excited, propagation then being by means of Lamb waves.

Modification of ultrasonic waves at interfaces between different materials may occur because of reflection and refraction, which may cause direction of propagation of the wave to change. For example, mode conversion from a transverse to a longitudinal wave may occur at a solid/liquid interface. Such effects are of particular importance in the design of ultrasonic flowmeters where the transducers are clamped on the outside of the pipework. Reviews can be found in Sanderson and Hemp (1981), Lynnworth (1979) or McShane (1974).

3.7.2 Time of flight (transit time) flowmeters

3.7.2.1 *General*

Time of flight flowmeters are designed for use with clean liquids where they find their major application, but can also be used for gases. They present no obstruction to the flow and hence have no additional head loss, and have no moving parts. They measure the difference in transit times for two ultrasonic beams transmitted upstream and downstream in the fluid as shown in Figure 3.7.1. In the general situation shown in (a) of Figure 3.7.1 the derivation of the equation for flow velocity is complex. An illustrative derivation is presented for the simpler arrangement shown in (b) of Figure 3.7.1.

Pulses going from transducer 1 to transducer 2 are slowed by the component of the flow velocity along the path. In the simplified case the pulse velocity L/t_{12} is given by the equation:

$$L/T_{12} = c - U_m \cdot X/L \qquad (3.7.2)$$

Conversely pulses in the opposite direction are speeded up so:

$$L/T_{21} = c + U_m \cdot X/L \qquad (3.7.3)$$

Subtracting these equations eliminates velocity of sound c, and gives:

$$L/T_{12} - L/T_{21} = -2\, U_m \cdot X/L \qquad (3.7.4)$$

Rearranging gives:

$$U_m = (L^2/2X) \cdot (T_{12} - T_{21})/(T_{12} \cdot T_{21}) \qquad (3.7.5)$$

where

- L is the separation of ultrasonic transducers (in mm);
- T_{12} is the transit time for ultrasonic pulse travelling from transducer 1 to 2 (in ms);
- T_{21} is the transit time for ultrasonic pulse travelling from transducer 2 to 1 (in ms);
- U_m is the mean axial velocity of fluid crossing the path between a pair of ultrasonic transducers (in m/s);
- X is the axial component of the ultrasonic path in the fluid flow (see Figure 3.7.1).

Though the derivation only applies to the simplified situation in (b) of Figure 3.7.1, the result, equation 3.7.5, applies equally to the general situation. It should be noted that the equation is exact for the average velocity of fluid in the plane of the path between two transducers and that all the parameters used can be measured directly. However this value of velocity is different from that of the average velocity of the fluid in the pipe.

The frequency of the ultrasound employed is a compromise between beam divergence, which for a given transducer size decreases with increased frequency, and attenuation, which in clean fluids goes up as the square of the frequency. The frequencies used in transit time flowmeters for liquids are in the region 1 MHz to 5 MHz. The frequencies used in gas flow measurement are somewhat lower and are typically in the range 100 KHz to 300 KHz.

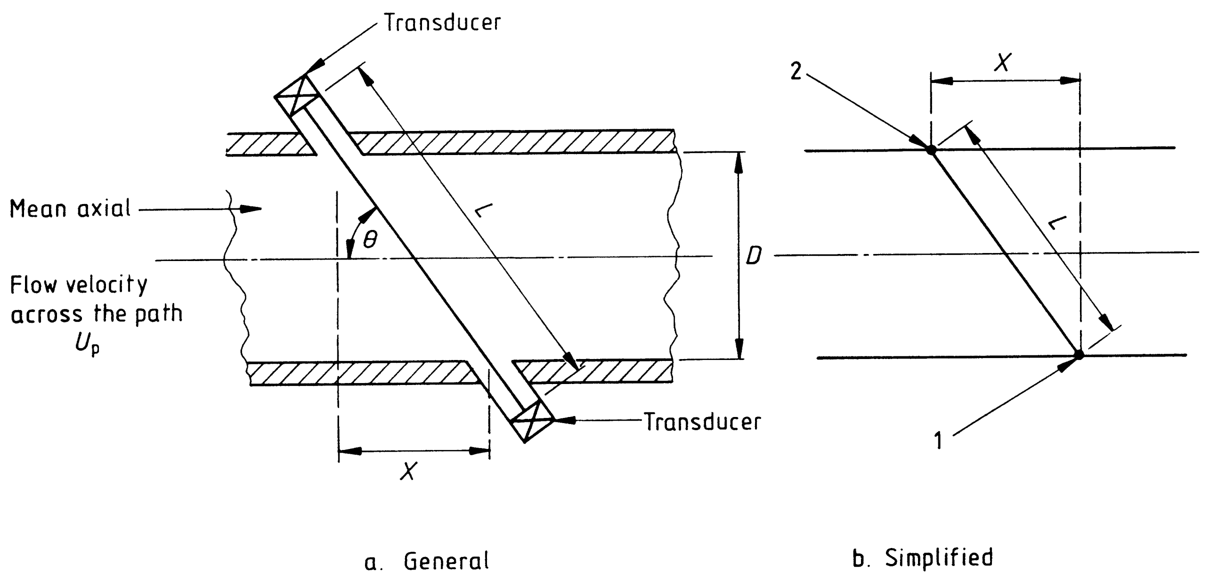


Figure 3.7.1 — Principle of transit time ultrasonic flowmeter

3.7.2.2 ***Mechanical construction***

Transit time flowmeters are constructed as spool piece devices, wetted sensor kits or clamp-on devices. Spool piece devices are of two basic forms as shown in Figure 3.7.1 and (b) of Figure 3.7.2. In diametrical or chordal flowmeters, the ultrasonic transducers are mounted in recesses in the wall of the spool piece. The side wall is sealed at its wetted end by an acoustic window of metal or plastics and the piezoelectric transducer is coupled to the window by a low vapour pressure liquid couplant such as silicon oil. An alternative construction is shown in (a) of Figure 3.7.2 in which the recess is completely filled by an epoxy resin, finished flush with the pipe wall. The acoustic wave is coupled to the fluid through this epoxy window. The design suffers from refraction effects at the epoxy/fluid interface. In small pipe sizes the axial flowmeter shown in (b) of Figure 3.7.2 is often used. In comparison to the diametrical construction, this design has the advantages of increased path length, i.e. increased transit times and transit time differences. It also has the advantage of providing good velocity profile averaging over almost the entire cross-section. It suffers from the effects of turbulence created at the bends feeding the fluid into the measurement section.

Wetted sensor kits enable users to install transit time flowmeters into existing pipework. Holes are drilled in an existing pipe and the transducers are then welded or clamped into position.

Clamp-on flowmeters employing tranducers mounted on the outside of the pipework, as shown in (c) of Figure 3.7.2, enable non-invasive flow measurements to be made on fluids. The performance of such devices is affected by refraction effects at the interfaces between the various materials. These effects also modify the dependence of time difference, ΔT, on the velocity of sound in the fluid to $1/c$ rather than $1/c^2$ as in the case of the wetted transducers. These devices are discussed further by Schmidt (1980).

3.7.2.3 ***Secondary design for transit time flowmeters***

There are two electronic systems commonly used with transit time flowmeters. These are known as the leading edge and sing-around techniques. In the leading edge system shown in Figure 3.7.3 the transducers are used as both transmitters and receivers with the role change being effected by the multiplexer. A voltage pulse is applied to one transducer, and the time for its arrival at the other is measured by an analogue, digital or hybrid time measurement technique. The system thus sequentially measures T_{12} and T_{21}. Alternative leading edge techniques simultaneously apply voltage pulses to both transducers, and compare the received signals to measure ΔT directly. Leading edge techniques are suitable for use with wetted or clamp-on transducers. If equation 3.7.5 is used to calculate the flow velocity, no errors are caused by changes in the velocity of sound. Sing-around systems for wetted transducer flowmeters provide an output which does not require velocity of sound compensation. The operation of the sing-around system is shown in Figure 3.7.4. The received pulse is used to trigger another pulse at the transmitter and the frequency f' of the resulting pulse train measured. The roles of the transducers are reversed and a new frequency f' is measured.

$$f' = \frac{\sin\theta\,(c + u\cos\theta)}{D} \qquad (3.7.6)$$

and

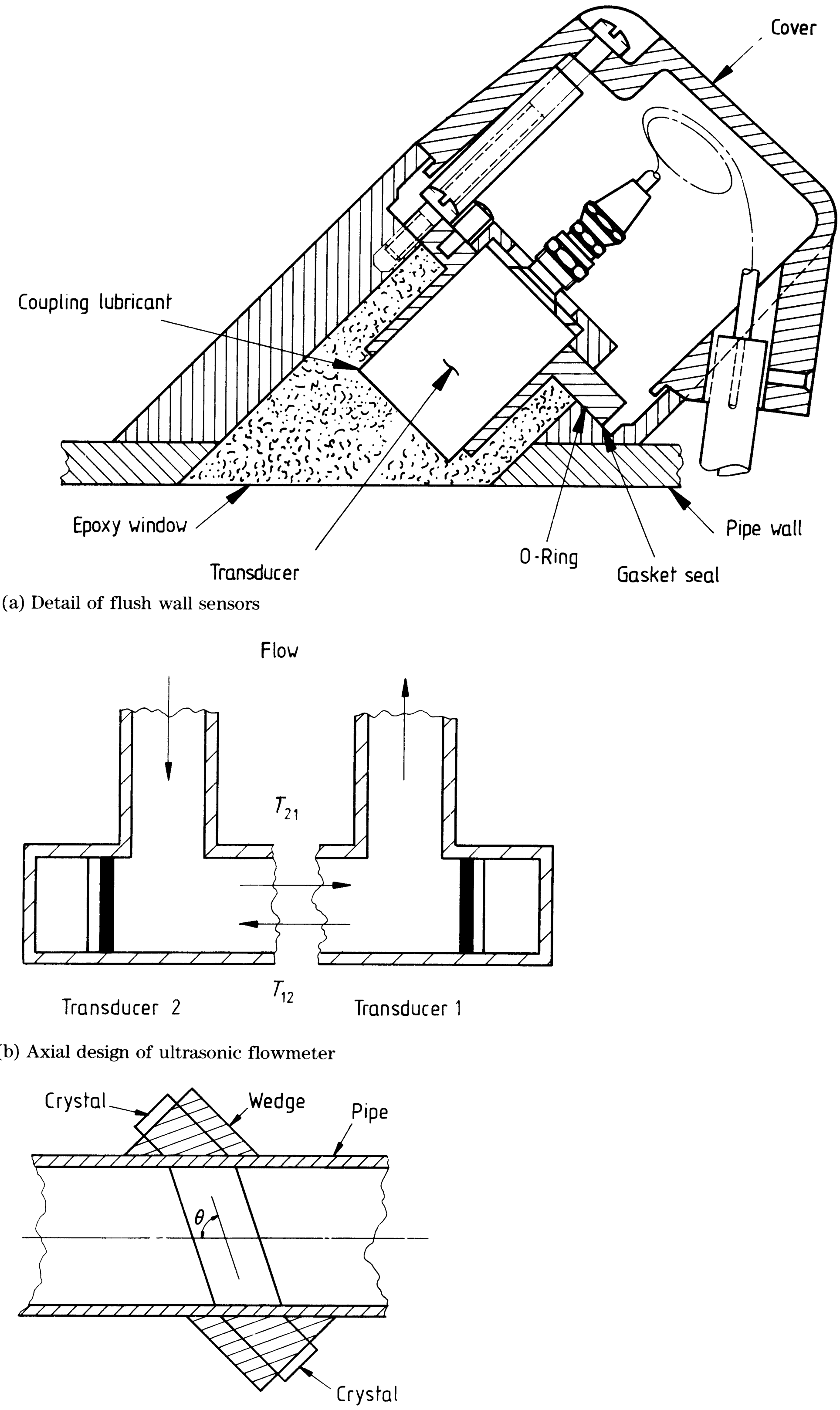
$$f'' = \frac{\sin\theta\,(c - u\cos\theta)}{D} \qquad (3.7.7)$$

and thus

$$f' - f'' = \frac{2u\,\sin\theta\,\cos\theta}{D} \qquad (3.7.8)$$

where

θ is the angle of the ultrasonic beam in the fluid.



(a) Detail of flush wall sensors

(b) Axial design of ultrasonic flowmeter

(c) Clamp-on sensor design

Figure 3.7.2 — Ultrasonic flowmeter designs

Delays in the non-liquid sections of the flowmeter and in the electronics cause the sensitivity of the flowmeter to be altered and also make it sensitive to the velocity of sound in the liquid. One of the major difficulties experienced by sing-around techniques is that any obstruction between the transmitter and receiver will cause errors in the sing-around frequency. The two pulse phase comparison method is a variation which overcomes this problem by using two continuously running voltage-controlled oscillators, whose frequencies are adjusted in turn to correspond to f' and f''. In this way it is claimed that only 2 % of the pulses need be received in order to achieve the required performance.

Sing-around techniques require that the angle of the ultrasonic beam in the fluid, θ, should remain constant since it appears in the equation relating frequency difference to velocity. As such they are suitable for wetted transducer devices in which no refraction at the transducer/liquid interface occurs and where the angle is fixed by geometric considerations. Modified sing-around techniques are available for use with clamp-on sensors which overcome the problem associated with changing beam angle in the fluid caused by refraction effects.

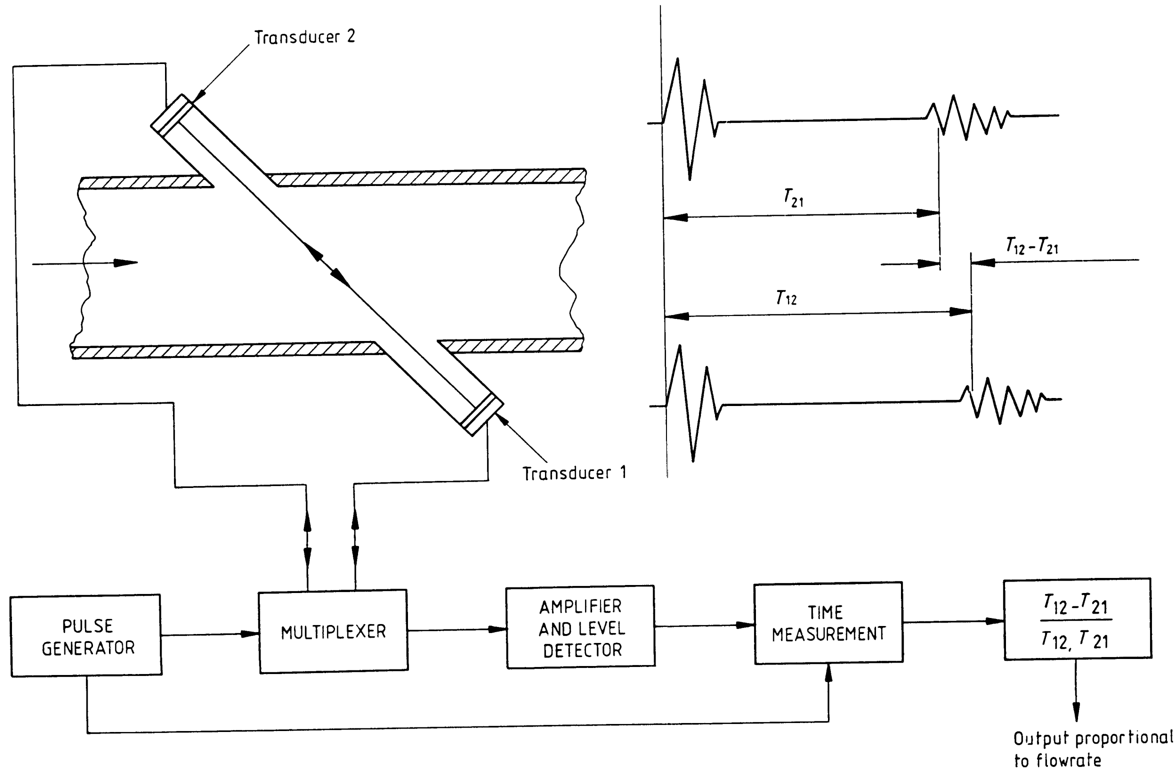


Figure 3.7.3 — Ultrasonic leading edge technique

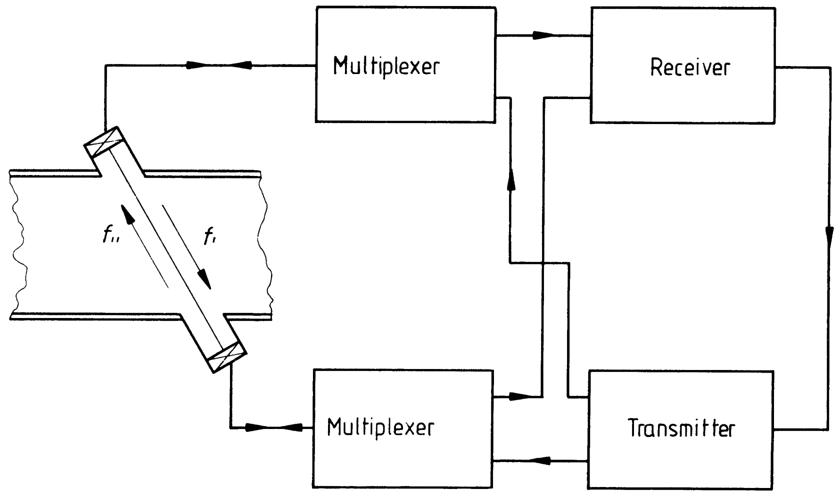


Figure 3.7.4 — Ultrasonic sing-around technique

3.7.2.4 ***Velocity profile effects***

In fully developed flow, if the axial velocity of the fluid varies across the ultrasonic beam then the transit time difference, ΔT (in s), is given by:

$$\Delta T = T_{12} - T_{21} = \frac{2D\, u_{\mathrm{m}} \cot\theta}{c^2} \qquad (3.7.9)$$

where

u_{m} is the mean axial velocity measured over the length of the beam (in m/s).

For fully developed laminar flow $u_{\mathrm{m}} = 1.33U$. For fully developed turbulent flow in smooth pipes

$$\frac{u_{\mathrm{m}}}{U} = 1.12 - 0.011 \log_{10} \times$$

$$\times\ Re (4 \times 10^3 \leq Re \leq 3 \times 10^6) \qquad (3.7.10)$$

This indicates that the sensitivity of the flowmeter will decrease by approximately 1 % for every factor of 10 change in Re within the range 4×10^3 to 3×10^6. Thus, if the meter is used over a 100 : 1 flow range, sensitivity will decrease by 2 %. A change of approximately 30 % in sensitivity will occur in the transition from the laminar to the turbulent flow regimes.

In fully developed flow errors can occur as a consequence of pipe surface roughness, unknown Re, or profile uncertainty in the laminar/turbulent transition region. Uncertainty in fluid composition, or temperature can result in a corresponding uncertainty in Re, even for Newtonian fluids. For non-Newtonian fluids the fully developed profiles differ from the universal velocity distribution power law with a consequent change in flowmeter sensitivity. In practice, it is difficult to ensure a fully developed flow profile, since even after long lengths of straight pipe (or well downstream of flow straightening devices) thermal effects or minor irregularities can disturb the flow profile.

The sensitivity to velocity profile in fully developed turbulent flow can be reduced in a single beam device by the use of an off diameter chord as shown in Figure 3.7.5(a). For a beam offset from the diameter by 0.25 d the change in flowmeter sensitivity is less than 0.25 % for a change in Re from 3×10^3 to 3×10^6. Multiple beams as shown in Figure 3.7.5(b) can produce significantly reduced sensitivity both to fully developed velocity profiles and also to the disturbed profiles found downstream of disturbances such as bends, valves, and pumps. Devices using two, three and four beams are commonly used and systems with up to eight beams are available in very large pipe sizes. Two beam devices are available for pipe sizes > 0.05 m. The three and four beam devices are generally used with pipe sizes > 0.5 m, and eight beam with sizes > 3 m.

Table 3.7.1 gives one set of chordal positions for three and four beam systems together with the weightings to be given to the transit time differences measured along these beams in order to approximate integration of the velocity over the entire cross section by the Gaussian quadrature technique.

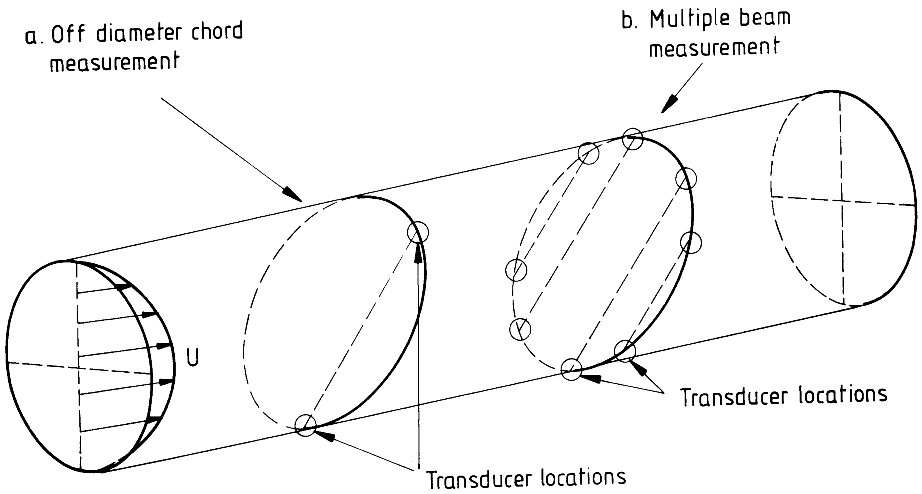


Figure 3.7.5 — Time-of-flight design variation

Table 3.7.1 — Example multi-beam ultrasonic meter weighting factors

Number of beams	Position	Weighting
3	0.000*r* ± 0.7745*r*	0.8888 0.5555
4	± 0.3399*r* ± 0.8611*r*	0.6521 0.3478
NOTE *r* is the radius of the internal pipe bore.		

3.7.3 Doppler flowmeters

3.7.3.1 *General*

Doppler flowmeters depend upon the well-known Doppler shift in frequency of sound transmitted from a moving source when detected by a stationary observer. They require air-bubbles or solid particles within the liquid flow to act as a scatter for the transmitted ultrasound. For the configuration shown in Figure 3.7.6(a), the frequency of the signal received from a scattering particle, f_r (in Hz) is given by:

$$f_r = f_t \left(1 - \frac{u}{c} \cos\theta_1 - \frac{u}{b} \cos\theta_2\right) \qquad (3.7.11)$$

where

f_t is the frequency of the transmitted signal (in Hz);

θ_1 is the transmission angle (in degrees);

θ_2 is the reception angle (in degrees);

$\left(\frac{u}{c}\right)^2 << 1.$

The Doppler shift, f_d is thus given by:

$$f_d = f_t - f_r = \frac{f_t u}{c} (\cos\theta_1 + \cos\theta_2) \qquad (3.7.12)$$

Typically, an industrial flowmeter would use the arrangement shown in Figure 3.7.6(b), where $\cos\theta_1 = \cos\theta_2 = \cos\theta$ and thus:

$$f_d = f_t - f_r = \frac{2f_t\,u}{c}\cos\theta \qquad (3.7.13)$$

i.e. the Doppler shift is proportional to the velocity of the scatterer. As an example of the orders of magnitude involved, consider the case of a flow of 1 m/s in a medium for which the velocity of sound is 1 500 m/s. If the transmitted frequency is 1 MHz and the angle θ is 65° then the Doppler shift is 563 Hz. Typical transmission frequencies in industrial Doppler flowmeter are in the region 0.5 MHz to 2 MHz.

In practice the Doppler signal consists of a spectrum of frequencies from different scatterers moving with different velocities. The detection electronics in general provides some average measure of the Doppler shift. The relationship of the measured velocity to the mean flow velocity is uncertain and may vary from situation to situation.

The performance of a Doppler flowmeter is influenced by the following:

a) the nature of the scatterers, their size distribution, and their special distribution in the flow;

b) special broadening of the Doppler shift caused by the transit time effects of the scatterers, velocity gradients within the flow, the finite width of the beam, and non axial velocity components such as turbulence;

c) the non-uniformity of the interrogating beam and the non-uniformity of weighting from different scatterers caused by attenuation;

d) uncertainty in the location of the interrogated volume;

e) slip between the measured phase and the primary phase.

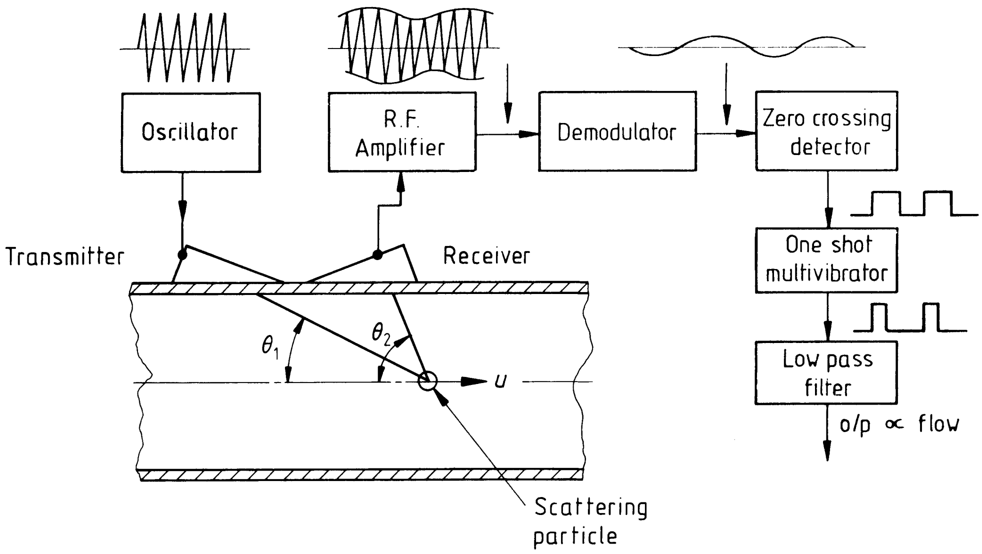
Doppler flowmeters provide a low cost non-invasive method for measuring low concentration two-phase flows. They provide a moderately repeatable though often inaccurate measurement and therefore find better use as flow switches or flow indicators rather than flowmeters.

3.7.3.2 ***Mechanical construction***

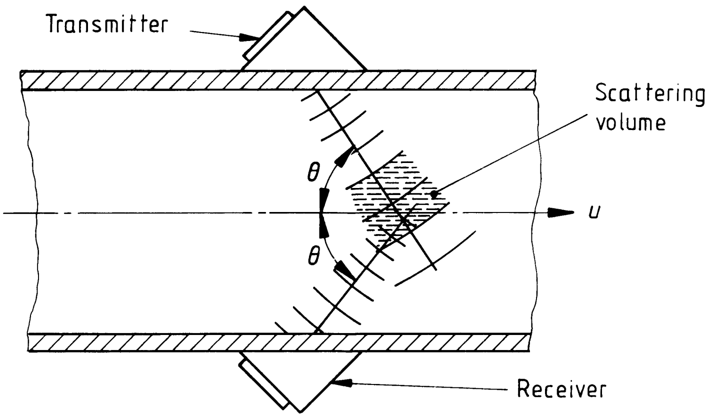
Doppler ultrasonic flowmeters are generally clamp-on devices although spool piece devices are available. The most common construction is as shown in Figure 3.7.6(a) with the two piezo-electric crystals mounted side by side. An alternative industrial configuration is shown in Figure 3.7.6(b) where the two sensors are mounted diametrically opposite each other. This design has the advantage of defining the scattering volume to be in the centre of the pipe.

3.7.3.3 ***Secondary design for industrial Doppler systems***

The electronics used in a typical industrial Doppler flowmeter is shown in Figure 3.7.6(a). The Doppler-shifted received signal is mixed with the transmitted frequency usually by adventitious leakage of the ultrasonic signal which occurs between the transmitter and the receiver. The resultant signal is amplified and demodulated. The usual estimate of the Doppler frequency is made by means of a zero crossing detector, firing a fixed width monostable every time a zero crossing occurs. This gives an output which is proportional to the r.m.s. frequency of the Doppler spectrum rather than its mean value. The electronics within an industrial Doppler flowmeter provide no directional sensitivity and will give the same output for flow in either direction.



(a) Common construction-block-diagram



(b) Industrial configuration

Figure 3.7.6 — Doppler meter design details

3.8 Group 8 meters: direct and indirect mass types

3.8.1 Introduction

Flowmeters which measure mass flow have recently been developed commercially. In the majority of cases, all flow measurements are converted into mass so that plant efficiencies and material balances can be calculated. There has been a clear need for accurate and reliable mass meters and with the instruments now on the market, the industrial need is slowly being satisfied.

3.8.2 General principles

The use of mass flow metering is growing in all areas of flow measurement and control. This is because many plants are run on material balance considerations. Plant efficiencies and heat balances rely on a knowledge of mass flow rate and, as a result, many different techniques and designs have evolved. Mass flow rate is the mass of a fluid flowing per unit of time. This is different from volume flow since the density of the flowing fluid is required to compute the mass flow rate. The mathematical expression for the mass flow rate is:

$$q_m = \rho A U \quad (3.8.1)$$

This equation shows that two variables are involved, fluid velocity and density and this gives rise to two basic ways of measuring mass flow.

The first approach is to use a transducer whose output is a direct function of mass flow only. This implies that pressure, temperature and other properties do not affect the output. The second, and up to now the more common approach, is to make simultaneous measurements of flowing volume and fluid density. The product of these measurements is the mass flow rate as indicated in equation 3.8.1. If the fluid composition is constant and temperature and pressure are known, the density can be calculated from an equation of state. One form of mass meter could therefore be a conventional meter with temperature and pressure transducers, the outputs of which are fed to a flow computer. If the flowing fluid is made up of a mixture of components then the flowing density should be measured with an on-line densitometer (see **5.3**) with the output, plus that of the flowmeter, again being fed into a flow computer. This basic approach of computing mass flow, rather than measuring it directly, is known as the inferential method as opposed to the indirect method of the first approach. A recent survey by Gast and Furness (1986) illustrates some of the approaches that can be adopted.

Mass flow can also be determined by weighing methods. Such an approach is certainly acceptable for batch processes but there are some problems in continuous processes. The use of modern load cells provides a cost effective method of mass flow determination for non-continuous processes.

3.8.3 Momentum methods

Mass flow can be measured by sensing the change in angular momentum of rotating elements. The basic principle of operation is as follows. The fluid to be measured flows through a rotor turning at constant speed. It acquires an angular momentum per unit length proportional to angular frequency, cross section, density and the geometry of the device. If the fluid then passes through an identically shaped but stagnant wheel a torque is developed. This torque is a function of mass flow. Two designs based on this principle have evolved.

In the first type, the rotor is driven at constant speed by a synchronous motor mounted in the centre of the flowmeter assembly. This motor is magnetically coupled to an impeller through which the fluid to be measured flows. The magnetic coupling is accomplished by means of a hysteresis clutch which transmits a constant torque from the motor to the impeller. Measuring the rotational speed of the impeller gives a signal that is inversely proportional to mass flow rate. This design is shown in Figure 3.8.1.

In the second design, shown in Figure 3.8.2, two rotors are mounted on a single shaft. They are linked together by a torsional member. A magnetic reluctance pickoff is mounted over each rotor. Swirl from the first rotor should cause the downstream rotor to spin faster. However since the two rotors are restricted and held together by the torsional member, the entire assembly rotates in unison at some average velocity and an angular phase shift develops between the rotors. This is a direct function of angular momentum of the fluid, which in turn is a function of mass flow rate. Thus the angle between the two rotors is proportional to mass flow.

3.8.4 Vibration and acceleration methods

Oscillating or vibrating elements show the greatest promise and performance in industrial service. The most common form of this type of meter is the Coriolis meter. Coriolis forces are associated with a combination of radial and rotary motion. The measurement of the torque required to produce Coriolis forces in the fluid gives a measure of mass flow.

Applying this to flow measurement, there are two methods of measuring mass flow. If a rotor is driven at a constant angular velocity ω, then any particle travelling through the rotor will experience a Coriolis force resulting in a torque acting in the plane of rotation. If this torque is measured with a strain gauge then we can write:

$$q_m = K' \frac{M}{\omega} \qquad (3.8.2)$$

where

K′ is a constant;

M is the torque (in Nm).

This type of meter has a rapid response time and has been used in transient two-phase situations. The moving parts and rotating seals do, however, present maintenance problems.

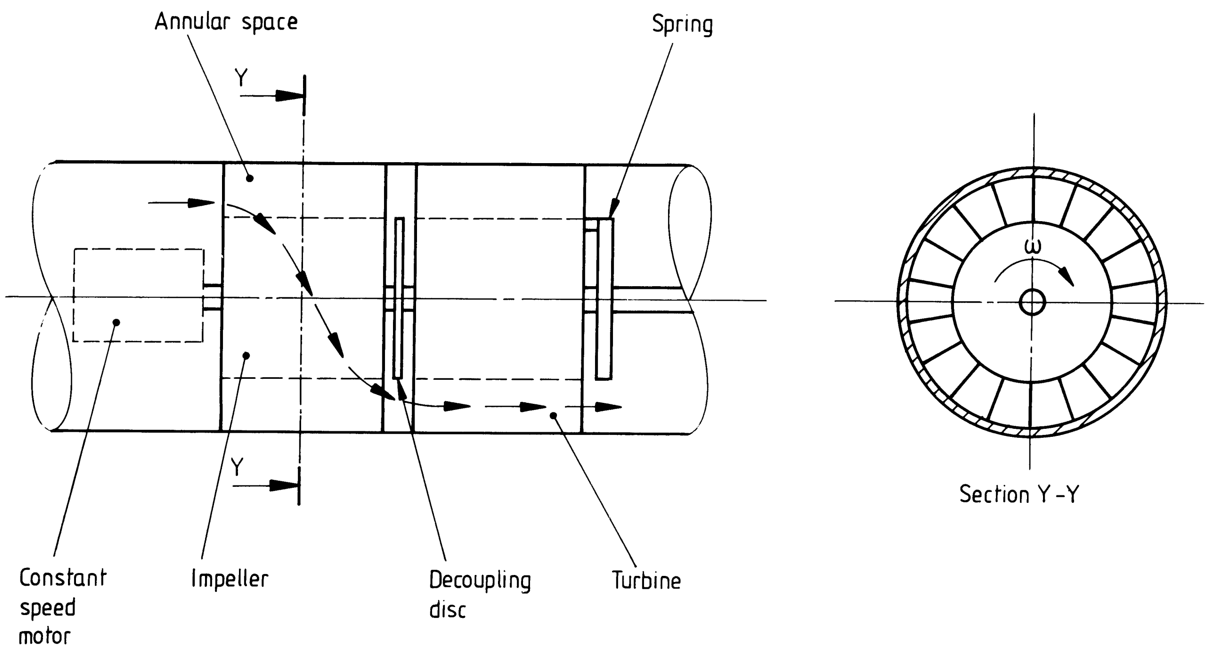


Figure 3.8.1 — Driven angular momentum mass flowmeter

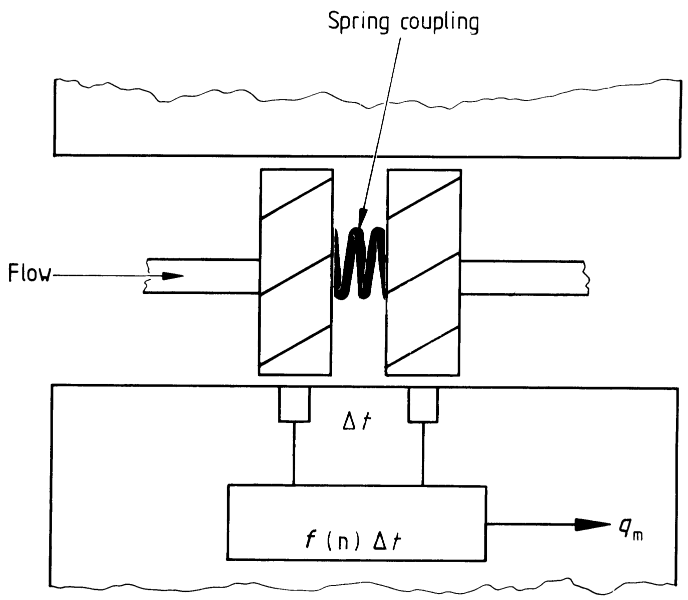


Figure 3.8.2 — Schematic of a twin turbine mass meter

The second type of Coriolis mass meter is the gyroscopic variety. Gyroscopic precession occurs when a torque is applied perpendicular to the axis of rotation. If a tube is rotated at a constant angular velocity, a torque is generated perpendicular to the plane of rotation. Rotating the tube is not practical, but Coriolis forces can be produced by vibrating the tube. This is the basis for commercial mass meters which are now selling in some quantities. One design is shown in Figure 3.8.3. In limb A-B, the amplitude of vibration increases from zero to a maximum at B. In the other limb the forces decrease from a maximum at C to zero at D. The fluid exerts an opposing force to resist the perpendicular motion. As these are in opposite directions forming a mechanical couple, they cause the tube to twist through an angle θ that is proportional to the mass flow rate. Magnetic position sensors measure the amount of twist by timing the passage of the twisting tube past a reference line. This time interval is a direct function of mass flow rate via the relationship:

$$q_{\mathrm{m}} = \frac{\mathrm{K_s}\,\Delta T}{8r^2} \qquad (3.8.3)$$

where

ΔT is the measured time difference (in ms);

r is the tube radius (in m);

$\mathrm{K_s}$ is a constant for the tube material.

Full mathematical derivation and design details are given in Plache (1979).

At zero flow the two vibrating limbs remain parallel but as flow increases, so the output of the sensors increases. Electronics process the output to generate a mass flow signal. The sensors measure the twist angle at the centre position of the vibration amplitude. This is the point where the angular acceleration is close to zero and any inertial effects are small. It is this basic principle which makes the device relativity insensitive to fluid property effects. The full form of the basic equation does however show a small dependence on fluid properties but for most industrial applications this can be neglected.

The tube need not be looped, but may be straight as shown in Figure 3.8.4. This tube is vibrated at the centre and the amplitude is measured at two points on the straight section as indicated. There are now at least eleven commercial designs all with different tube configurations and others are expected to be developed in the near future. One characteristic of most designs is the higher pressure loss at maximum flow than other types of flowmeters. They are, however, all extremely linear and are finding increased use in industrial applications.

3.8.5 Differential pressure methods

Differential pressure devices can be arranged either in parallel or in a Wheatstone bridge arrangement to measure mass flow rate. In the first of these methods, the flow is divided equally between two venturi tubes as shown in Figure 3.8.5 without the pump operating. If the pump extracts fluid from one tube and adds this to the second, then the pressure difference between the two venturi throats, Δp_{m} can be shown to be proportional to the mass flow rate, q_{m}.

In the second design, four orifices, an independently driven pump and a differential pressure sensor are linked together to form the hydraulic equivalent of a Wheatstone bridge. The arrangement is shown schematically in Figure 3.8.6. The position of the differential pressure gauge is variable, being dependent on whether the flow to be measured is greater or less than the flow through the pump (Figure 3.8.6 shows the two positions). By analyzing the flow in the branch network mathematically, it can be shown that the pressure drop is directly proportional to the mass flow.

Since the indicated mass flow rate for a constant volume flow rate through the pump, q_{p}, is directly proportional to the pressure rise across the pump, errors due to the pressure measurement and flow variations in q_{p} directly affect the performance.

The variations in discharge coefficient must also be minimized so q_{p} must be small compared to q_{v} as indicated in Figure 3.8.6. The system characteristics are such that the density has to be the same in both sides of the bridge. Performance claims for the commercial instrument range from ± 0.25 % of reading over limited flow ranges up to ± 1.5 % of reading over 100 : 1 flow range. Rangeabilities in excess of 1 000 : 1 are claimed with reduced performance. The device has limited size ranges however but is ideal for low mass flow rate measurements.

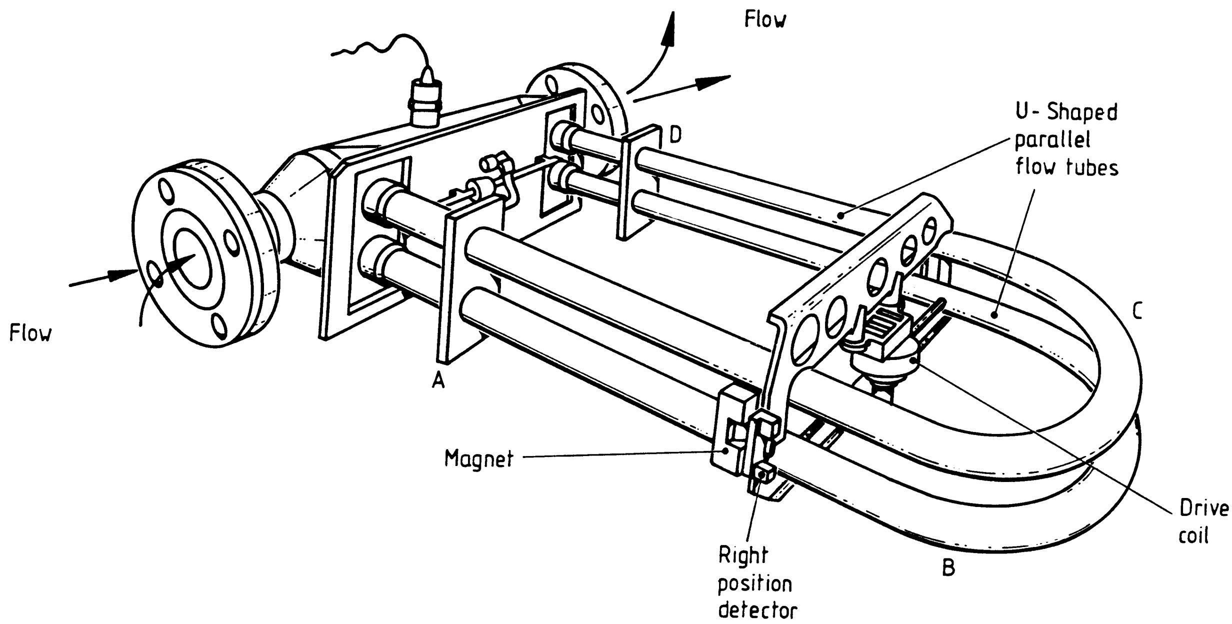


Figure 3.8.3 — Modern industrial Coriolis mass meter

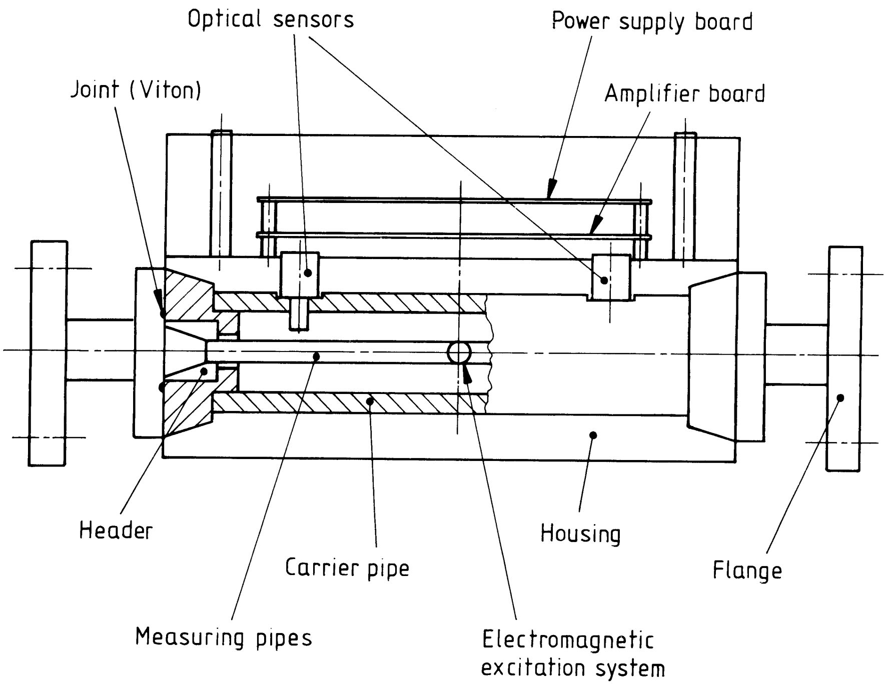


Figure 3.8.4 — Coriolis mass meter with straight tube sensing section

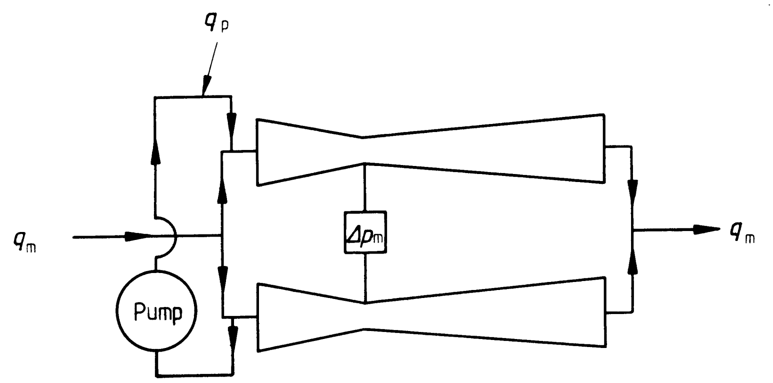


Figure 3.8.5 — Parallel venturi mass meter

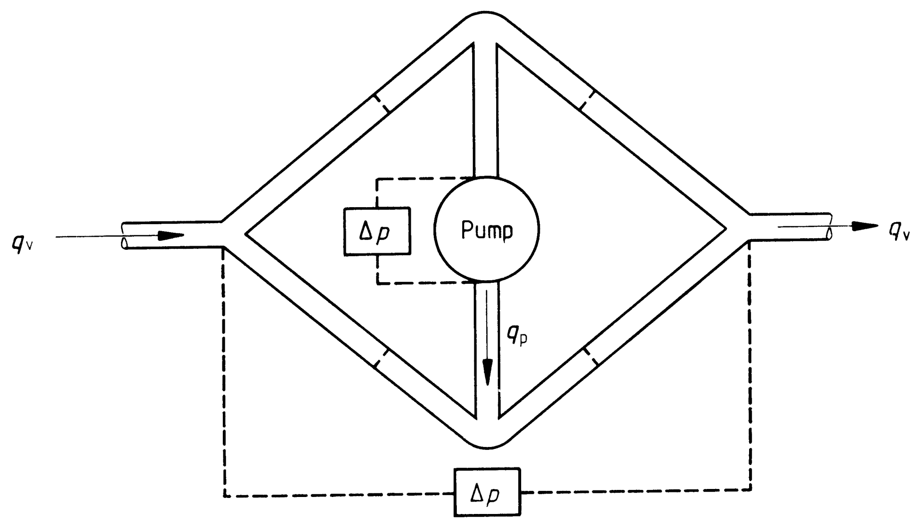


Figure 3.8.6 — Orifice based differential pressure mass meter

The sonic nozzle is often used as a standard for gas mass flow measurement. The critical or sonic nozzle is described in **3.2**. Provided the flow remains in a critical state, a throat tap is not required and only upstream pressure and temperature require measurement.

3.8.6 Hybrid methods

It is possible to infer mass flow rate from the output of various transducers without the need to measure flowing temperature, pressure and composition. These methods known as hybrid systems can be combinations of volume meters, velocity sensors, momentum flux transducers and densitometers in a variety of designs. Examples may be turbine meters in series with target meters, vortex meters with orifice meters or venturi meters with turbines meters. The mass flow is given by the ratio of the output signals. In the third combination for example, the venturi pressure drop, Δp, and the turbine frequency, f, are related to mass flow by the following equations:

$$q_m(\text{venturi}) = \frac{1}{K}(\rho\ \Delta p)^{1/2} \quad (3.8.4)$$

$$q_m(\text{turbine}) = \frac{1}{K}\rho f \quad (3.8.5)$$

The mass flow is given by the ratio of the signals:

$$q_{\mathrm{m}} = \frac{\lambda \, \Delta p}{K^2 f} \qquad (3.8.6)$$

Using this basic approach, the mass flow rate may be determined by the use of any head differential pressure flowmeter (groups 1 and 2) with any linear velocity dependent meter (groups 4, 5, 6 or 7). Strangely however, this approach is not often encountered, presumably because two flowmeters need to be purchased.

Considine (1985) recently surveyed the field of mass meters and gives further data on the many techniques discussed.

3.8.7 Thermal methods

Thermal meters are generally associated with mass flow although they are a distinct class of meter in their own right. Mass flow can be deduced from heat loss but only if the heat capacity, thermal conductivity and viscosity of the flowing medium are known. As a thermal flowmeter does not measure these other parameters, it is not a true mass flowmeter.

Thermal types of flowmeter are described in more detail in **3.9**.

3.9 Group 9 meters: thermal types

3.9.1 General

These types of meters find use in certain specific areas. Until recently they were more suited to research applications but several industrial variants have appeared. They use the properties of the fluid (usually clean gases) to infer flow and, as most operate by sensing mass flow, they are incorrectly called thermal mass flowmeters. Thermal meters are a distinct class in their own right and are beginning to find general acceptance in the process industries. Benson (1974) gives a general review of thermal flowmeters.

3.9.2 Modes of operation

Thermal flow measuring devices can be divided into two classes. Their basic modes of operation are given with more details in the following clauses.

a) A heated body is exposed to the flow and the cooling action is a measure of the flow velocity.

b) Heat is transferred into a confined flowing stream. The heat energy input and stream temperature rise are then related to the mass flow rate.

Thermal meters were first studied at the turn of the century, although the first successful hot wire anemometer did not appear until 1931. Much of the basic research for this type of meter was performed in the USA in the 1950's but it is only during the past decade that rugged industrial meters have appeared.

3.9.3 Hot wire/hot film anemometers

The basic principle of these point velocity measuring devices is described in item (a) of **3.9.2**. The resistance of the heated element is affected by its temperature and this can be utilized in two different ways. In both cases the heated element is connected as one arm of a Wheatstone bridge. If the current through the element is kept constant the change in resistance can be correlated to the fluid velocity over the element. Alternatively, the resistance can be kept constant by varying the supply voltage and monitoring the variations. A schematic diagram of the operating principle of one type of commercial instrument is shown in Figure 3.9.1.

The velocity sensing element of a hot wire anemometer is a very fine metal wire typically 1 mm to 2 mm in length and 0.005 mm in diameter (see Figure 3.9.2). Tungsten is a widely used sensor material, others are platinum and nickel. Their advantages are fast response time and good spatial resolution, but they are susceptible to fouling or damage caused by high velocities and careless handling.

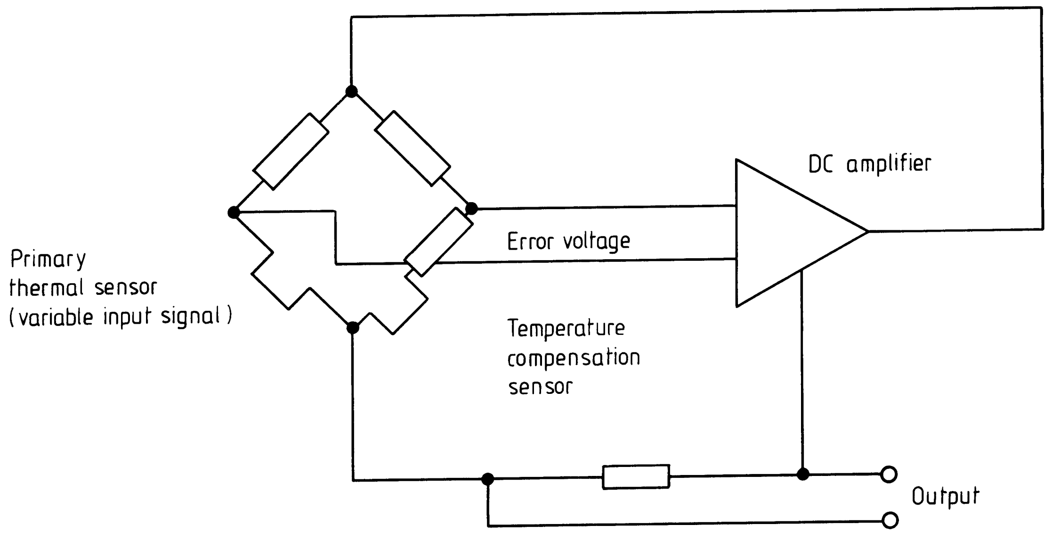


Figure 3.9.1 — Schematic arrangement of a thermal anemometer

Hot film anemometers consist of metallic films deposited on vitreous or ceramic substrates. They are designed in various shapes as shown in Figure 3.9.3. They have a slower response time but they are more rugged and less susceptible to fouling than the hot wire probes. The body where the thermal sensor is held is usually stainless steel although other materials such as aluminium, brass and Monel are used by the various manufacturers.

Lomas (1986) describes the fundamentals of hot wire anemometry.

Another type of thermal probe uses two thermistors as shown in Figure 3.9.4. One is subject to the flow and the other is in zero flow conditions but is in contact with the fluid. Both are operated in the constant temperature mode and the ratio of the power supplied to each is a measure of the fluid velocity. By using two probes the effects of temperature difference between the probe and fluid and the thermal conductivity of the fluid are eliminated. This meter has high rangeability of about 40 : 1 with an accuracy of ± 2 % to ± 3 % of full scale. Specially designed multi-element probes are also available for measuring components of velocity in two or three directions.

The rate of heat loss for a single wire is based on the King equation:

$$\frac{H}{L} = t\{K + 2\,(\pi\, K\, c_{\mathrm{v}}\, \rho\, v\, d)^{1/2}\} \qquad (3.9.1)$$

where

H/L	is the rate of heat loss per unit length of wire (in J/m·h);
t	is the mean temperature elevation of wire above that of the free stream (in K);
K	is the thermal conductivity of the fluid (in J/h·m·k);
c_{v}	is the specific heat at constant volume (in J/kg·k);
ρ	is the density (in kg/m^3);
v	is the velocity of fluid (in m/h);
d	is the wire diameter (in m).

From this equation it can be seen that the probes are mass flow sensitive, fluid composition dependent and extremely non linear. However if the fluid properties are known and are constant then thermal meters may be used to indicate mass flow rate.

The main advantage of hot wire anemometers is their very rapid response to changes in velocity over a very small region of the flow. The accurate interpretation of the output signals is very complicated and is always performed using sophisticated electronic equipment. The probes are individually matched to the equipment, but for the highest accuracy individual calibration of probe and measuring device together is necessary.

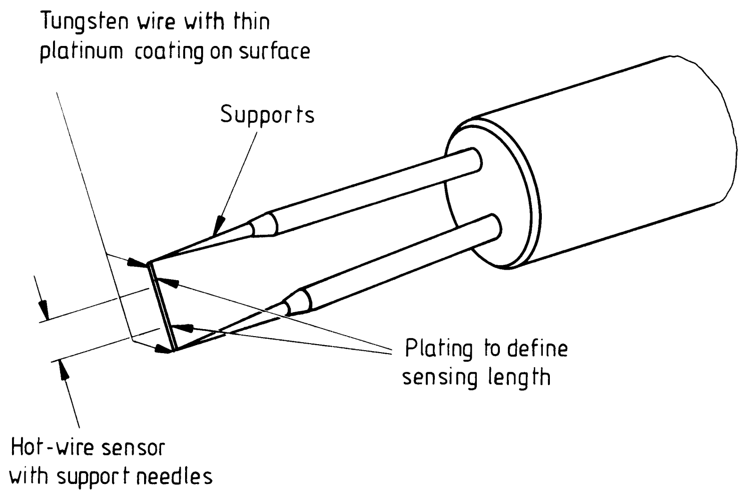


Figure 3.9.2 — Typical hot wire probe head

3.9.4 Stream temperature rise types

These devices are based on the principle described in item (b) of **3.9.2** and are used for determining the total mass flow rate in a pipe or duct. This type of flowmeter is available in several design variations.

Figure 3.9.5 shows a Thomas thermal flowmeter in which the stream is heated by a constant heat source and the temperature difference is monitored as an indication of mass flow rate q_m(in kg/h). This type of flowmeter, sometimes referred to as the heated grid flowmeter is characterized by the equation.

$$q_m = \frac{H}{c_p \, \Delta t} \qquad (3.9.2)$$

where:

- H is the heat input (in J/h);
- C_p is the specific heat at constant pressure (in J/kg · k);
- Δt is the temperature difference (in k).

They are mainly used for low pressure, low flow rate applications. High mass flow rates require large amounts of energy.

Another version of this type has the heat source external to the pipe thus heating only the boundary layer of the flow. This requires a lower power input but the performance is influenced by viscosity and Reynolds number since these affect the boundary layer.

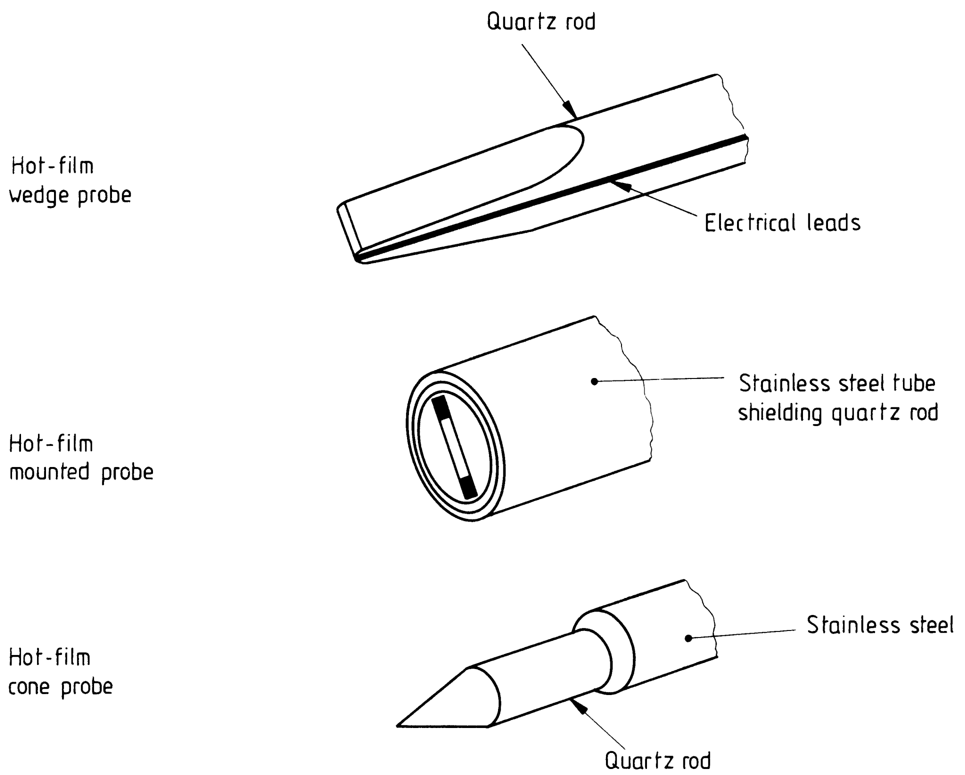


Figure 3.9.3 — Designs of hot film anemometers

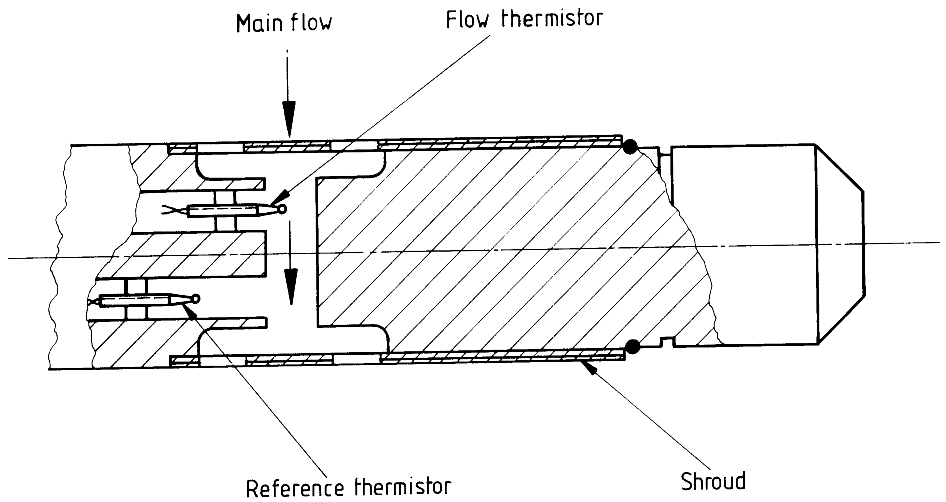


Figure 3.9.4 — Sensing tip of typical flare gas thermal meter

A third variation of this type is the Hastings® flowmeter [see Figure 3.9.6(a)] where a constant quantity of heat is supplied to a small tube. Heat sinks at each end of the tube cause a temperature gradient to exist along the tube [see Figure 3.9.6(b)]. Thermocouples, TC1 and TC2 attached to the outer wall of the tube record zero temperature difference with no flow. When flow passes through the tube, heat is transferred between the wall and the flow. At the upstream thermocouple, TC1, heat is transferred from the tube to the flow causing its output to reduce. Part of this heat is then returned to the tube on the downstream side causing the output of TC2 to rise.

In this type of meter capillary tubes are used to transfer heat from the transformer to the fluid and sensors. The tubes are made from constantan to maintain good thermal conductivity. Any contamination between the tube and the gas will result in meter drift. The tube is usually very small (e.g. 1 mm) and has a maximum linear range of about 100 cm^3/min.

This method can be used in the measurement of much higher flow rates if the tube is part of a by pass arrangement where a fixed percentage of the flow goes through the small tube.

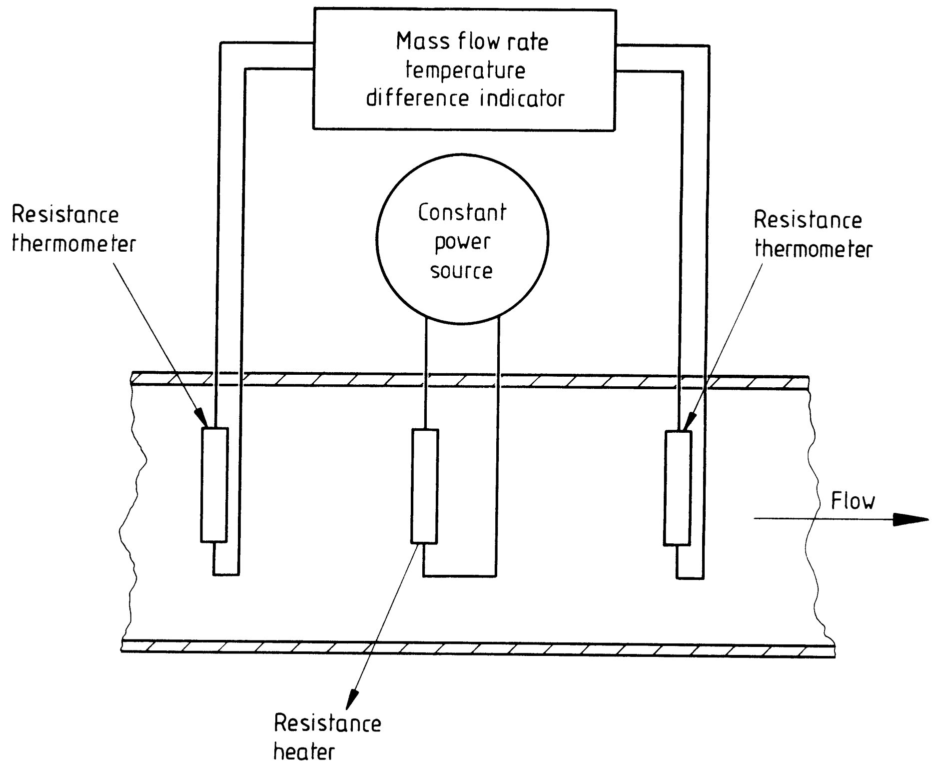
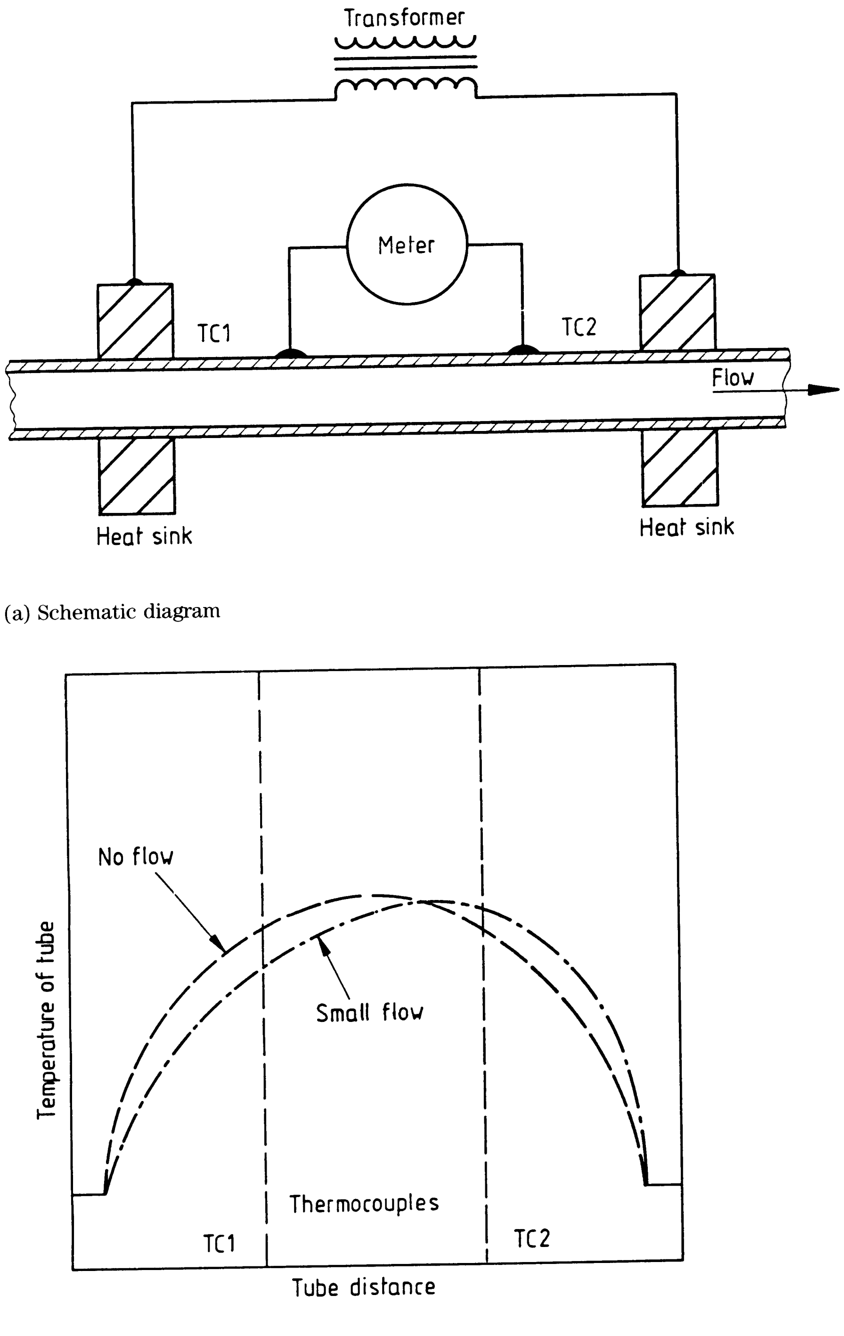


Figure 3.9.5 — Thomas thermal flowmeter

3.10 Group 10 meters: miscellaneous types

3.10.1 General

This group of meters include all those which do not conveniently fall into the other groups. Unlike the other major groups discussed, they operate on widely differing principles. In the majority of cases they are complex expensive instruments, more suited to research applications than industrial applications. The exception is the tracer technique which finds widespread use in flowmetering and diagnostic applications. It is the one technique in this group that is also not under continuing research. Most of the rest are still undergoing considerable research and development and industrial experience is limited. However this should not preclude their use in industrial situations in the future.



(a) Schematic diagram

(b) Temperature gradient

Figure 3.9.6 — Thermal profile meter (Hastings® flowmeter)

3.10.2 Cross correlation meter

The cross correlation meter is slowly emerging from the development stage and into the industrial market place. A schematic diagram of the device is shown in Figure 3.10.1(a) to illustrate the principle of operation. At least two transducers are positioned a known distance apart. These are used to time the passage of naturally occurring phenomena in the flow (turbulence eddies, particles, etc.). The detection of variations in other fluid properties (density, temperature or conductivity) can also be used as a measure of the flow between the two points. Transducers designed for the property of interest are clearly required. The actual signals from the transducers themselves are not particularly useful, since in most cases the output is random or possesses a poor signal to noise ratio. However when a cross correlator is used to compare them, as shown in the figure, a shift in the maximum correspondence between the signals is a measure of the mean flow velocity.

The cross correlation function R_{xy} (β) is defined as:

$$R_{xy}(\beta) = \frac{1}{T}\int_0^T x(t - \beta) \cdot y(t) \ \mathrm{dt} \qquad (3.10.1)$$

where

β is the variable time delay (in s);

$x(t)$ and $y(t)$ are the output signals from the detectors (in s);

T is the total integration time.

From Figure 3.10.1(b), it can be seen that $x(t - \beta)$ is most similar to $y(t)$ when $\beta = \tau$. This gives a maximum value to the function $R_{xy}(\beta)$. Hence if we continually correlate until a maximum value of R_{xy} is obtained, the system is continually sensing the average stream velocity.

Until recently the correlation meter required elaborate and expensive dedicated computing systems to enable the correlation function to be processed. As a consequence the purchase price was high. With the availability of microprocessor and multi-channel transducer systems to enable the correlation function to be obtained more rapidly, the cost has decreased but owing to the few meters currently sold is still high by industrial standards. Ultrasonic transducer systems are the most common since they are relatively robust and can be clamped on the outside of the pipe.

This type of meter can be used for measuring the velocity of conveyor transported solids. In this application the correlator would time the passage of particular surface contours created by the solids. The cross correlation meter also shows considerable promise in two-phase and flare gas applications, both of which present very difficult flow metering problems. Further details can be found in Ong and Beck (1977) or Keech (1982).

3.10.3 Tracer techniques

3.10.3.1 *General principles*

Tracer methods are used primarily to provide spot measurements of flow rate. The basic principle of tracer flow rate measurements is that a tracer in a form compatible with the flowing material is injected into the stream of interest. The tracer possesses some property which distinguishes it from the stream material to facilitate detection and assay downstream of the injection point. Measurements are directed towards establishing either the velocity of the tracer or its concentration in the stream. From these data the flow rate can be calculated.

For the velocity method, gamma ray emitting radioactive tracers are particularly appropriate since the tracer response curves at the detection stations can be determined directly by external radiation detectors positioned adjacent to the conduit without the need for sampling points. In the dilution method, the duration of the tracer injection is not critical, although in practice pulse injection is usually employed. The measurement of the tracer concentration should continue long enough to ensure that all of the injected tracer has passed the detection station. It should also be noted that dilution techniques provide direct measurements of volume flow rate. No knowledge of conduit dimensions is required. Further data can be found in Charlton (1984).

3.10.3.2 ***Simple theory***

The tracer velocity method consists of measuring the transit time of labelled fluid particles between two points a known distance apart. The labelling can be with any of the tracer types listed. The transit time is determined by mean arrival times at each of the detector positions downstream of the injection point as shown in Figure 3.10.2. The flow rate is given by:

$$q_v = \frac{V}{t} \qquad (3.10.2)$$

where

t is the transit time (in s);

V is the volume between the detectors (in m^3).

The method is documented in BS 5857 for both water and gas flow. The relevant parts give details of the location of the measuring points, the tracer injection procedure, detection techniques and the computation of flow rate from the data.

In the dilution method, the concentration of an injected sample after mixing with the stream is used as a measure of the flow rate. If the marker is discharged into the flow at a constant rate, a balance equation can be written between the injection point and the sample point as:

$$q_v = \left(\frac{C_1 - C_2}{C_2 - C_0}\right) \cdot q \qquad (3.10.3)$$

where

q_v is the injection rate of the tracer (in m/s);

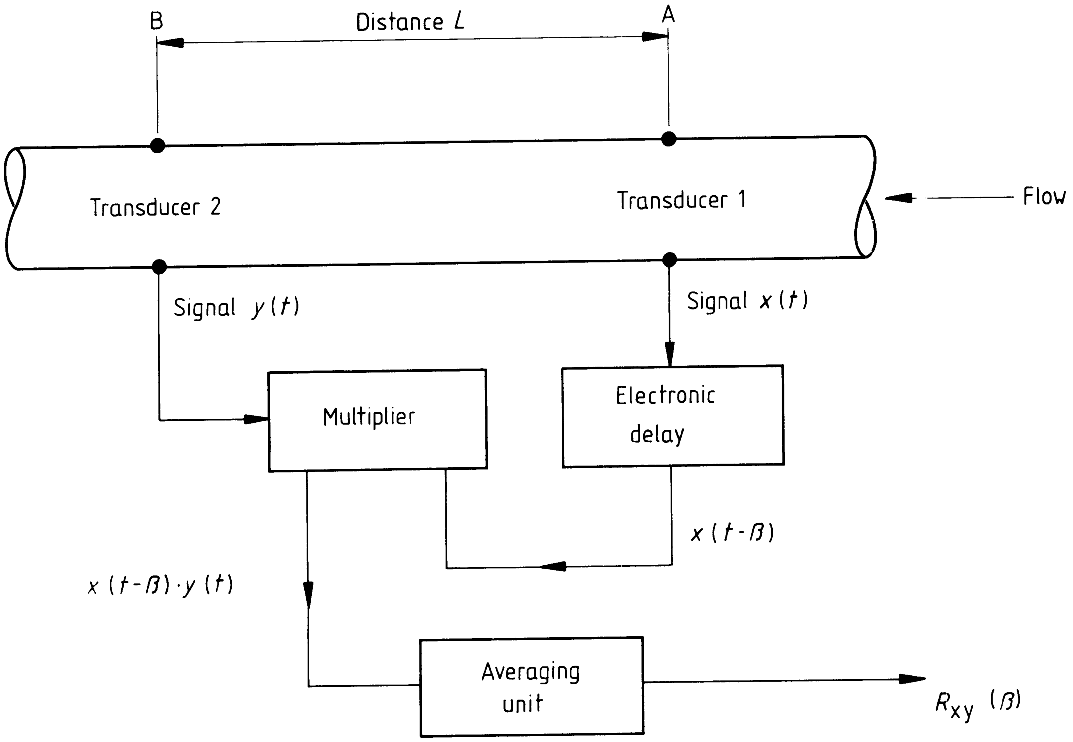
C_0 is the naturally occurring tracer concentration (in g/mL);

C_1 and C_2 are the concentrations at injection and sample points respectively (in g/mL).

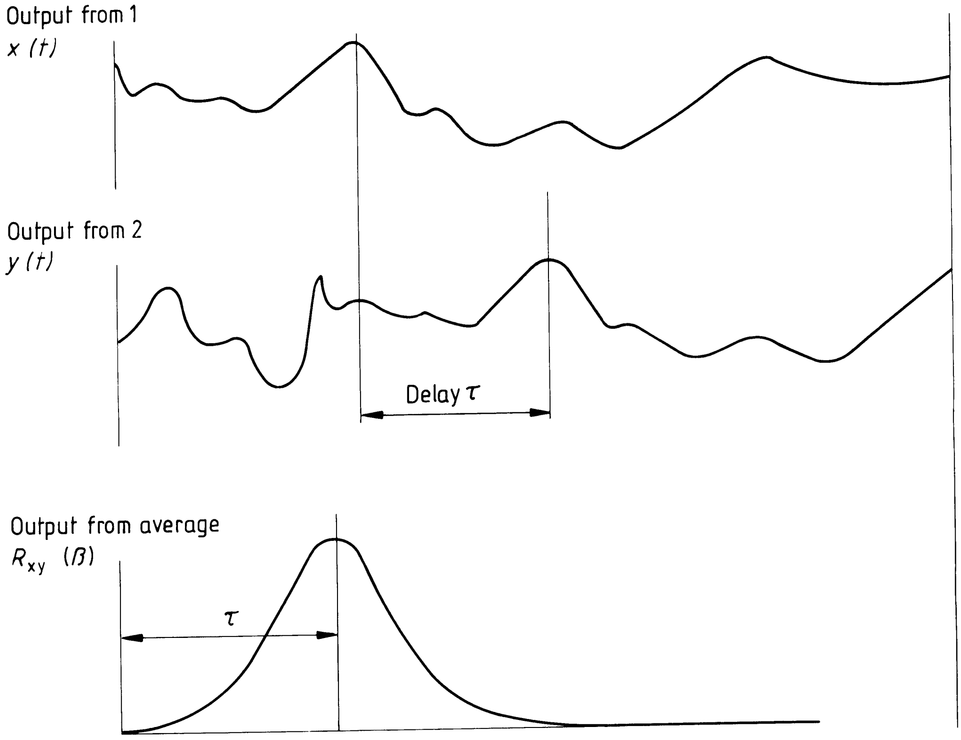
In the dilution integration method a volume, v, of tracer is injected and samples are then taken at regular intervals downstream to enable a time/concentration curve to be constructed. Using the same notation as equation 3.10.3 we can write:

$$q_v = \frac{v \cdot C_1}{\int_0^t (C_2 - C_0)\,dt} \qquad (3.10.4)$$

This general expression is applicable to both continuous and intermittent sampling at a constant rate. The integral in equation 3.10.4 is normally evaluated graphically. Figure 3.10.3 shows typical curves for both the constant injection rate and the integration method but reference to the standards quoted will give full details of the procedures, equipment and the calculations. These methods are used for the certification of large diameter magnetic (group 6) and ultrasonic (group 7) flow meters, where direct calibration rigs do not exist.



(a) Cross correlation flowmeter



(b) Typical correlation meter output signal

Figure 3.10.1 — Cross correlation flowmeter

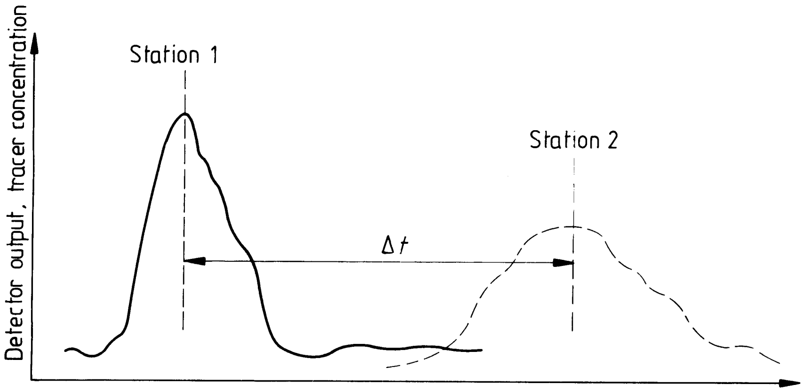


Figure 3.10.2 — Tracer transit time method

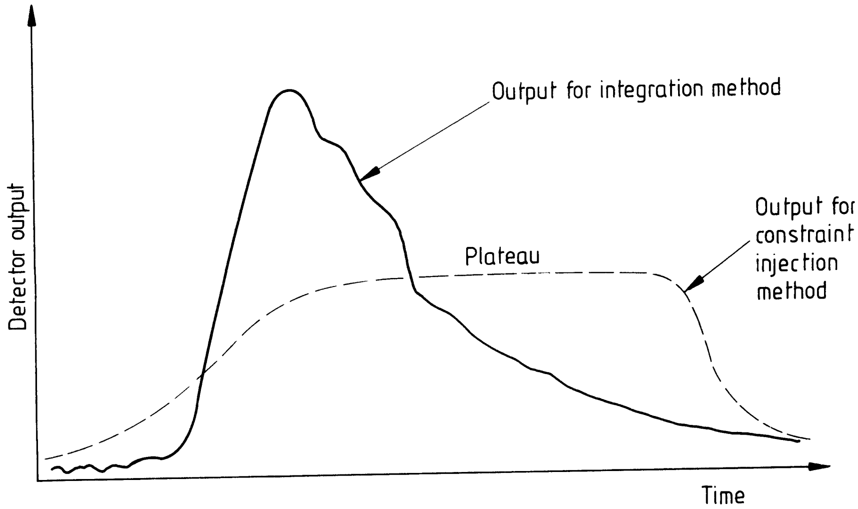


Figure 3.10.3 — Output curves for dilution tracer techniques

3.10.3.3 ***Types of tracer***

The tracers can be of varying types, such as dyes (detected by colorimeters), radioactive isotopes (detected by radiation meters) or salt solutions (detected by conductivity probes). The general requirements for a tracer are as follows:

a) it should mix well with the flowing stream;

b) it should not significantly perturb the flow;

c) there must be some known (preferably linear) relationship between the property of the tracer measured by the detector and the concentration of the tracer in the stream;

d) it has to be capable of detection and analysis at low concentration. This is particularly relevant in the case of certain tracers, which in concentrated form, may have toxic, corrosive or other undesirable properties;

e) it has to be chemically stable and not interact with the flow or the conduit under conditions of use;

f) ideally it should not be present naturally in the flowing material at significant concentrations;

g) it should be readily available at reasonable cost.

Tracers which have been widely used for industrial and laboratory flow measurements include the following:

1) For aqueous flows:
   Sodium chloride
      (analysis by conductivity probes)
   Lithium chloride
      (analysis by flame photometry)
   Sodium iodide
   Potassium iodide
      (analysis by a catalytic spectrophotometric method)
   Rhodamine WT
   Sulphorhodamine B
   Pyranine
      (fluorescent tracers)
   Tritium, as tritiated water
   Na^{24}, as sodium carbonate solution
   Br^{82}, as potassium bromide solution
      (radio active tracers)

2) For organic flows:
   Na^{24}, as sodium salicylate or sodium naphthenate
   Br^{82}, as para-dibromobenzene
   H^{3}, in chemical form capatible with the flow

3) For gas flows:
   Kr^{85}
   Ar^{41}
   Xe^{133}
      (radio active tracers)
   Helium with mass spectrometer detection system
   Methane with flame ionization detection apparatus
   Hydrogen with gas chromatograph detection system

3.10.3.4 ***Advantages and disadvantages***

The main advantages of tracer methods are as follows.

a) They are (virtually) non-invasive. The only requirement is that the injection point and (for some methods) the downstream sampling points have to be present. There is no disruption or significant perturbation of the flow.

b) Associated equipment can be made rugged and portable. The measurements can be carried out on systems to which access is difficult. Additionally, since no plant modifications or elaborate preparations are required, measurements can be carried out on systems where no flowmeters are installed. On line calibration of installed meters is also facilitated.

c) By judicious selection of the tracer, practically every type of commonly encountered flow can be measured.

The main disadvantages of tracer methods are as follows.

1) The methods are not appropriate for continuous flow rate measurements. No installed system based upon tracer principles is commercially available at present.

2) In most cases the methods do not give an instantly available result. Laboratory sample assay or data analysis is usually required.

3) The criterion of good mixing has to be met. The techniques are not normally suitable for non-turbulent flows (*Re* < 5 000).

3.10.4 Nuclear magnetic resonance

The nuclear magnetic resonance meter was first investigated in the 1960's and prototype meters are now undergoing evaluation. The basic principle of operation depends on tagging the fluid and timing its passage between known points, as with the tracer technique described in **3.10.3**. The tagging of the flow is performed by alternately magnetizing and demagnetizing strips of fluid.

The meter is shown schematically in Figure 3.10.4. It consists of a pipe around which are mounted magnets. These are enclosed in a soft iron housing and cast in a cement-like material. Downstream of the magnetizer section is the detector. This consists of a high alumina ceramic flow tube upon which four coils are mounted. These four coils act as the resonator coil, the static field coil, the modulator coil and the detector coil. The detector coil is mounted in a magnetic shield can and vacuum impregnated with high temperature epoxy. There is a comprehensive electronics package which generates the necessary magnetic fields, modulates and detects the actual nuclear magnetism and provides phase locked loop control for the measurement of flow. More details can be found in Genthe (1974).

The magnetic resonance principle is used to detect flow. Hydrogen or fluorine nuclei are first magnetized in the inlet section. They then flow into the detector section where the magnetization is direction modulated. This is then sensed at a point just downstream. The modulated frequency is then changed to give a fixed phase angle between the first measurement point and the final detector point at the end of the meter. This produces a modulation frequency proportional to the fluid velocity within the section. By pulsing the coils, the nuclear magnetism can be aligned parallel to or anti-parallel to the field direction.

Performance on a number of applications in the USA showed typical performances of ± 1 % of rate over a 5 : 1 flow range using a number of fluids. These included hydrocarbons, slurries, water, non-newtonian liquids and emulsions. The disadvantages are high cost and complexity and the device has not made the inroads into industrial applications that were expected.

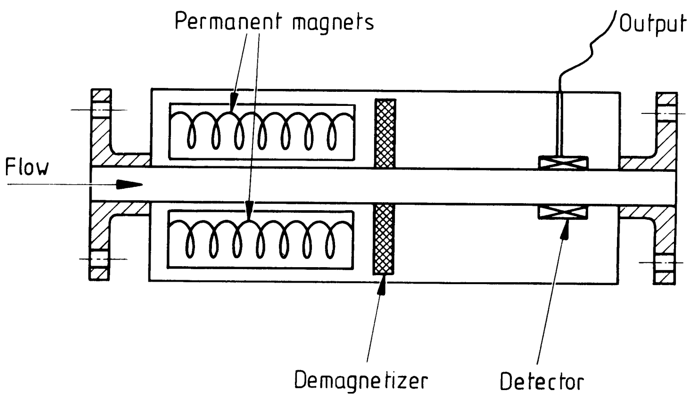


Figure 3.10.4 — Schematic of a nuclear magnetic resonance meter

3.10.5 Laser Doppler anemometry

The laser anemometer is the most important of the meters in this group, from a research viewpoint, since fairly accurate local velocity measurements can be made without disturbing the flow. Light beams are used to make the measurements and hence transparent pipe sections are required. This is the main reason for its low importance from an industrial standpoint.

The operating principle depends on focusing two beams of light from a laser at a point where the velocity is to be measured. Any particles passing through the intersection of the two beams scatters light in all directions which can be sensed with a photodetector. The velocity of the particles, assumed to be that of the stream at the intersection point, causes a Doppler shift in the frequency of the scattered light. This shift produces a signal in the detector directly proportional to local velocity. The particles could be naturally present or can be introduced into the stream to enhance the signal. Such a method is often needed in gases where naturally occurring particles may be absent. Research in many areas has shown that the particle velocity is, in most cases, very close to the stream velocity.

The laser anemometer has been operated in several different configurations, depending on application. The popular two beam system shown in Figure 3.10.5 gives rise to another explanation of operation, the so-called differential Doppler or fringe mode. Where the two beams cross, there are alternate light and dark bands or fringes. This produces a fixed fringe spacing within the intersection area, shown arrowed in Figure 3.10.5. If a small particle passes through the area, there will be a flash of light at each bright band, and the rate of flashing will be a direct function of the velocity perpendicular to the fringe pattern. This frequency, f (in Hz), produced by the particle motion is given by:

$$f = \frac{2\ \ u \sin(\theta)/2}{\lambda} \qquad (3.10.5)$$

where

- λ is the wavelength of the light beam (typically 5×10^{-5} cm);
- θ is the angle between the light beams (in degrees);
- u is the velocity of the particle (in cm/s).

Thus, when θ is 30°:

$$f = 10.340 \cdot u \text{ Hz} \qquad (3.10.6)$$

The fringe pattern can be rotated through 90° to measure the second of the two components of velocity or, alternatively, more than two beams can be used to measure both components simultaneously. The two beam forward scattering arrangement (fringe mode) is the most common but reference beam and back scatter systems have also been used successfully in high particle concentration applications where the detector requires less critical alignment or access is only available from one side.

There are also two types of signal processing systems, frequency trackers and counter type systems. The first of these works best with high particle concentration or seeded systems, gases for example, while the counter based arrangement is better for high velocity flows or those with low particle concentrations. Generally both are high performance instruments and in skilled hands can yield much data about the flow profile. They are capable of operation over a wide range of velocities, typically from zero to 400 m/s in both forward and reverse direction with very high frequency response.

3.10.6 Gas ionization meter

This meter, which is still basically at prototype stage, uses a dedicated radio active source to ionize a gas flowing in a pipe. Both alpha and beta particle sources have been used. Much development work has been performed at NEL (see Brain et al 1974) and their design is shown in Figure 3.10.6. The basic principle involves the application of an electrical potential to the ionized stream between an outer electrode and a central electrode. This results in an electrical current flow and the collection of positive ions at the central device. As flow increases fewer ions are collected at the centre electrode and the collected current drops at a rate proportional to flow velocity.

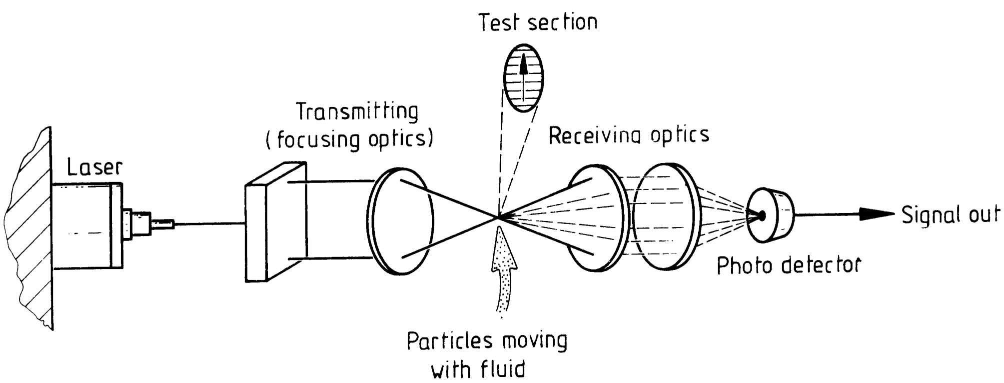


Figure 3.10.5 — Laser Doppler anemometry

In the NEL design, a pulsed voltage is applied to the first electrode and a stable voltage to the second. During the application of a pulse, ions are collected at the first station and this causes a decrease in current when this ion packet reaches the second detector. The time between the increase in current at the first detector and the decrease in current at the second detector is the transit time between the two stations. If the signal from the second station is used to trigger the pulse applied to the first station, a frequency output is obtained which is directly proportional to flow.

3.10.7 Velocity area integration methods

This method involves the measurement of the flow velocity at a number of mathematically positioned points on one cross section of a pipe. The mean velocity and hence the flow rate can be calculated using integration formulae. The velocity measurements can be made either by an array of individual devices (mainly applicable to large pipe sizes) or by one device which can traverse the pipe. If measurements are made by traversing the pipe diameter, then allowances should be made for changes in flow rate during the traverse.

Numerical methods of integration are recommended since they are quick and easy to use. The three methods most commonly used are as follows:

a) log-linear method;

b) log-chebychev method;

c) method of cubics.

Full details can be found in BS 1042-2.1.

3.10.8 Weighing methods

Flow rate can also be determined by weighing techniques. This is certainly acceptable for batch type processes but is less practical for continuous processes. In industrial plant the weighing system can replace the flowmeter completely and this represents a very cost effective alternative to the installation of mass meters.

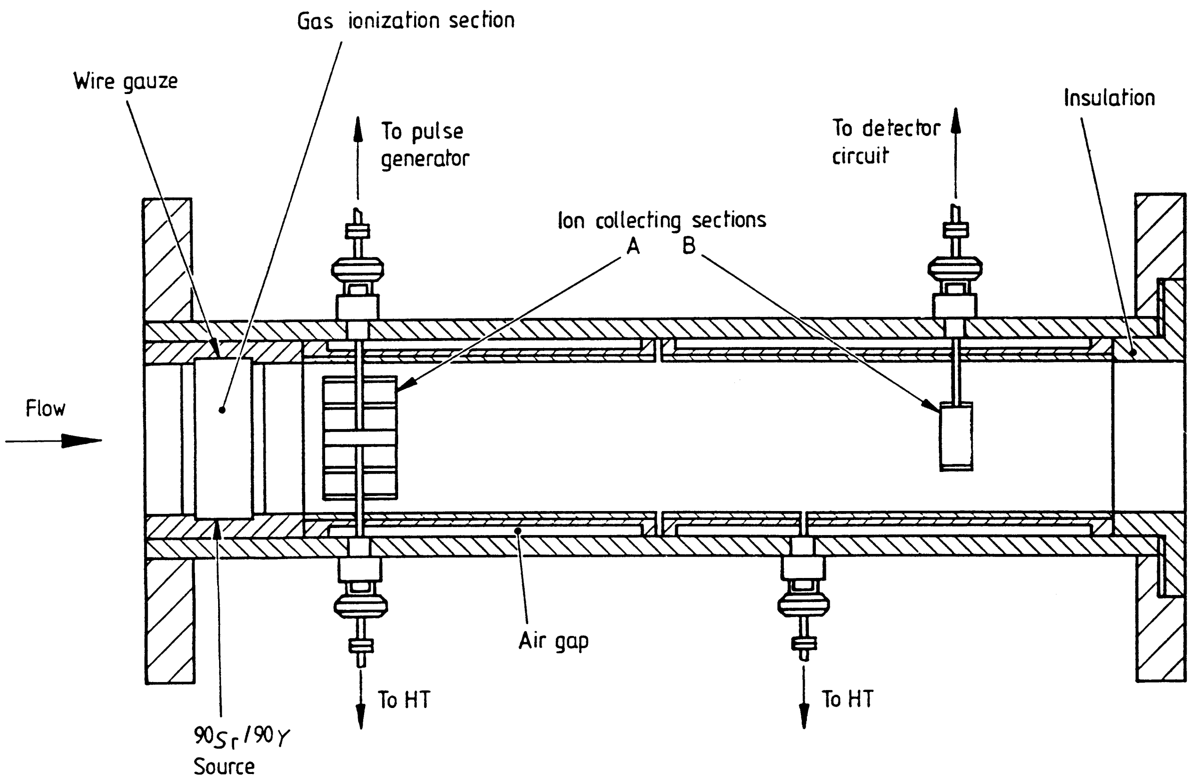


Figure 3.10.6 — NEL gas ionization meter

Section 4. Flowmeter applications

4.0 Introduction

4.0.1 General

This section of the guide examines the various applications of flowmeters. A complete definition of the end use is essential to the successful use of any type of flowmeter and all too often a particular meter is installed without due regard to the limitations of the product. As a result certain types of flowmeter have obtained tarnished reputations, generally as a result of misapplication and misuse rather than poor operating principle and/or poor development engineering. This is the case particularly with the newer designs and techniques that have appeared on the market in the past twenty years.

Some types of meter, particularly group 1 (orifices, venturis and nozzles), group 3 (displacement types) and group 6 (electromagnetic types) are well accepted to industrial flow measurement and reasonably well developed operational guidelines exist. In custody transfer applications the same is true of some group 4 meters (e.g. turbine types). In most other cases applications guidelines are still developing as more flowmeters of all types are being installed in unproven applications.

Applications guidelines for the ten groups are reviewed in **4.1** to **4.10**, some in more detail than others. Once metering techniques suitable for a particular application have been identified using section 2, it is advisable to discuss with the suppliers (and independent third parties where possible), the full details of the application. This will enable better operational data bases to be developed. General reviews by McNulty and Crane (1988), Furness (1989), Baker (1989) and Scott (1982) give useful additional data to supplement the information given in this guide.

4.0.2 Layout

This section examines the five basic areas covered in the general selection procedure (section 2) for each of the flowmeter groups. The clause number corresponds to the group number being discussed. Thus group 4 meters (inferential) are found in **4.4** and group 8 (mass types) are found in **4.8**.

In each clause the format is the same, the five major areas of influence are then discussed in the same order throughout this section of the guide. These are numbered as follows:

4.-.2 general applications

4.-.3 influence of meter performance on applications

4.-.4 influence of fluid properties on applications

4.-.5 influence of installations on applications

4.-.6 environmental influences on applications

4.-.7 economic influences on applications

The dash refers to the relevant meter group. Thus for example **4.4.6** covers the influence of the environment on group 6 meters (electromagnetic types) and **4.10.3** discusses performance constraints on group 10 meters (miscellaneous types).

4.1 Group 1 meter applications: orifices, venturis and nozzles

4.1.1 General

Most industrial plants use at least one of the types of meters found in this group. A major advantage of these meters is the absence of any moving parts. Also the secondary part of the system, the differential pressure sensor, can be removed without the need to shut down the line. They are versatile, simple and reasonably cost effective, factors which have contributed to their widespread use in flow metering.

4.1.2 General applications

These meters can be applied to measure the steady flow of most low viscosity fluids, liquids or gases, provided they are used in the turbulent flow regime. The standards used throughout the world give guidelines on the range of Reynolds numbers within which the discharge coefficient data is valid. The meters can be used outside the recommended ranges, provided it is realized that the uncertainty of the measurement will increase.

The majority of data and applications experience is available for sharp-edged concentric orifice plates. These meters can be machined from plate stock to accepted standards and can be manufactured in a wide range of materials to ensure compatibility with the fluid being metered. The output signal, although non-linear with flow, is well suited to control applications because there is a well defined signal variation with flow. They can be purchased in a very wide range of sizes and if designed in accordance with BS 1042-1.1 will not need to be flow calibrated, unless precise measurement is required. This makes their use in large pipes very common since most other large flowmeters do need to be flow calibrated and there are few facilities available for this purpose.

When installed in properly designed metering runs and operated within acceptable ranges, they present the user with a very cost effective, simple and robust form of industrial flowmeter. As a result they can be found on water, process liquid, chemical, steam, air and natural gas lines to name but six basic examples. They can be sized to match specific requirements and are therefore available in an infinite number of sizes. They are the primary measuring element for gases and the new generation of flow computers (see **5.5.6**) has enabled a greater accuracy of on-line calculations to be performed in recent years. Full details of the calculations can be found in the BS 1042-1.1, ASME Handbook (1971) or Miller (1989).

Venturis are used in applications where there are solids present, for general dirty industrial flows or where high pressure recovery is critical. They are widely used on water distribution and closed conduit irrigation systems, in waste water and industrial disposal applications and in applications where DP meters are preferred but pumping power is limited. They have the same basic characteristics as the orifice however, limited rangeability and simple operation but are more expensive for the same size.

Flow nozzles are used in high velocity applications such as those encountered in gas lines. They work more satisfactorily on wet steam than venturis or orifice plates because of their greater immunity to erosion. Where headloss is a consideration but installation lengths do not permit the use of a venturi, the flow nozzle represents a good compromise. They are used in applications where the Reynolds number is above 5×10^4. Industrial applications include inlet and exhaust flows to engines and compressors, steam flow in power generation installations, and corrosive chemical flows. Total uncertainty is the same as for the venturi meter.

All meters like orifices, venturis and nozzles respond to changes in ρU^2 and thus are neither true volumetric nor mass flow devices. The volumetric flow rate is determined from the quotient of the differential pressure and the fluid density whereas the mass flow is found from the product of these two quantities.

4.1.3 Influence of meter performance on applications

4.1.3.1 *General*

The performance of meters in this group is generally very stable with respect to time except in those circumstances where the nature of the fluid changes the characteristics of the edge or erodes surfaces. It is also important to control ambient and process temperature changes and rapid changes in flow rate and pressure. These first two factors affect plate dimensions and secondary instrument performance while the second two can give rise to permanent mechanical damage to the meters.

4.1.3.2 *Sizing and flow range*

Differential pressure flowmeters have a range which typically is only about 3 : 1 or possibly 4 : 1 and this may be reduced if they are not correctly sized. It is possible to extend this range in two ways; by using secondary devices in parallel or electronically based secondary instruments as described in **5.1.6**. It is usual to make a preliminary calculation of β ratio on the basis that the normal flow rate is 0.7 of the maximum, i.e. that the normal differential pressure is about half the maximum. The information required, assuming a provisional selection of the type of primary device has been made, includes:

a) maximum flow rate;

b) maximum differential pressure;

c) working line pressure and temperature;

d) pipe bore;

e) fluid properties such as viscosity, density, and for gases, isentropic exponent and compressibility data.

The selection of β ratio may have to be modified by constraints such as system pressure loss, available straight pipe lengths, type of upstream pipe fittings and the need for an acceptable expansibility factor. Computer programs are available to enable sizing to be performed very rapidly. Alternatively the Shell Handbook (1986) lists simple sizing programs for the more common types of DP device.

4.1.3.3 ***Linearity and signal processing***

The main effect of the inherent non-linearity of differential flowmeters is the restriction of the flow range as already discussed. Industrial DP signal processing equipment incorporating linearizers has been available for some time. In recent years, however, dedicated flow computer/microprocessors have been available which take the non-linearized signal and generate appropriate flow rate display and process control signals. On-line flow rate or flow totalization can also be easily achieved using a flow computer, as discussed in **5.6.6**.

4.1.3.4 ***Dynamic response***

The dynamic response of the complete meter is usually governed by the response of the DP cell. Industrial DP cells can usually give a true response to signals varying at up to a rate of about 2 Hz. DP transducers with a faster response are available but users should be aware that the acoustic properties of the connecting leads between pressure tappings and transducer in gas flow systems can severely distort rapidly changing pressure signals such that even the mean indicated values are incorrect.

4.1.3.5 ***Pressure drop***

The overall pressure drop of the various types of primary device are shown in Figure 4.1.1, where group 1 and some group 2 meters are compared. This parameter may well affect the selection of the type of meter and, in the case of the DP types, the β ratio. It should be noted that, for a given differential pressure, both orifice plates and nozzles have the same pressure loss. The venturi, on the other hand, can handle 25 % to 50 % more than orifices for comparable size and head loss. The venturi's diffuser reduces the loss but increases the meter's overall length.

4.1.4 Influence of fluid properties on applications

4.1.4.1 ***Type of fluid***

The fluid can be either a liquid or a gas or a dry vapour. Two-phase or non-homogeneous fluids cannot be measured within the scope of BS 1042-1.1. Some of the problems of metering the more difficult fluids are briefly discussed below.

4.1.4.2 ***Liquids***

The density of liquids varies with composition and to a lesser extent with temperature. The variation with pressure can be neglected except when close to the critical point. Thus for liquids of constant composition a measurement of fluid temperature can be used to infer density.

The fluid temperature is required, not only for density, but also to infer the viscosity needed for Reynolds number calculation and to make a correction for expansion in the primary device bore. The bore at flowing conditions can be calculated from:

$$d = d_r\{1 + \lambda\,(t - t_r)\} \qquad (4.1.1)$$

where

d is the bore at flow rate conditions;

d_r is the reference bore.

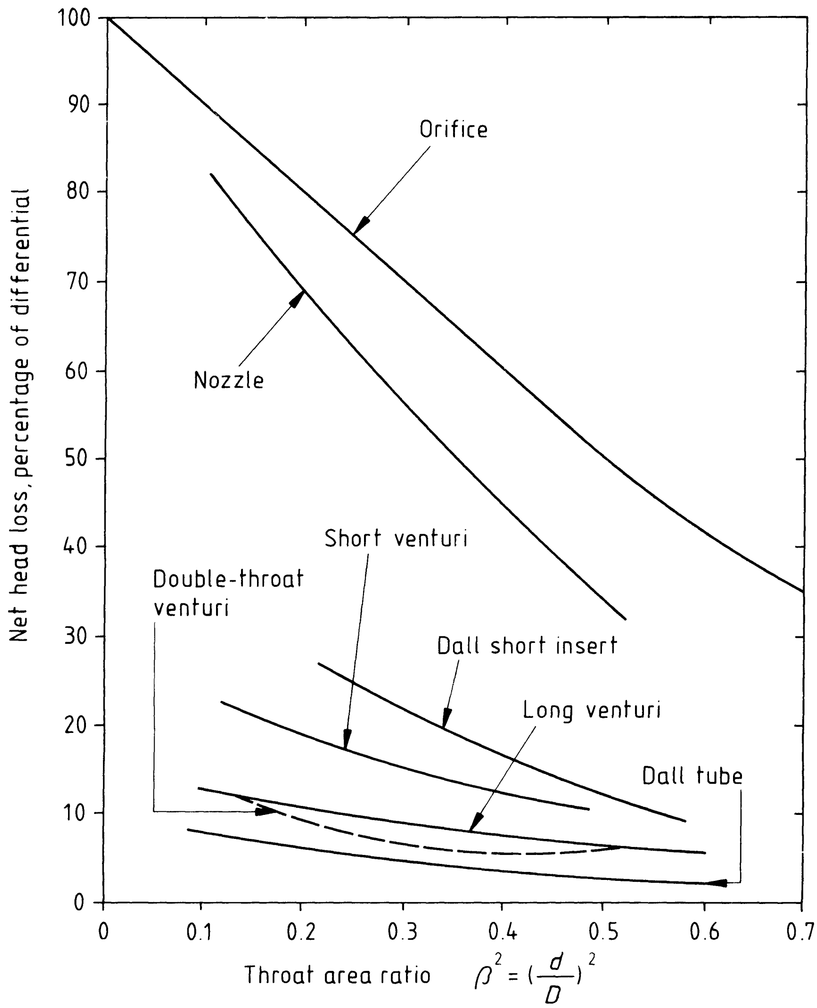


Figure 4.1.1 — Comparison of head loss for different DP devices

4.1.4.3 ***Gases***

The density of gases varies strongly with composition, pressure and temperature and can be calculated from:

$$\rho_1 = p_1/(T_1 Z_1 R/M) \tag{4.1.2}$$

NOTE The suffix $_1$ refers to the upstream tapping. In practice the temperature is usually measured downstream. It is possible to calculate the temperature change across the meter corresponding to the overall pressure loss assuming an isenthalpic process. The resulting correction, however, is usually small.

For a mixture of gases appropriate values of M and Z have to be used for a given composition. For moist gases the partial pressure of the water vapour is required for separate calculations of the vapour and dry component densities which can then be added.

An alternative to calculating gas density from pressure and temperature is to measure it directly with a densitometer (**5.3.5**). These instruments can either be inserted directly into the pipeline or located in a bypass across a suitable differential pressure generator.

The viscosity of gases depends on composition, pressure and temperature and is determined from tabulated data.

4.1.4.4 ***Reynolds number limits***

The pipe Reynolds number limits for the use of these meters is specified in detail in BS 1042-1.1. The upper limits are as follows:

- 10^8 for the square-edged concentric orifice;
- 10^7 for ISA 1932 and long radius nozzles;
- 2×10^6 for venturi nozzles and venturi tubes (except tubes with a machined convergent section for which 10^6 is the high limit).

The lower limits depend on the β ratio but go down to:

- 5×10^3 for an orifice with corner taps;
- 10^4 for a long radius nozzle;
- 2×10^5 for a venturi tube.

From the above we see that the orifice has the widest Reynolds number range and the venturi tube the narrowest. Industrial experience has shown that venturi meters are best used when the Reynolds number is above 2×10^5. The discharge coefficient variations above that value are relatively small.

If the application requires measurement at Reynolds numbers below 5×10^3 then quarter circle or conical entrance orifice plates, or possibly a wedge meter (see **4.2**) should be considered.

4.1.4.5 ***Two-phase fluids***

The measurement of two-phase fluids is not within the scope of BS 1042-1.1. If gas/liquid mixtures have to be measured by a differential pressure flowmeter the following points may help to keep errors to a minimum:

a) a nozzle would be a better choice than an orifice plate because it is not subject to erosion damage by liquid droplets or to buckling due to plug flow following system start-up;

b) liquid running along the pipe walls should be removed by means of a separator installed upstream of the flowmeter.

It should be borne in mind that large errors are to be expected in measuring two phase fluids using group 1 meters. Empirical conditions exist but they need to be carefully chosen and even then they only reduce the error.

4.1.5 Influence of installation on applications

4.1.5.1 ***Orientation***

All the standard DP primary devices can be mounted in horizontal, inclined, or vertical pipes. Provided the connections to the DP cell are in the same horizontal plane, the indicated differential pressure will automatically compensate for any height differences between the tappings. Where the steam contains solid particles it is preferable to mount the primary element vertically and ideally with the flow downward. This will tend to sweep fouling materials through the primary element more easily and prolong life.

4.1.5.2 ***Direction of flow***

The only primary device which can be used to measure flow in either direction is a symmetrical square-edged orifice plate. For such an application corner or flange taps would be preferable to D and $D/2$ tappings. For the latter, two separate sets would have to be provided. Even with corner or flange taps it might be necessary to provide separate DP cells for forward and reverse flows. Orifice plates with bevels complying with the standards, venturis and nozzles are uni-directional devices only.

4.1.5.3 ***Pipe configuration***

The upstream and downstream straight pipe length requirements are specified in BS 1042-1.1 for the more common types of pipe fittings. Since the venturi tube is less susceptible to distorted velocity profiles and to swirling flow than are orifice plates and nozzles, it generally requires shorter straight pipe lengths. For all types of primary device, BS 1042-1.1 gives alternative shorter straight pipe lengths that can be used, provided an additional 0.5 % uncertainty is added arithmetically to the discharge coefficient uncertainty. It should be remembered that these tables contain the minimum recommended lengths and wherever possible longer pipe lengths should be used.

If the upstream pipe fitting is not one of those for which minimum straight pipe lengths are given, a suitable flow straightener may be interposed between the fitting and the flowmeter. It is also possible that the use of a straightener may reduce the straight pipe length that might otherwise be required for one of the specified fittings.

Three designs of flow straightener are specified in BS 10421.1, namely the Zanker, the Sprenkle and the tube bundle straightener. The most common of these, the bundle, is shown in Figure 4.1.2. They should be installed at least 20 *D* downstream of the fitting with a further 22 *D* of straight pipe between the straightener and the primary device. It is acceptable to use shorter lengths and/or other designs of straightener if it can be demonstrated that the flow at the meter is swirl-free and that the velocity profile is typical of fully developed turbulent flow. The criterion for swirl-free flow is that the swirl angle anywhere in the pipe cross section has to be less than 2°. The velocity profile may be taken as typical if the ratios of local to maximum axial velocities at any point in the pipe cross section agree within 5 % with the corresponding values at the end of a very long straight length (at least 100 *D*) of similar pipe.

4.1.5.4 *Pulsating flow*

BS 1042-1.1 applies only to steady flow or to flow which varies only slowly with time. Flow pulsations can cause significant errors for two main reasons:

a) the flow rate/differential pressure relationship is non-linear (square root error);

b) the secondary device may not measure the true differential pressure.

The square root error (SRE) is the more common source of problems. The concept is illustrated in Figure 4.1.3. In steady conditions a flow q produces a differential pressure Δp_0. If sinusoidal pressure variations occur, the figure illustrates two points:

1) the time average of the Δp signal [called Δp (t)] is no longer Δp_0;

2) the differential pressure waveform Δp (t) is not sinusoidal.

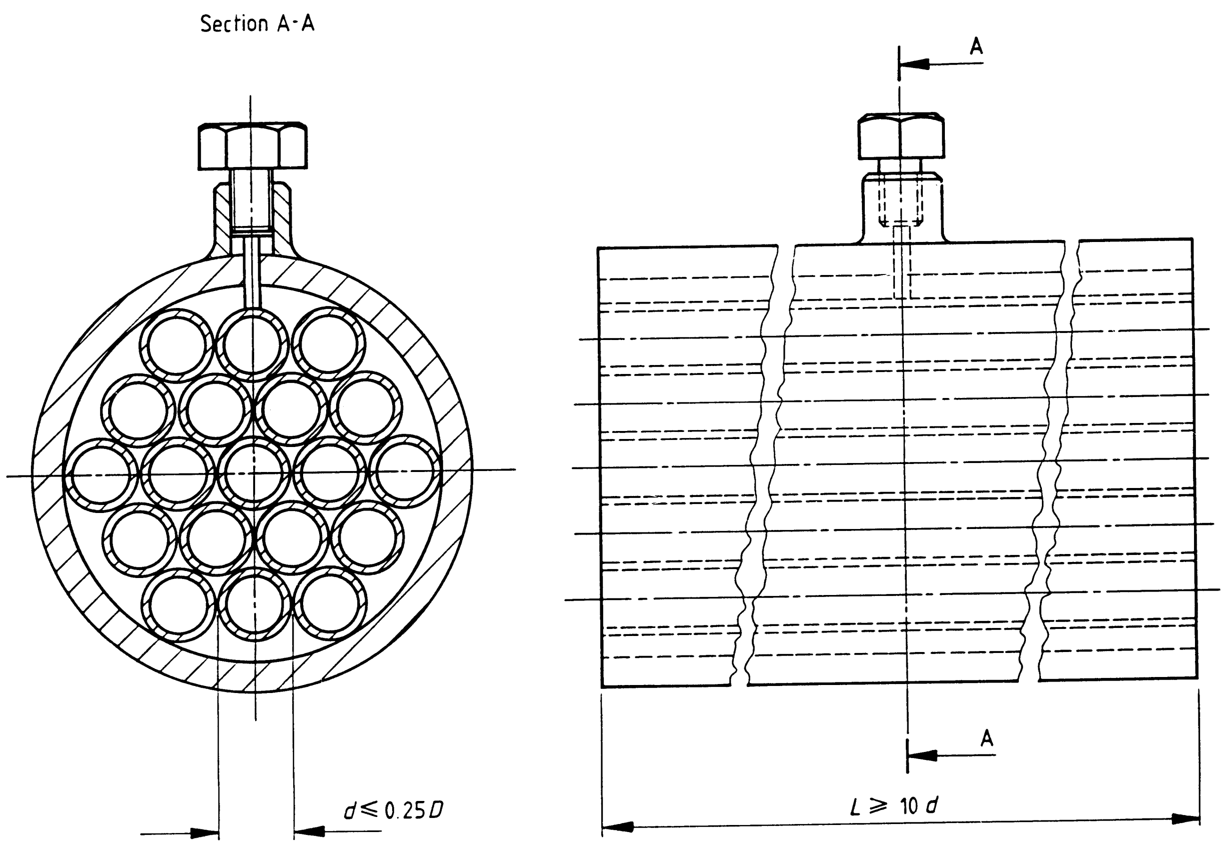
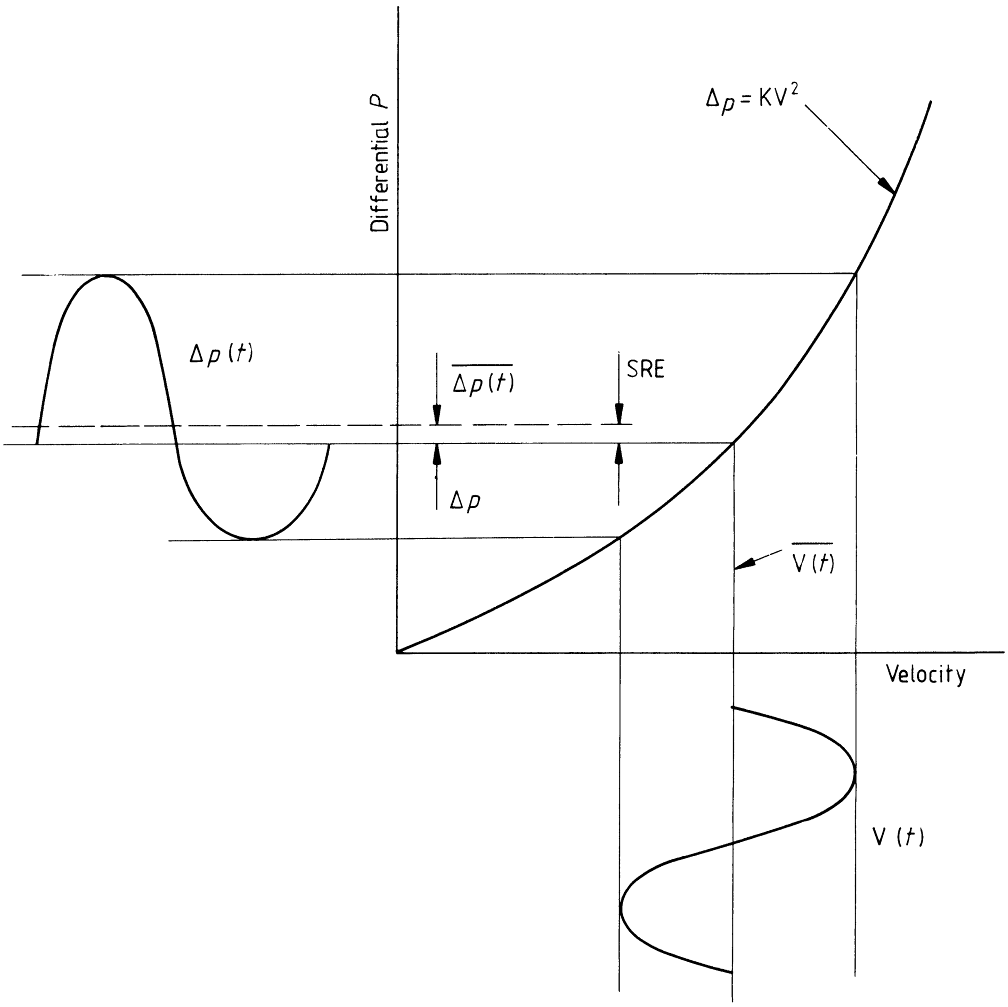


Figure 4.1.2 — Tube bundle flow straightener



NOTE Assumes K remains constant with pulsation.

Figure 4.1.3 — Square root error effect from pulsating flow through a DP meter

Figure 4.1.3 shows that the average pressure drop changes with pulsations present, even though average flow and orifice discharge coefficient have not changed. The error results simply from the process by which the Δp data is used to derive flow. SRE results from taking the square root of the average pressure rather than the average of the square root of the differential pressure. If instantaneous square root values are taken then SRE can be minimized. Some DP system manufacturers can supply suitable algorithms already programmed inside secondary flow computers. The square root error plotted against the RMS amplitude of the fluctuations in the differential pressure is shown in Figure 4.1.4. The curve shown in this figure assumes true differential pressure measurements.

In most circumstances the recommended remedy for pulsating flow is the installation of sufficient damping into the system. Examples of methods incorporating damping in gas flow systems are shown in Figure 4.1.5. Further guidance on dealing with this problem can be found in **2.4.12** and in BS 1042-1.4.

4.1.5.5 *Swirl*

Swirling flow can cause very large errors in differential pressure-type flowmeters as is illustrated in Figure 4.1.6. This type of flow can be generated by two or more bends in different planes, tangential or offset entries, partially open valves, cyclone separators, and many other devices. Two methods of attenuating swift are as follows:

a) provide sufficient length of straight pipe for dissipation by frictional effects;

b) install a flow straightener.

Both methods involve constraints on the meter installation.

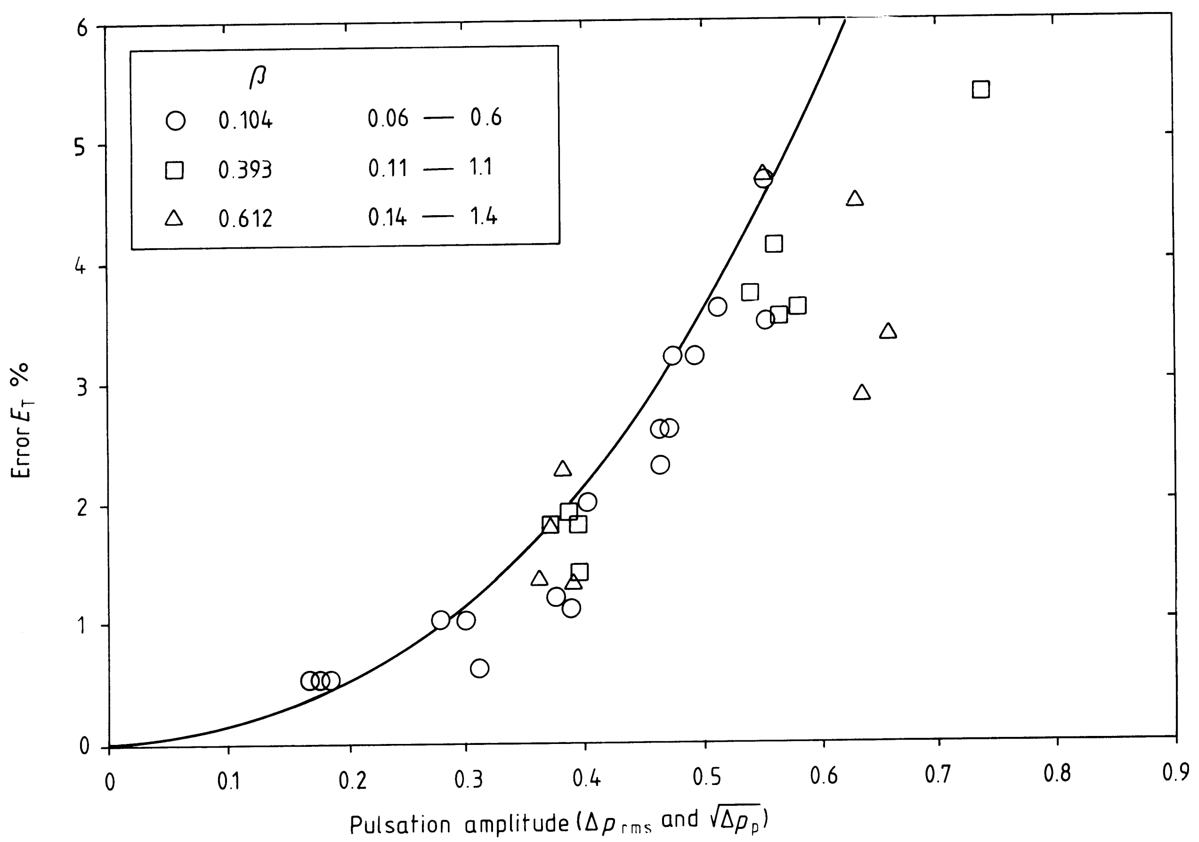


Figure 4.1.4 — Total error at low pulsation amplitude (frequency range 50 Hz to 500 Hz)

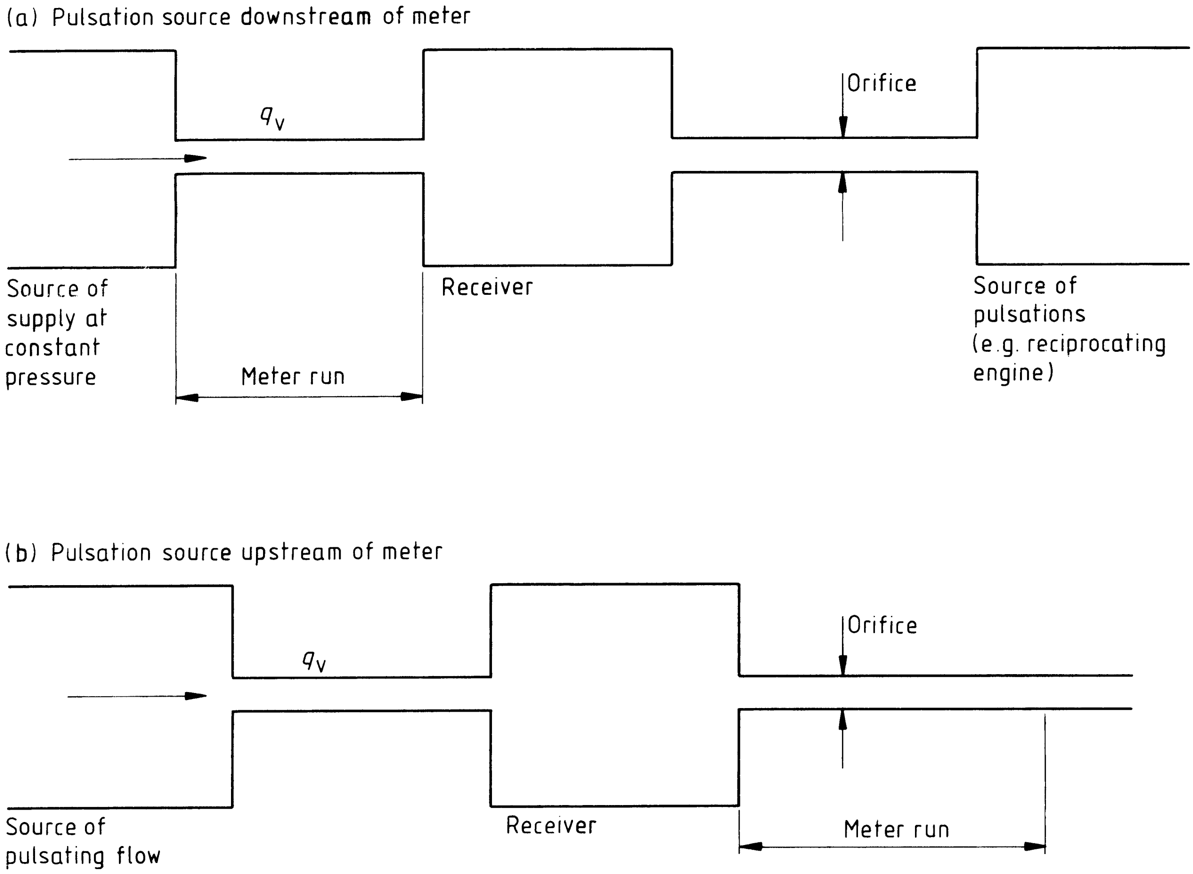


Figure 4.1.5 — Examples of methods of reduction of pulsation effects in gas flow

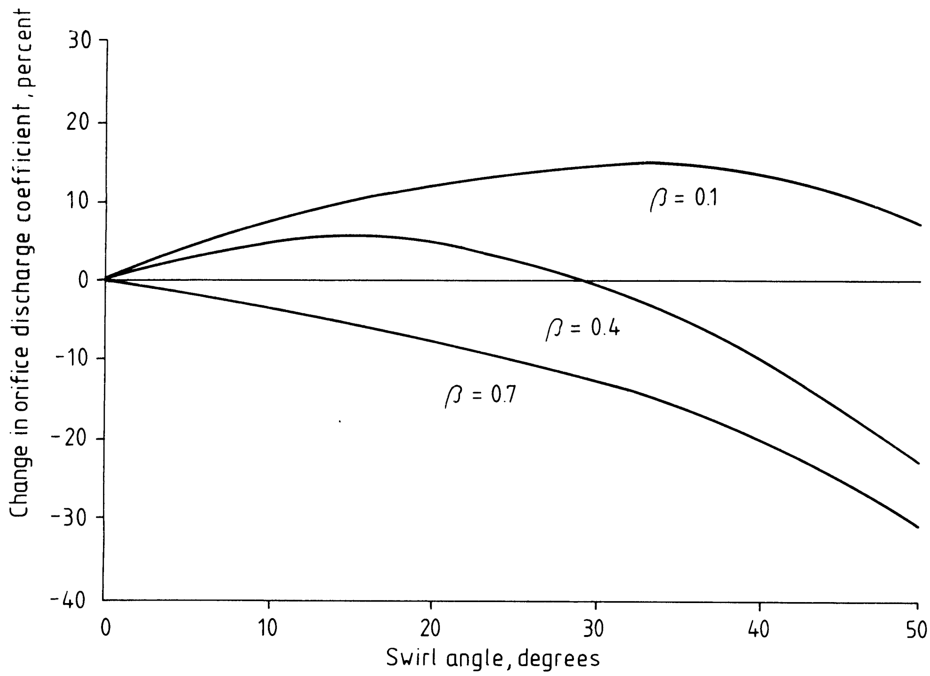


Figure 4.1.6 — Effect of swirl on orifice flowmeters

4.1.5.6 ***Velocity profile***

The coefficient data in the standards apply only if the velocity profile in the pipe is typical of fully developed turbulent flow. Most pipe fittings create a flow disturbance which can be rectified either by means of a sufficient length of straight pipe or by a flow straightener. In both cases further constraints are placed on the installation.

4.1.6 Environmental influences on applications

The primary device will not be susceptible to the environmental conditions surrounding the meter installation. It is possible, however, that the secondary device and the ancillary instrumentation for pressure, temperature and density might be affected. It may be necessary to have long pressure connecting leads to sensors located in an area with a less hostile environment.

Intrinsic safety in potentially explosive atmospheres is a very important consideration and may require pneumatic signal conditioning and transmission away from the danger area.

4.1.7 Economic influences on applications

4.1.7.1 ***General***

The economics of buying, installing, calibrating, running and maintaining a particular type of flowmeter should be analysed during the meter selection procedure although it may not necessarily be the deciding factor.

4.1.7.2 ***Purchase costs***

It is important that the price comparisons are made for meters with similar performance and degree of sophistication. Clearly there would be a very great difference in price, for example, between:

a) an orifice mounted between flanges and fitted with a simple manometer; and

b) an orifice plate mounted in a carrier with a mechanism for withdrawing the plate from the line under pressure and with electronic DP cells, signal conditioning and transmission and supplied with a flow computer.

It is also possible to obtain misleading comparisons if prices are obtained assuming that different types of meter all need to be of the same nominal size. Different meters rated for the same flow may require different meter run nominal bores, as outlined in Figure 2.5(a) and Figure 2.5(b).

4.1.7.3 ***Installation costs***

Costs under this heading include:

a) the provision of ancillary instrumentation for pressure, temperature, density, etc.;

b) alterations to existing pipework, provision of bypass pipe runs, etc.

4.1.7.4 ***Calibration costs***

One of the major advantages of using a flowmeter such as an orifice, nozzle or venturi is that, if made and installed according to the specifications laid down in BS 1042 or other standard, calibration is not usually necessary. If it is important to obtain the highest possible performance, however, the cost of having the meter calibrated in a recognized laboratory has to be taken into account.

4.1.7.5 ***Maintenance costs***

Both primary and secondary devices need regular maintenance to ensure reliability and the lowest possible uncertainty. When orifice plates are used in fluids with corrosive or abrasive properties, frequent inspection is essential to check that the square-edge remains sharp. Pressure tappings have to be checked frequently if there is any danger of them becoming blocked.

4.1.7.6 ***Running costs***

The major item under this heading is likely to be the cost of providing pumping power to overcome the meter head loss. In certain applications this cost may be significant and be a deciding factor governing the initial choice of the meter type. Comparative head loss characteristics of DP meters are shown in Figure 4.1.1, (see also **4.2**).

4.2 Group 2 meter applications: other differential pressure types

4.2.1 General

This mixed group of differential pressure meters offer the widest selection of applications of all the groups covered in this guide. The many and varied designs permit use from very low to very high flows, cover pipe sizes of around 1 mm bore up to several metres bore and use on liquid and gases, both clean and dirty. As a result many are regarded as industrially acceptable meters.

4.2.2 General applications

4.2.2.1 ***Proprietary low loss tubes***

These designs, the Dall tube®, Gentile tube, Epiflo and similar primary elements described in **3.2** are considered as alternatives to orifice meters where head loss and throughput are important factors. They can be used on liquids, gases and with care in the choice of design, on slurries and contaminated process fluids. They have the advantage of even lower head loss than venturi meters, but this advantage is offset by increased cost and in some designs by an increased inlet pipe length because of higher sensitivity to disturbances. They are only used where low inlet heads or limited motive power in the system is available.

In general the application constraints are similar for all differential pressure devices, although they are prone to two-phase and Reynolds number effects. Some designs are particularly affected by cavitation which can cause a sudden step change in the calibration with errors of around 15 %. Cousins (1975) has carried out experimental studies into design features of these devices. Cavitation should be avoided at all costs by ensuring that the throat pressure is always well above the vapour pressure of the liquid. The Gentile tube appears to be less affected by Reynolds number than other DP devices. However, distorted profiles (particularly swirl), may cause problems. Particles and bubbles may cause problems by fouling tappings.

4.2.2.2 ***Special design orifice plates***

Eccentric and chord orifice meters are used where orifice meters are not suitable because of fluid characteristics. Examples are entrained gases in liquids or high droplet concentrations in gas flows where the conventional plate would act as a weir in the pipe and fluid would build up on the front face. The actual orientation of the plate depends on the application and the amount of the second phase component present. Other successful applications include low concentration slurries.

There is little documented data on applications constraints, particularly on the presence of pulsations and two-phase flow. Profile and swirl have slightly less effect on variable area orifice designs (e.g. the Gilflo®) than on standard meters, largely due to the higher pressure loss. The data available indicates that particles and bubbles should be avoided, as they could affect the operation of the spring. Reynolds number effects are less than for a standard orifice plate and this type of meter is very useful for high viscosity fluids.

4.2.2.3 ***Integral orifice meter***

This design of meter is applied to small pipe bores, both on liquids and gases. Initially acceptance was slow but as they were applied to general low flow rate process measurement with good results, confidence grew and they are now commonly found on many small bore process plant lines.

4.2.2.4 ***Wedge meter®***

This fairly recent addition to this group of meters finds widespread application on the more viscous liquids and on slurry flows. The design also permits successful application on low concentration gas-liquid flows. The effect of profile is not well documented, but is probably similar to equivalent orifices. Particle and bubble presence can be coped with by virtue of the design and with correct installation. Similarly with Reynolds number effects, the meter is claimed to be linear to such a low value that for most practical purposes it is unaffected.

4.2.2.5 ***Variable area (VA) meters***

These are important meters in general industrial monitoring. They are applicable to both liquids and gases but not to multi-phase fluids. The liquids need not be clean but any deposits, condensation or crystallization occurring within the meter will affect both performance and visibility of the float in the tube. Special float designs can be used to reduce the sensitivity to viscous changes.

Flow profile is less important to VA meters than most other meters. The presence of particles and bubbles can be a severe problem from density, viscosity and blockage considerations. Reynolds number is also a limiting factor, between 250 and 950 for flows below 400 L/m and approximately 4 400 for flows above 400 L/m. 10 : 1 is a generally accepted flow range for a VA meter. Flow limits are determined by the VA meter design. In general ball type floats are used for low flows. The streamlined float is more economical for larger meters as its shape provides a higher capacity. Special viscosity compensated floats improve the sensitivity of VA meters to viscosity changes.

4.2.2.6 ***Pitot tube type meters***

These probes, particularly the multi-port averaging types, are becoming increasingly important in the metering of water and air flow in very large bore pipes. Recently several different designs have appeared and, whilst accuracy is not as good as with full bore meters, they are a very economical means of measuring flows in large pipes. They have recently been used in steam mains for energy management purposes and can be used over wide temperature and pressure ranges. Conventional pitot and pitot-static tubes are used in research and development testing of fans, duct air flow and general aerodynamic studies (see Ower and Pankhurst 1977).

Pipe roughness is very important with a pitot tube as this could influence the wall measurement of static pressure. If there is a large static pressure gradient then a pitot-static tube has to be used. Obviously, they are both sensitive to flow profile and if there is any evidence of profile variations a full profile check must be carried out. They are very sensitive to swirl and as such can be used to investigate swirl. Particle and bubble presence will cause blockage of the pressure tappings. Both devices are in themselves very sensitive to Reynolds number. The velocity profile is highly dependent on Reynolds number and if this is not known errors in volumetric measurement will arise. Flow range is largely determined by the secondary manometers or DP cells. However, the differential pressure is generally very low, and so finding a sufficiently sensitive DP cell may be a problem.

The effect of various application parameters for the averaging pitot is well documented. Profile is accounted for in the recommended upstream pipe requirements, like most flowmeters swirl can cause major errors. Particle and bubble presence can be alleviated by correct positioning and by the addition of purging. Reynolds number affects the meter largely through profile changes in the pipe, but correction data can be provided for low flow operation to reduce pipe Reynolds number effects. Flow range is largely a function of secondary devices. The differential is greater than for a standard pitot-static tube but is still rather low and sizing may be a problem.

4.2.2.7 ***Bypass meters***

For large pipes these are an alternative to the designs described in **4.2.2.6** and give the user more freedom in the choice of meter. Applications are similar to all other meters in this group.

Profile and swirl potentially give greater problems than for conventional meters because of the use of two dissimilar meter types. Equally particles and bubbles have to be kept away from the secondary meter. Reynolds number is also a problem as it affects both meters differently and at different points. Pick-off techniques vary, with Rotary Shunt® meters the output is geared mechanically, with the option of a proximity detector; the Metre Meter type uses proximity detectors.

4.2.2.8 ***Elbow meters***

These provide a measure of flow without the need to install a dedicated flowmeter. Where head loss, space and costs are limited then instrumenting an elbow in the pipe system is often the only means of obtaining a flow rate measurement.

4.2.2.9 ***Sonic nozzles***

Sonic nozzles are important in gas metering. Their stable performance and well defined flow characteristics have ensured their widespread acceptance to calibrate custody transfer gas meters of all types and they are the laboratory standard in many parts of the world. The head loss generally makes them unacceptable for the average industrial application.

There is little data on the effect of pulsations and the few results are not clear. Profile and swirl change the calibration of a nozzle. For high performance installations the same precautions must be taken as for high performance orifice installations. Sonic nozzles are Reynolds number dependent, the effect on linearity being more pronounced below a throat Reynolds number of 10^5. The sonic nozzle is a mass flow meter dependent upon direct pressure and temperature measurement to calculate the flowrange.

4.2.2.10 ***Linear resistance (laminar) flowmeters***

Generally the meter is used for gas measurement, particularly at very low flows. A typical application would be one where a maximum flow of 0.5 mL/min of low pressure air requires metering. With careful design of the flow element however, flows of up to 10 m^3/min can be accommodated.

4.2.3 Influence of meter performance on applications

4.2.3.1 ***Dall tube®***

The performance of Dall tubes® is subject to manufacturing tolerances and for uncertainty better than 2 % of rate they should be calibrated. The permissible minimum Reynolds number is higher than for most conventional DP devices. The long-term repeatability is similar to that for most DP devices; however the short-term repeatability can be adversely affected by the unsteady output. By virtue of the amplifying mechanism the differential pressure fluctuates and may require damping. It is essential that the meter is used as a closed pipe meter, with the pipes running full. Figure 4.1.1 shows the improved head loss to differential pressure ratio when compared to conventional orifices and nozzles.

4.2.3.2 ***Epiflo tube***

Performance is similar to orifice plates, all that would be recommended is that it be calibrated. The linearity is comparable with an orifice plate, a typical linearity for a 0.6 area ratio meter being ± 1 % full scale down to a throat Reynolds number of 1.5×10^5. The actual head loss is low compared to an orifice plate, and is similar to the Dall tube® curve in Figure 4.1.1.

4.2.3.3 ***Gentile tube***

Uncalibrated performance is not particularly good because of the problems of locating the pressure tappings precisely. It is therefore recommended that they should always be calibrated. The linearity is similar to other DP meters but it is claimed that the low flow limits are lower, i.e. less Reynolds number dependent.

4.2.3.4 ***Lo-Loss meter***

The uncalibrated performance is poor due to the sensitivity of the throat tappings to position, and the meter should be calibrated for even moderate performance. Due to the design of the device, the differential pressure is less steady than in conventional meters. Repeatability for a given flowmeter is similar to an orifice plate. The actual head loss is similar to that of the Dall tube® shown in Figure 4.1.1.

4.2.3.5 ***Wedge meter®***

It is claimed that the low flow limit for a linearity of better than ± 1 % of full scale is in a pipe Reynolds number range of 500 to 1 000. This is very low compared to standard meters. In addition a repeatability of ± 1% of flow rate and a calibrated uncertainty of 0.5 % full scale is claimed. The meter should be calibrated otherwise errors as much as 10 % can be incurred.

4.2.3.6 ***Segmental/eccentric orifices***

Both types are primarily for closed pipes, although by appropriate installation they can cope, to a degree, with pipes which are not completely full of liquid (see Figure 4.2.1). Uncalibrated performance is variable, an example being the strong dependence of discharge coefficient on tap position, particularly in the larger sizes as shown in Figure 4.2.2. This and other factors mean that discharge coefficients cannot be predicted reliably and flow calibration is recommended. The head loss is similar to an equivalent area ratio orifice plate. Linearity is similar to a standard concentric orifice.

4.2.3.7 ***Bypass meters***

By virtue of design they have reasonable flow range of at least 10 : 1. Generally, the linearity is worse than for either the main meter (usually orifice) or the secondary meter (turbine, Pelton wheel or variable area meter) individually. Typically a linearity of ± 2 % of rate is achievable under specified conditions. As the two measurement methods have different dependence on Reynolds number, viscosity and density, the meters have to be calibrated on a fluid of similar physical properties to the process fluid. With turbine and Pelton wheel secondaries, the output is usually given as totalized flow.

4.2.3.8 ***Variable area (VA) meter***

A typical flow range for this type of meter is 10 : 1 for a reasonable performance, although with the linearity at ± 1 % or ± 2 % of full scale at 10 % of flow the errors become very large (± 10 % or ± 20 %). To obtain performance better than ± 2 %, VA meters have to be wet-calibrated, preferably on a fluid of similar physical properties to the process fluid. Repeatability (as well to some extent as linearity) is dependent upon the graduation resolution. Obviously the higher the graduation resolution the easier it is to read the instrument with accuracy.

4.2.3.9 ***Variable orifice***

A particular feature of them is the improved flow range compared to standard differential pressure meters. Usually a 20 : 1 flow range gives a tolerable performance. The Gilflo® has the advantage of having a linear differential output compared to the square law of a basic orifice. For an uncertainty of 1 % of full scale or better, they should be calibrated, preferably on a fluid of similar physical properties to the process fluid. Linearity is better than ± 1 % full scale for the primary device, with a full scale error for the secondary instrument to be added. Repeatability is worse than for a basic orifice plate. The dynamic response may be worse than for standard differential pressure flowmeters if the springs have to be damped to reduce output noise. The pressure drop is higher than for standard DP meters.

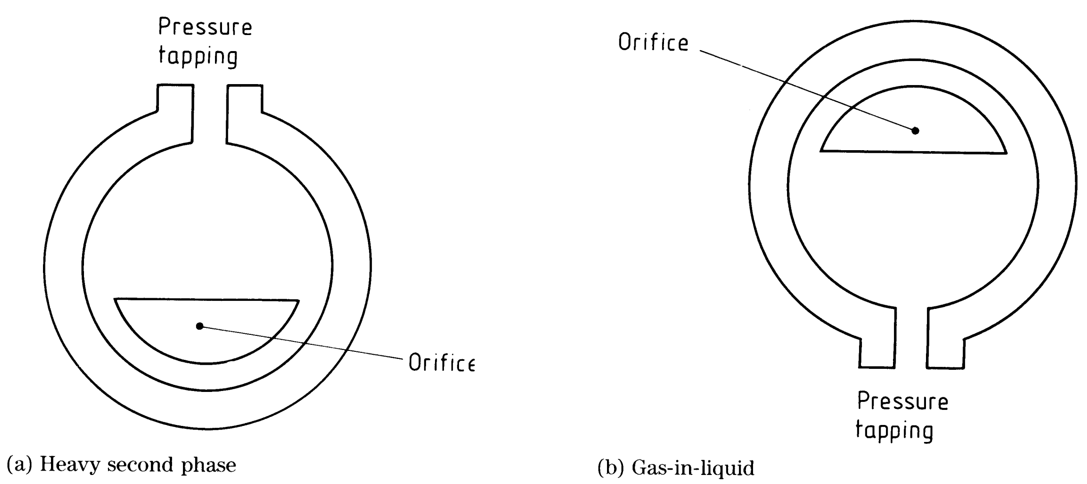


Figure 4.2.1 — Orientation of segmental orifice plates

4.2.3.10 ***Pitot and pitot-static tubes***

Flow range is restricted, usually between 3 : 1 or 4 : 1 by differential pressure measurement. However stacked DP cell systems may be used to relieve this restriction. Both linearity and measurement uncertainty are a function of the intrinsic linearity of the device, positioning error and profile changes in the fluid. For measurement of a point velocity the pitot tube and pitot-static tube have a calibrated uncertainty of better than 1 % of full scale, under ideal flow conditions. The total system uncertainty when measuring volumetric flow is dependent upon effort and skill. If a fully detailed traverse is carried out, an uncertainty of 1 % of flow rate can be achieved. If this is done across the flow range then an equivalent linearity is possible. Without traverses, the uncertainty can vary from 5 % to 20 % of rate. Repeatability is also a function of positioning and is difficult to define. The pressure drop is very low for both types of instrument.

4.2.3.11 ***Averaging pitots***

Linearity limits vary with design and pipe size; the lower flow limit on pipe Reynolds number for a fully developed profile varies from 10^5 to 3×10^5. The claimed uncalibrated uncertainty is 1 % full scale over most of the range. The pressure drop is very low and claimed repeatability, both long and short term is ± 0.1 % full scale deflection.

4.2.3.12 ***Inlet devices***

These devices are used at the inlet to pipes where flow is drawn into the pipe from a volume which can be regarded as a large reservoir. They have the flow range of basic group 1 devices, usually 3 : 1 or 4 : 1. The uncertainty in the discharge coefficient of uncalibrated devices is about 1 %, but they can be calibrated by the temporary installation of an in-line flowmeter downstream of them where this is practicable. Their advantage is that they are relatively cheap to make, and have a low head loss (usually a fraction of one velocity head). The discharge coefficient is normally constant within 1 % for pipe Reynolds numbers in excess of 3×10^5.

4.2.3.13 ***Critical (sonic) nozzle***

For a given nozzle, flow range is limited by the pressure range available for varying the mass flow while retaining the critical conditions at the throat. The uncalibrated uncertainty for different types of nozzle is generally quoted as 0.5 % over the throat Reynolds number range of 3.5×10^5 to 2×10^7. Linearity above a minimum Reynolds number, for a venturi nozzle throat Reynolds number of 10^5, is better than ± 0.5 % of rate. Providing the nozzle has a diffuser, the pressure recovery is high, resulting in a low head loss.

4.2.3.14 ***Elbow meters***

The flow range of elbow meters is the same as for any DP meter. The uncertainty for an uncalibrated device is high and has been shown to be around 4 % full scale. There is little data on linearity but the repeatability is reported to be as good as 0.2 % full scale. There is no additional pressure drop since an existing bend may be used as the meter.

4.2.3.15 ***Linear resistance (laminar) meter***

Calibration of these meters depends on a factor of r^4 for tube designs and similar figures for the plate and honeycomb devices. The uncalibrated uncertainty is likely to be moderate and they should always be calibrated for highest precision measurements. Uncertainty is around 2 % full scale because of the end effects.

4.2.4 Influence of fluid properties on applications

4.2.4.1 ***Dall tube®***

The meter can measure both liquid and gas and requires density knowledge for either volumetric or mass flow measurement. Viscosity effects are taken into account by Reynolds number. The effect of compressibility is similar to orifice plates. Two-phase flow can be a problem for Dall tubes® . Special purgable designs are available for slurry measurement, however gas-in-liquid in small volumes of less than 2 % can have a dramatic effect on the discharge coefficient as it breaks down the throat attachment mechanism. A step change of around 15 % in discharge coefficient is then possible. Abrasive particles in the fluid may cause problems by abrading and rounding the throat inlet, resulting in a progressive change in discharge coefficient. Providing the correct materials are used, chemical attack should not cause problems.

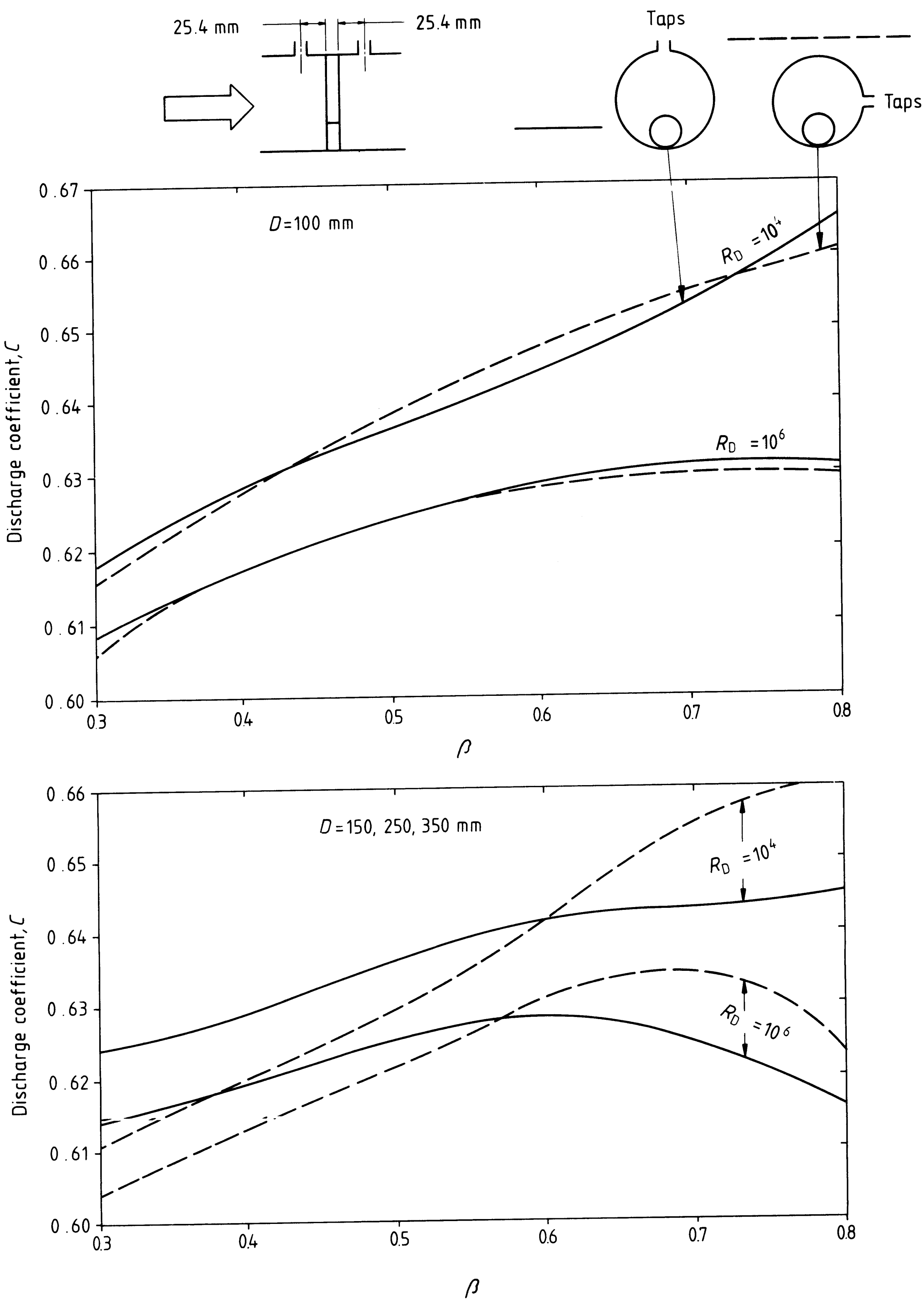


Figure 4.2.2 — Typical discharge coefficient curves for eccentric orifices showing effect of tap position

4.2.4.2 ***Epiflo meter***

The meter can be used on liquid or gas. The effect of compressibility on gas flow is important and is similar to that for an orifice. There is very little data on two-phase flow. As with the orifice plate, abrasiveness of the fluid is very important as it can affect the edges of the throat orifice causing large errors. Corrosion should not be a problem if the appropriate materials are used.

4.2.4.3 ***Gentile tube***

This device can be used for liquid or gas, but is probably more sensitive to two-phase components than basic meters, particularly with blockage of upstream tappings. It does not appear to be too sensitive to abrasive or corrosive fluids as there are no sharp edges.

4.2.4.4 ***Lo-Loss meter***

The Lo-Loss meter can be used on liquid or gas. Compressibility corrections are similar to a nozzle or venturi-nozzle. Because of the curved throat abrasive fluids do not affect the calibration. Similarly, with the correct materials, corrosive properties of the fluid are not important.

4.2.4.5 ***Wedge meter®***

The meter can be used on gas and liquid. Viscosity is accounted for in the Reynolds number. A particular feature of the meter, and its main design concept is its ability to deal with two-phase flow. It is recommended for use in the measurement of slurries. The meter is immune to abrasive fluids and generally to corrosive fluids if made of appropriate materials.

4.2.4.6 ***Segmental/eccentric orifice***

Both designs of orifice can be used on liquid and gas. Primarily their use is for fluids containing small quantities of a second phase, see Figure 4.2.2. Fluid compressibility has a small effect but there is data available for corrections. As with all sharp edge orifices, the calibration is severely affected by abrasive fluid attacking the edges. Chemical resistance can be obtained by correct use of materials.

4.2.4.7 ***Bypass meter***

Bypass meters can be used on both liquid and gas. Changes in density affect the meters because of variations in driving torque on the secondary flowmeter. Similarly, viscosity significantly affects the performance of both the orifice plate and the secondary bypass meter. The orifice is Reynolds number dependent and in addition, the turbine meter or Pelton wheel is highly Reynolds number dependent. In general this type of meter is not recommended for two-phase flow. Abrasiveness is also a problem both on the orifice plate edges and as a cause of damage to bearings. Similarly, care must be taken that the chemical properties of the fluid are compatible with all components.

4.2.4.8 ***Variable area (VA) meters***

VA meters can be used for liquid or gas, a different design of float being required for each application. Density is very significant in calibration as a particular float is used for a particular density range. Of greater importance is the fact that changes in density directly affect the calibration, a typical variation of 1 % in density changes the calibration by 0.5 %. There is a recommended upper limit of approximately 0.03 Pa·s depending on meter size before viscosity affects the calibration of the device. Compressibility is usually avoided by proper sizing. Two-phase flows are to be avoided because of adherence of the second phase to the float (or, in the case of gas-in-liquid, trapping of gas around the float), density and viscosity changes and opaqueness of fluid with glass meters. In general, abrasion and chemical aggression can be accommodated by appropriate material selection. Although filtration is not normally specified, magnetic filters are recommended upstream of magnetically coupled VA meters if the fluid contains ferrous particles.

Operating pressure and temperature are limited because of the design. Glass VA meters have upper pressure limits typically between 4 bar and 8 bar. This upper pressure limit can be increased by use of metal casings. Some VA designs can be operated at temperatures up to 350 °C.

4.2.4.9 ***Variable orifice***

These meters, which may be used for measuring both liquids and gases, have found wide application in steam measurement. Because of density dependence the meters may have to be calibrated on fluid of similar physical properties to the process fluid. In general they are less affected by viscosity and so are very good for high viscosity fluids such as heavy fuel oil. Compressibility of gases have to be taken into account, usually in the form of a manufacturer's correction. There is little data on two-phase flow performance. Chemical and abrasive properties of the fluid are very important. In particular the internal spring may be subject to chemical attack if the material is not suitably chosen. Temperature changes may result in differential expansion of components which will introduce systematic errors.

4.2.4.10 ***Pitot and pitot-static tubes***

They can be used on both liquid and gas, but the most common use is for air measurement in large ducts. Density affects them in the same way as other DP devices. Only at low Reynolds number does viscosity become important and affect the calibration. At high gas velocities compressibility becomes a major influencing factor. Abrasive and chemically aggressive fluids can usually be accommodated by appropriate material selection.

4.2.4.11 ***Averaging pitots***

They can be used for both liquid and gas measurement. Density effects are similar for all DP devices. Viscosity is accounted for in the Reynolds number variations of the meter. Compressibility of gases affects the calibration, with the data to make the appropriate corrections available from the manufacturer. Abrasive and chemically aggressive fluids can be accommodated by appropriate choice of materials. These meters have a flow factor that is temperature dependent to a small degree.

4.2.4.12 ***Inlet meters***

With the exception of the Borda inlet, which has sharp edges, nozzles and similar meters may be used for measuring abrasive fluids.

4.2.4.13 ***Critical (sonic) nozzles***

The critical nozzle is only used for gas applications. Its discharge coefficient is a function of both the geometry of the device and its Reynolds number. The mass flow rate through a critical nozzle depends on the upstream density and also on the thermodynamic properties of the gas being metered. Hence, in addition to the gas composition, the meter upstream stagnation pressure and temperature should be measured in order that the mass flow may be calculated correctly.

4.2.4.14 ***Elbow meters***

Elbow meters can be used on liquid or gas. There is very limited data on viscosity effects and the compressibility factor is assumed to be close to unity. Two-phase flow will cause problems and elbow meters are not recommended for this application. Fluid abrasiveness and chemical aggressiveness will not be a problem if the appropriate materials of construction are used.

4.2.4.15 ***Linear resistance (laminar) meter***

The meter can be used for liquid or gas measurement, the latter being the more common. The fluid should be clean or adequate filtration should be provided.

4.2.5 Influence of installation on applications

4.2.5.1 ***Dall tube®***

Orientation is only a problem with slurries and two-phase flow where the pressure tappings should be carefully positioned to avoid fouling or blockage. Dall tubes® are normally uni-directional and must be installed with the diffuser downstream. Special Dall tubes® have been made which are bi-directional but these are not common. The effect of pipe configuration is similar to equivalent area ratio orifice plates, and the recommended installation conditions would be similar. The same is true for valve positioning and pulsations.

4.2.5.2 ***Epiflo tube***

The meter is uni-directional with the diffuser always downstream. It is claimed to be less affected by upstream disturbances than any other low loss meter.

4.2.5.3 ***Gentile tube***

Orientation can be a problem for dirty fluids as it is difficult to place the meter such that the tappings are away from the top or bottom. It is slightly prone to the effects of poor velocity profile caused by upstream fittings. An outstanding feature compared to most other DP meters is that this device is capable of bi-directional flow applications.

4.2.5.4 ***Lo-Loss meter***

The meter is uni-directional with the nozzle upstream. Pipework requirements are the same as for the nozzle (see **4.1**).

4.2.5.5 ***Wedge meter***

The orientation of the meter will be dependent upon the fluid. If there are particles heavier than the fluid, then the wedge should be at the top of the pipe, if there is gas in the liquid then the wedge and tappings should be towards the bottom, see Figure 4.2.3. The wedge is bi-directional. There is little data available on the effect of pipe fittings, but it would appear that the effect is similar to equivalent area ratio orifices.

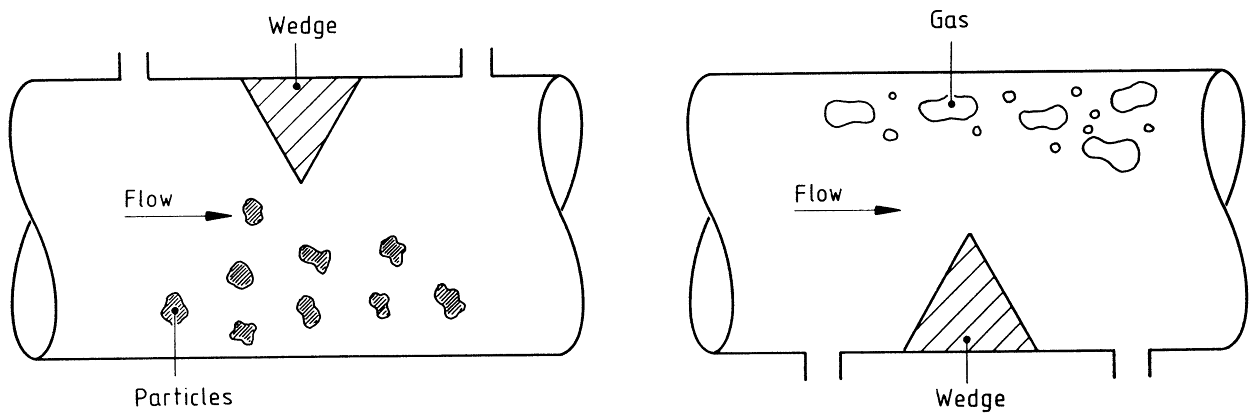


Figure 4.2.3 — Influence of fluid properties on wedge meter orientation

4.2.5.6 ***Segmental/eccentric orifice***

Orientation is very critical both in relation to flow and pressure tappings. With flow where the fluid is gas-in-liquid or where there are particles present which are lighter than the process fluid, the aperture has to be mounted at the top of the pipe. If the particles are heavier, then the aperture has to be at the bottom, see Figure 4.2.2. Installation of the orifices is critical, as the apertures are tangential to the pipe bore and should not be covered by the pipework or protruding gaskets. The requirements for the pipework configuration are the same as for concentric orifices.

4.2.5.7 ***Bypass meter***

Because a square edge orifice is usually the main meter, they are uni-directional with the square edge upstream. The secondary meter is normally vertically orientated or at 45° so that particles or gas-in-liquid cannot enter the bypass meter. Generally the pipework design is the same as for the basic orifice plate.

4.2.5.8 ***Variable area (VA) meter***

VA meters have to be mounted vertically and are uni-directional. Pipe vibration can cause readability problems, as does pulsating flow, in both cases the float will oscillate. Upstream pipe conditions are relatively unimportant, but control valves should always be on the outlet.

4.2.5.9 ***Variable orifice***

Orientation may be important as the effect of the weight of the spring loaded core will alter the zero flow position. This is not true of all types. In general they are uni-directional. Vibration can be a problem if the spring loading is not damped sufficiently, similarly pulsating flow can cause dynamic instability of the spring loaded core. Pipe configuration is slightly less important than for basic orifices, however the data for orifices is a good guide.

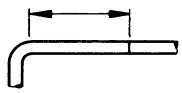
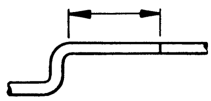
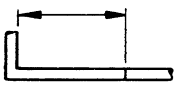
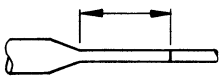
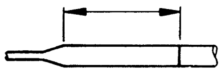
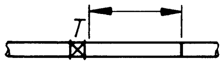
4.2.5.10 ***Pitot and pitot static tubes***

Orientation is unimportant, but flow direction is critical. Both types are uni-directional and alignment of the pitot tube will affect the calibration. It is usual to carry out alignment by sweeping the tube through an arc and finding the maximum velocity. In this way it is possible to determine whether there is swirl in the pipe. Vibration or pulsations can cause severe problems and errors. If the tube is excited either by the pipe or flow induced vibrations (such as vortex shedding) the readings may be in error. Pipe configurations may be a source of large errors if proper flow profiling is not carried out.

4.2.5.11 ***Averaging pitots***

Orientation is only important if there is concern over the content of the fluid. If gas-in-liquid or heavy particles are present the device should be mounted horizontally. This is the preferred installation for steam metering. It should be remembered that most types are uni-directional. Flow induced and pipeline vibration can both be a problem, but there are variations in design to support the meter and reduce these effects. Alignment limits and orientation recommendations are summarized in Figure 4.2.4. Calibration is affected by adverse upstream conditions; to achieve the stated performance certain criteria have to be met for the distance of fittings upstream. Recommended upstream pipe lengths are given in Table 4.2.1. Servicing is relatively simple as withdrawing the sensing tube from the line under flowing conditions can be achieved via a stop valve arrangement as shown in Figure 4.2.5. Pulsating flow affects the meter as described for other DP meters.

Table 4.2.1 — Typical upstream pipe lengths for multi-port averaging pitots

	Without straightener		With straightener	
	In plane	Out of plane	In plane	Out of plane
	7	9	6	6
	9	14	8	8
	19	24	9	9
	8	8	8	8
	8	8	8	8
	24	24	9	9

4.2.5.12 ***Inlet devices***

The major installation constraint arises from flow conditions local to the inlet. As these are usually open, protection should be provided to avoid cross-winds, or the proximity of any obstruction. Usually the inlet is surrounded by a mesh cover to help to reduce the effects of interference.

4.2.5.13 ***Critical (sonic) nozzle***

Orientation is not important for critical flowmeters. They are uni-directional with the nozzle inlet upstream. They are not as prone to disturbances from upstream pipe fittings as DP devices although, because they are used in high performance applications as transfer standards, every care should be taken to ensure the flow into the nozzle is fully developed.

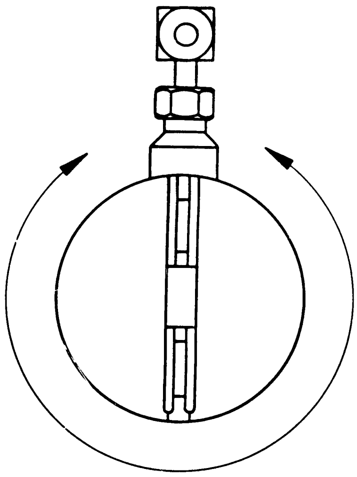
4.2.5.14 ***Elbow meters***

Pipe configuration should be the same as for high area ratio venturi tubes. There is very little data on the effects of flow pulsations.

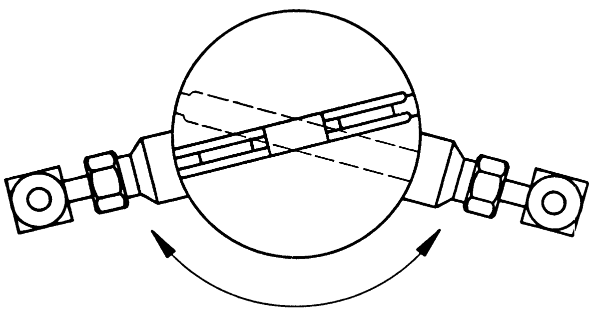
4.2.5.15 ***Linear resistance (laminar) meters***

There is relatively little installation effect data. The smaller devices have a relatively good immunity to upstream pipework effects, and the larger types usually require at least 10 pipe diameters upstream of the meter. Alternatively an inlet mesh, which may be part of the device, can reduce this length.

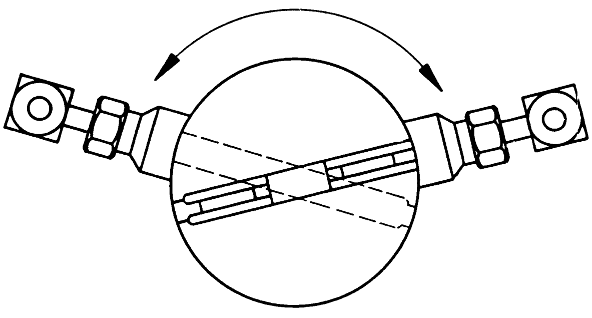
Position on pipe. Devices can be installed in any position on the pipe, 0° – 360°, (except steam). However for optimum result see below:



(a) Vertical lines:
Devices can be installed in any position on vertical lines.

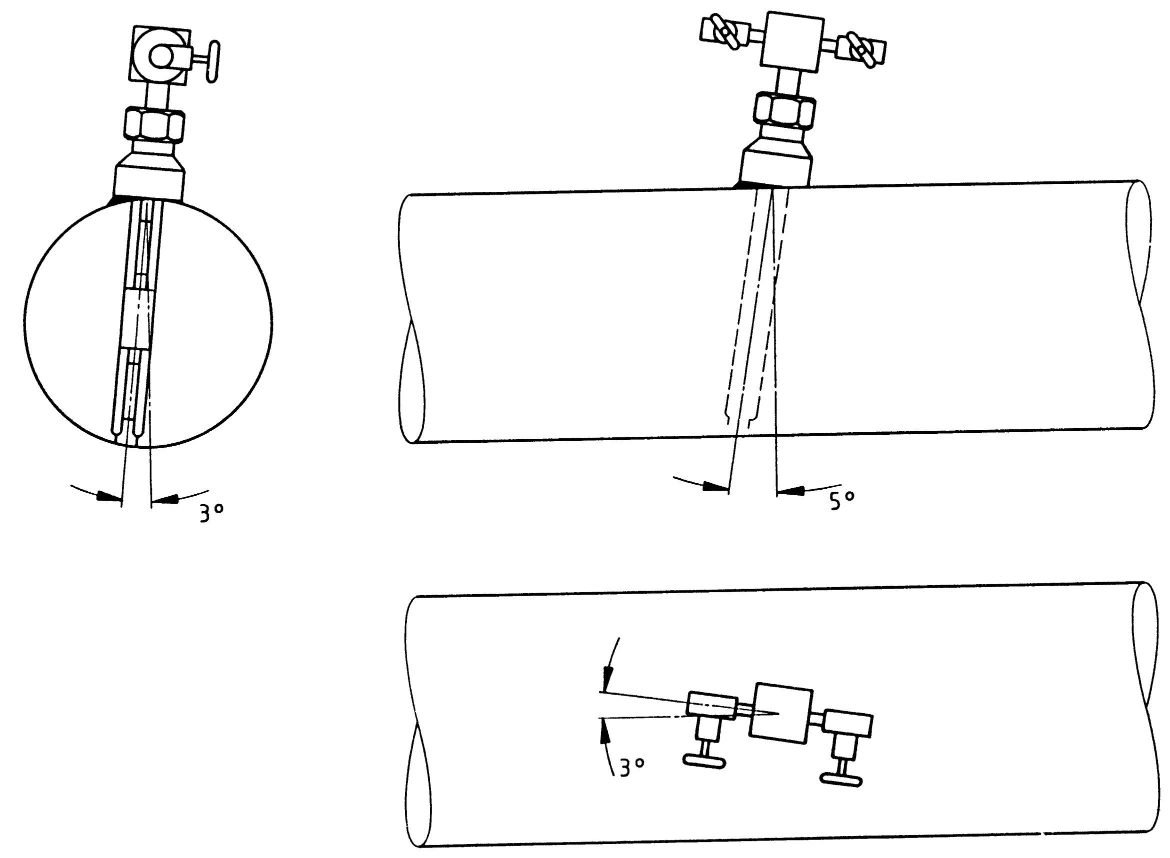


(b) Horizontal lines:
For liquid flow, insures full instrument lines and eliminates air/gas entrapment.



(c) For gas flow, prevents moisture or condensation from entering connecting lines.

Figure 4.2.4 — Installation guidelines for multi-port averaging pitots



(d) Permissible misalignment
Devices can be installed in any position on vertical lines

Figure 4.2.4 — Installation guidelines for multi-port averaging pitots *(concluded)*

4.2.6 Environmental influences on applications

Generally the environmental influences on most meters in the group are the same as for the standard DP meters as discussed in **4.1.6**. There is however one exception, namely in the case of the bypass flowmeter where its characteristics should also be taken into account. These can be found in the appropriate section of this guide.

4.2.7 Economic influences on applications

4.2.7.1 *Dall tubes*

To achieve an uncertainty better than 2 %, Dall tubes should be calibrated, to determine both the discharge coefficient and linearity. The major difference between the Dall tube® and the standard DP devices is running cost. The reduced pressure loss incurred, particularly on large sizes, can lead to significant savings in pump costs. As it is shorter than a venturi tube, installation and capital costs are less.

4.2.7.2 *Epiflo tube*

It is recommended that the device is calibrated. As it is a sharp-edged device, similar to an orifice, the edge has to be checked regularly to maintain a low level of uncertainty. Installation costs are low as the unit is clamped between flanges. Space should be provided for the insertion and withdrawal of the primary element. The pressure loss is moderately low with consequent saving in pump power. The meter is claimed to be less sensitive to upstream fittings and this should help reduce installation costs.

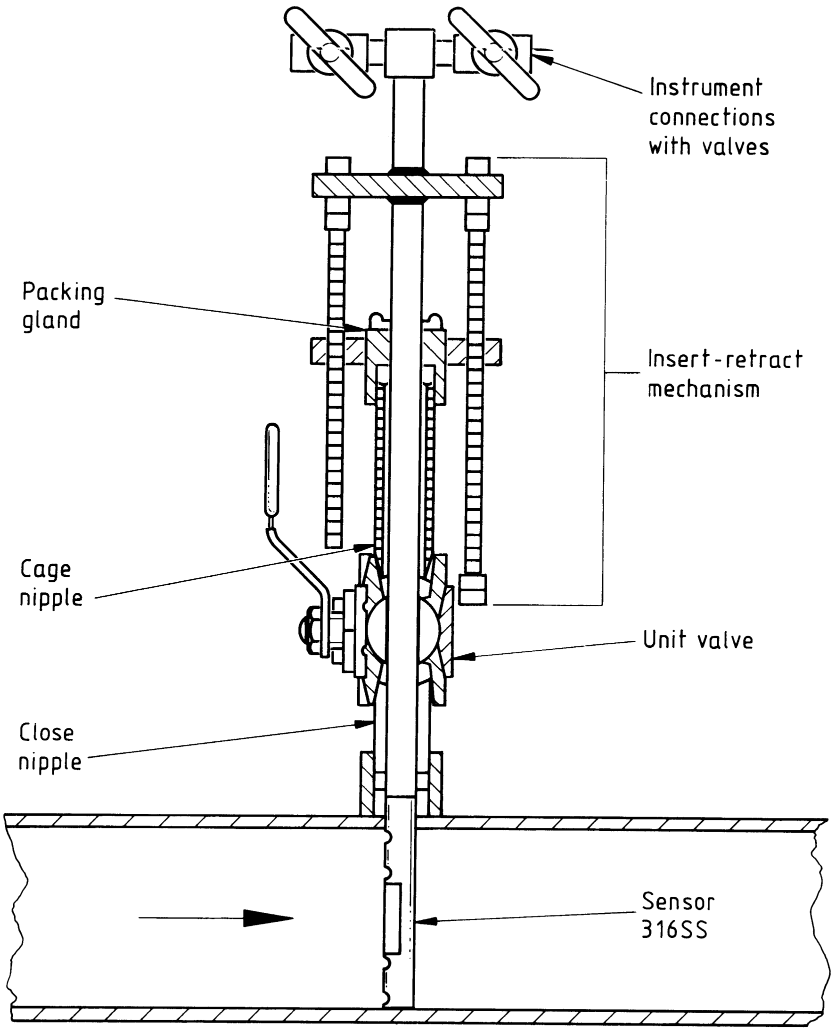


Figure 4.2.5 — Removable installation of a multi-port averaging pitot

4.2.7.3 ***Gentile tube***

It should always be calibrated. As the tube is short (1.5 *D*), installation into a pipe is relatively simple. In terms of the ratio of pressure loss to differential pressure, though not as good as a Dall tube®, it is better than a venturi (see Figure 4.1.1).

4.2.7.4 ***Lo-Loss meter***

The meter is difficult to manufacture because of the machining of the inlet curvature and the positioning of the throat pressure taps. Thus the meter should always be calibrated. The major economic advantage is the saving of pump power by reduction of pressure loss.

4.2.7.5 ***Wedge meter®***

The meter should be calibrated. It has the disadvantage of being very long, making high pressure and large sized meters more expensive than an orifice meter. However, particularly for smaller sizes of meter, construction is relatively easy. Its pressure loss is similar to equivalent area ratio orifice plates. The outstanding features are the low Reynolds number effects and the ability to measure slurries.

4.2.7.6 ***Segmental/eccentric orifices***

The same economic influences on applications discussed in **4.1.7** for concentric orifice meters apply.

4.2.7.7 ***Bypass meter***

The major economical advantage is the increased flow range of the main meter (orifice) without the use of extra orifices or DP cells and electronics. Meter life is shorter than ordinary DP meters because of the introduction of moving parts in the secondary meter. The pressure drop is as high as that for ordinary orifice plates, thus there are no pumping power benefits, other than that gained by the need for only one area ratio orifice for a large flow range. The meter should be calibrated on a fluid very similar to the process fluid, potentially a costly procedure.

4.2.7.8 ***Variable area meter***

This meter is a low cost device requiring very little maintenance. Installation costs may be high because of the pipework required to mount it vertically. The pressure drop across it can also be relatively high.

4.2.7.9 ***Variable orifice meter***

The meter is generally large and complex and, in consequence, expensive to manufacture. The pressure loss is high but the main economic advantage is in its large flow range.

4.2.7.10 ***Pitot and pitot static tubes***

The pitot and pitot static tube are among the lowest cost meters for installation, maintenance and initial costing. They can be routed into the pipe via a valved-branch welded into the pipe and can easily be removed for service. Pressure loss is very low.

4.2.7.11 ***Averaging pitots***

This is one of the more cost effective flowmeters currently available. Maintenance costs are low because of the ease of withdrawal of the meter from the pipe. Calibration is necessary in order to achieve an uncertainty of less than 1 %, but pressure loss is low.

4.2.7.12 ***Inlet devices***

The pressure loss is low and the meters are relatively inexpensive to manufacture. Calibration may prove to be expensive.

4.2.7.13 ***Critical (sonic) nozzles***

Sonic nozzles are very expensive to manufacture due to the complex curvature of the inlet, and the contouring between the throat and diffuser. Surface finish is also important. Calibration, if required, is very expensive as high performance gas calibration is a costly exercise. Pressure loss is low when a diffuser is fitted. To obtain a reasonable flow range, several nozzles should be used.

4.2.7.14 ***Elbow meters***

Elbow meters are very economical and introduce no additional head loss because they can be used as a bend or as a replacement for an existing bend. However the bend should be manufactured to a very high standard with correct dimensions, (see Figure 3.2.14), a constant diameter and the pressure tappings in line. For accurate measurement the elbow meter should be calibrated.

4.2.7.15 ***Linear resistance (laminar) meter***

Laminar meters are relatively expensive to construct and pressure loss is high. However, they have the economical advantage of a wide flow range. The fluid should be clean and filters may be necessary. Maintenance costs may be higher than for some other types of meter.

4.3 Group 3 meter applications: positive displacement (PD) types

4.3.1 General

Positive displacement metering is one of the oldest flow measurement methods currently available. Fluids were extensively measured by rotary and reciprocating piston meters in the last century and the number of applications in which these types of meters can be used is increasing. The whole group is characterized by industrial ruggedness and they find applications from domestic gas metering up to corrosive and highly viscous liquids. In terms of performance some types of positive displacement meters are among the best flowmeters currently available and a major application is in fiscal fluid measurement.

4.3.2 General applications

The many designs found in this group allow PD meters to be applied over a wide range of flow applications. While performance claims are often extravagant, usually as a result of commercial pressure, applications advice is generally widely available and is based on years of experience. Good quality meters are capable of maintaining a high level of performance for long periods without adjustment or maintenance. Often displacement meters are self-contained and require no external power to measure the quantity of fluid used. A good example is the diaphragm domestic gas meter. Although this contains many components, it is amongst the most reliable of all flowmeters, often giving repeatable performance over many years.

Because some types of PD meters require periodic maintenance, they should not be considered in those special applications where no servicing is permitted. The metering of radioactive or toxic fluids is therefore best performed with flowmeters with no moving parts (groups 5, 6 or 7 for example).

The principle of operation of the meters have been established for many years and the majority of developments in recent years have been related to advances in manufacturing and materials technology and, most importantly, to enhancement of meter performance by the application of electronics. The use of microprocessors and high resolution pulse transmitters/shaft encoders allows the meter error curve to be corrected to datum or close to datum over the complete flow rate range. While the potential to enhance meter performance by the application of modern electronics and fibre-optics is immense, a word of caution is necessary. It is essential that the device in question has the inherent repeatability for the proposed application. Electronics cannot enhance a basic poor performance. The advent of low cost, programmable electronic memory has made it possible to record both transaction data and, under passcode entry, evidence of meter over-speeding and other operator malpractice.

Displacement meters are widely used in legal metrology and in custody transfer applications, i.e. those applications in which the meter reading is an element in a contract between buyer and seller. Some legislation, e.g. European Directive 71/319/EEC "Meters for liquids other than water" is worded such that only positive displacement devices can be used. Jelffs (1982) reviews their characteristics for crude oil and petroleum product applications and further details can be found in the API Manual of Petroleum Measurement Part 5 (1977).

In the UK, retail metering pumps (e.g. petrol pumps) are prescribed under the Weights and Measures Act 1963 as amended and pattern (type) approval is given in accordance with the provisions of Section 12 of the Act. Petrol pumps incorporate exclusively positive displacement meters of the reciprocating piston type. In service the meter performance is checked both periodically and following a customer complaint by local Trading Standards Officers. It is worth noting that, in legal metrology terms, the complete petrol pump is designed as a flowmeter.

Some of the more common positive displacement meter applications are as follows.

a) **Reciprocating piston meter**

Petrol, diesel and LPG dispensing; both retail and non-retail

Barrel filling, usually with repeat preset mechanism

Engine test beds

Beer dispensing

Refrigerants

Chemical process plants

Oderant injection

Automobile fuel consumption measurement

b) **Rotary piston/oval gear/nutating disc/helix meter/BI and tri-rotor**

Legal metrology and fiscal metering, mainly hydrocarbon fuels and oils

Truckmeters for dispensing heating oils

Water metering, hot and cold

Hygienic and sanitary applications

Liquified gases

Gas metering, (servo-driven oval gear meter)

Chemical process plants

Lubrication oil blending

c) **Sliding vane meter**

Fiscal metering, mainly hydrocarbon fuels and oils

Reference or master meters

Audit metering to compare calibration facilities

Lubricating oil blending

Engine test beds

Truckmeters

d) **Liquid metering pumps**

Medical process and research applications

Dosing, additive and dye injection

Pharmaceutical and cosmetic process plants

Food and beverage manufacturing

Plastic manufacture

e) **Roots meter®**

Gas production and transmission

Chemical and process plants

Legal metrology

Reference standards

f) **Wet gas meters**

Flow measurement laboratories

Reference meter

g) **Diaphragm/bellow meters**

Domestic and commercial metering of natural gas

Automobile fuel consumption

4.3.3 Influence of meter performance on applications

Owing to its relative bulky size the positive displacement meter has lost ground in recent years to the turbine, vortex shedding and electromagnetic meters, particularly for high flow rate applications. It remains unmatched for many applications as a result of its repeatability, linearity and long-term stability. It dominates legal metrology metering applications and is unlikely to be displaced in the foreseeable future.

As a result of their mechanical construction, positive displacement flowmeters have comparatively high pressure drops. For an equivalent flow rate, the pressure drop will be higher for this type of meter than for the turbine meter and other intrusive devices and considerably higher than for non-intrusive meters which may have losses no higher than the equivalent pipe length. Pressure drop will increase with the number of mechanical ancillary devices driven by the meter. This increased loss is often acceptable for a self-contained metering system requiring no external source of power.

The overall uncertainty of PD meters varies from 0.1 % to 5 % of reading over flow ranges from 10 : 1 to over 100 : 1 but it is costly to over specify the range. It is important not to over specify the need at the expense of cost. It is also important to correctly size the meter to keep pressure drop to an acceptable value. If high vapour pressure liquids are being metered, excess pressure drop will cause cavitation within the meter, resulting in eventual damage to critical components if this condition is allowed to persist. Some designs permit overspeeding of up to 120 % of the maximum rated flow for short periods. Where this occurs the suppliers advice should be sought.

Such is the wide range of PD meters available, that there is no real restriction of application due to performance limitations.

4.3.4 Influence of fluid properties on applications

4.3.4.1 *General*

While performance generally does not limit applications, the properties of the fluid being metered certainly do. It is important to choose the correct design for the fluid. Liquid PD meters are unsuitable for gases and vice-versa. All types of PD meters suffer when two phases are present and they should not be subject to steam cleaning unless specially designed to do so. It is therefore important to ensure that the meter is working in single phase fluids only. It is also prudent to check that the materials of construction on high quality vane meters are compatible with the fluid. The chemical electrolytic nature of the fluid will also determine whether internal corrosion deposition and wear will occur. Designs are available using corrosion resistant materials. In the application to water based fluids, performance is enhanced by the addition of small quantities of water soluble oil to lubricate the internals.

Particulate matter cannot be tolerated in some designs without subsequent reductions in performance. Other types such as the nutating disc or rotary piston meters can be supplied with metering elements which will tolerate small quantities of particulate matter. Provided these do not become lodged between moving parts the meter should perform satisfactorily.

4.3.4.2 *Pressure and temperature*

Limitations on pressure and temperature result only from economic and structural integrity considerations. Suppliers' literature usually states the maximum working pressure for a meter. The statement may be qualified by the words "cold, non-shock". While there may be a large safety factor, it is important that the maximum pressure rating is not exceeded. In particular, equipment should be protected against shock pressures by slow opening and slow closing valves and, if necessary by shock alleviators. It is important that accumulator type shock protectors are matched to the system and do not cause spurious meter readings.

4.3.4.3 *Density and viscosity*

Viscosity and fluid lubricating are particularly important in liquid meters where performance and flow rangeability will be affected. Some displacement meters can be used on fluids with viscosities as high as 500 Pa·s. Such fluids only just flow and this group of meters are the only type that will meet these applications. The pressure drop through the meter is a strong function of viscosity, Figure 4.3.1 shows such a curve for oval gear displacement meters. This shows high pressure loss at high viscosities and may affect system efficiency unless allowed for in the complete design of the plant.

Sometimes corrections can be applied for a meter initially proved on one fluid but used on another. For example Table 4.3.1 shows the variations between kerosene and other hydrocarbons for a sliding vane meter.

It should also be remembered that viscosity is strongly temperature dependant and therefore additional corrections should be applied for operation at the service temperature.

Table 4.3.1 — Correction factors for a sliding vane meter for different fluids

Product	Approximate viscosity at test temperature	Correction factor
	m^2/s	%
gasoline	5.5×10^{-7}	+ 0.1
white spirit	1.75×10^{-7}	0
gas oil	5.5×10^{-6}	– 0.1
fuel oil	3.6×10^{-5}	– 0.22

4.3.4.4 *Compressibility*

This is important in gas metering. Most gas displacement meters run with very low pressure drops, even at maximum flow. Again the user should work closely with the supplier to ensure that the application is not introducing significant compressibility effects in the meter. Measurement uncertainty will increase in those applications where this occurs.

4.3.5 Influence of installation on applications

4.3.5.1 *General*

As a result of the mechanism of physically dividing the flow into discrete pockets, the positive displacement meter is, in general, very tolerant of both upstream and downstream flow conditions. Meter performance is largely unaffected by velocity profile, swirl or other flow disturbances, with the exception of pulsating flow. This allows particularly economic fluid handling systems to be designed since straight pipe lengths upstream and downstream of the meter are not required and other devices such as valves or flow controllers can be mated to the meter inlet and/or outlet flanges without degrading the meter performance.

Meters may be fully bi-directional, uni-directional or may allow reverse flow at a reduced level of performance. It is essential to obtain the suppliers' recommendations for any unusual potential installations and for flow directions other than those marked on the meter. Pipework should be arranged such that the meter is full at all times, since rapid corrosion may occur at liquid/air interfaces.

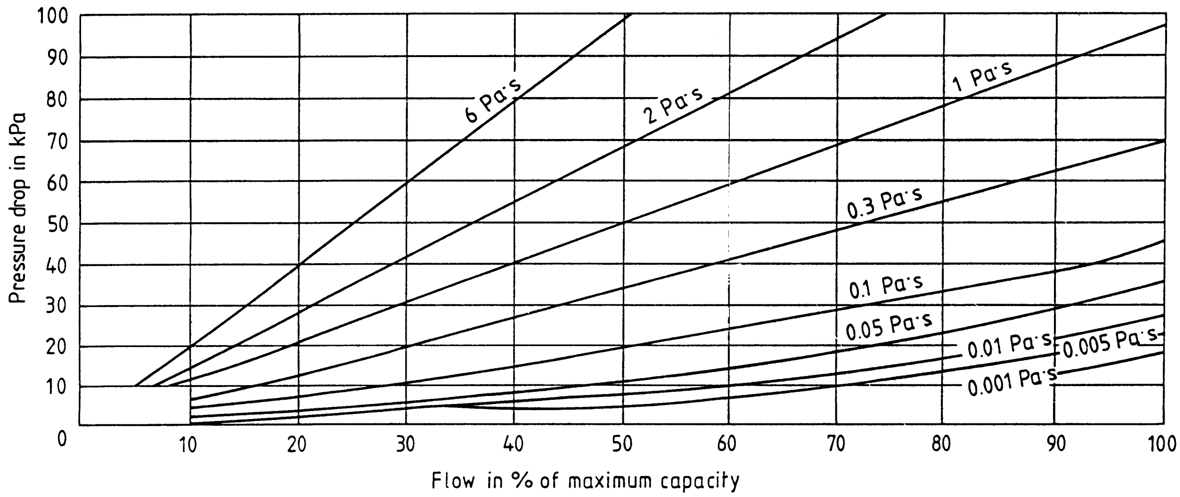


Figure 4.3.1 — Effect of viscosity on the pressure drop of an oval gear meter

4.3.5.2 *Pressure and pressure drop*

Pressure gauges or differential pressure gauges are usually fitted to monitor the condition of ancillary equipment, e.g. strainers or filters, rather than to measure true pressure drop. The measurement of pressure drop can be useful for diagnosing both meter and system problems. A useful rule-of-thumb is to take pressure tappings via a piezometer ring, 5 *D* upstream and 10 *D* downstream of the metering section and to connect these to a differential manometer or differential pressure gauge. The flow rate versus pressure drop relationship is of the form $\Delta p = Kq_v^n$. An idealized plot of Δp against q_v may not appear significant but a plot of the linearized relationship $\log \Delta p = \log K + n \log q_v$ may be revealing. A change in slope of the line may indicate malfunction of a system component or the mismatch of the various elements in the system. Pressure gauges are available with adjustable low level and high level trips to initiate automatic shutdown of the system in the event of a malfunction.

4.3.5.3 *Installation pitfalls*

Positive displacement meters can be damaged by pulsating flow and the pressure source should ideally be a centrifugal pump or a gravity head. If the use of a reciprocating pump is essential, the meter should be protected by an accumulator or shock alleviator. The meter may be irreparably damaged by overspeeding and if the system pressure will allow flow rates significantly in excess of the rated maximum flow rate of the meter, a flow controller or other excess flow protection should be provided. This is particularly important, for example, in hygienic meter applications where in-line sterilization is used.

Meters should always be installed on the discharge side of the pump though, in some limited applications, meters will operate successfully in the suction line. Metering pumps operate more effectively when supplied with a positive suction head, typically, from a header tank.

It is important when designing a metering system that consideration is given to access for maintenance. It is particularly embarrassing for example, to find when the installation is completed that the filter basket cannot be removed due to insufficient headroom. Servicing accessibility considerations should therefore include all components in the metering installation and not just the meter. Meters may be installed in parallel for high flow rate applications and, with automatic changeover provision, to provide for system redundancy in continuous process or critical metering applications.

Meters can be damaged by pipework stresses and care must be taken to ensure that pipework is correctly aligned and allowance is made for thermal expansion, if appropriate. Some installation pitfalls are summarized in Figure 4.3.2.

4.3.5.4 ***Overall system design***

When designing high performance metering systems, displacement meters are installed with ancillary equipment to safeguard the life and performance of the meter. Figure 4.3.3 illustrates a typical metering system with some of the more common elements. This also shows the compactness of such a complete system.

4.3.6 Environmental influences on applications

While the volume measuring elements of positive displacement meters are largely unaffected by environmental conditions, the meter and metering system should be protected from the effects of corrosion resulting from atmospheric pollution, humidity and, for example, the hosing down or steam cleaning of the plant. In particular, electrical/electronic equipment enclosures must provide protection against corrosion and the ingress of moisture and foreign bodies. The various levels of protection afforded by equipment enclosures are defined in terms of the Index of Protection (IP) by BS 5490. Examples of minimum levels of protection are:

Control rooms	IP 22
Sheltered external sites	IP 44
Unsheltered external sites	IP 56
Sites where immersion is possible	IP 68

Positive displacement meters are frequently installed in electrically noisy environments and must be protected where appropriate from mains-borne, radiated and static interference. Those mechanical meters fitted with mechanical readouts are unaffected by electrical interference. PD flowmeters, in common with other measuring instruments must also be protected against the effects of temperature and humidity variations, vibrations and equipment abuse.

Instruments prescribed under the Weights and Measures Act (1963) are required to meet Design Assessment Criteria defined by the National Weights and Measures Laboratory. Tests are carried out to assess immunity to power supply variations and interruptions, transient voltages, electrostatic discharges, RFI, vibrations and temperature and humidity variations.

Error checking circuits are required and an automatic 8's check of segmental displays before each transaction is mandatory. A code of practice prepared by the Institute of Petroleum "Petroleum measurement manual" (1983) gives guidelines on the protection of measuring equipment against electrical interference.

If a metering section is subject to temperature variations, for example due to sunlight, and the meter is situated between two valves which may be closed, then a pressure relief valve should be provided in the metering section. Thermal insulation is recommended in extreme sunlight or extreme temperature change locations.

Hazards due to static electricity can arise from the movement and storage of liquids. All liquids handling installations should be designed to ensure that hazards are assessed and controlled and particular attention should be paid to earthing and continuity. Flowmeters featuring any form of electrical or electronic device which are to be used in a flammable atmosphere must employ some form of explosion protection. In the UK equipment is usually certified by BASEEFA[2)] for the relevant hazard zone or may have some alternative certification acceptable to BASEEFA.

[2)] British Approvals Service for Electrical Equipment in Flammable Atmospheres.

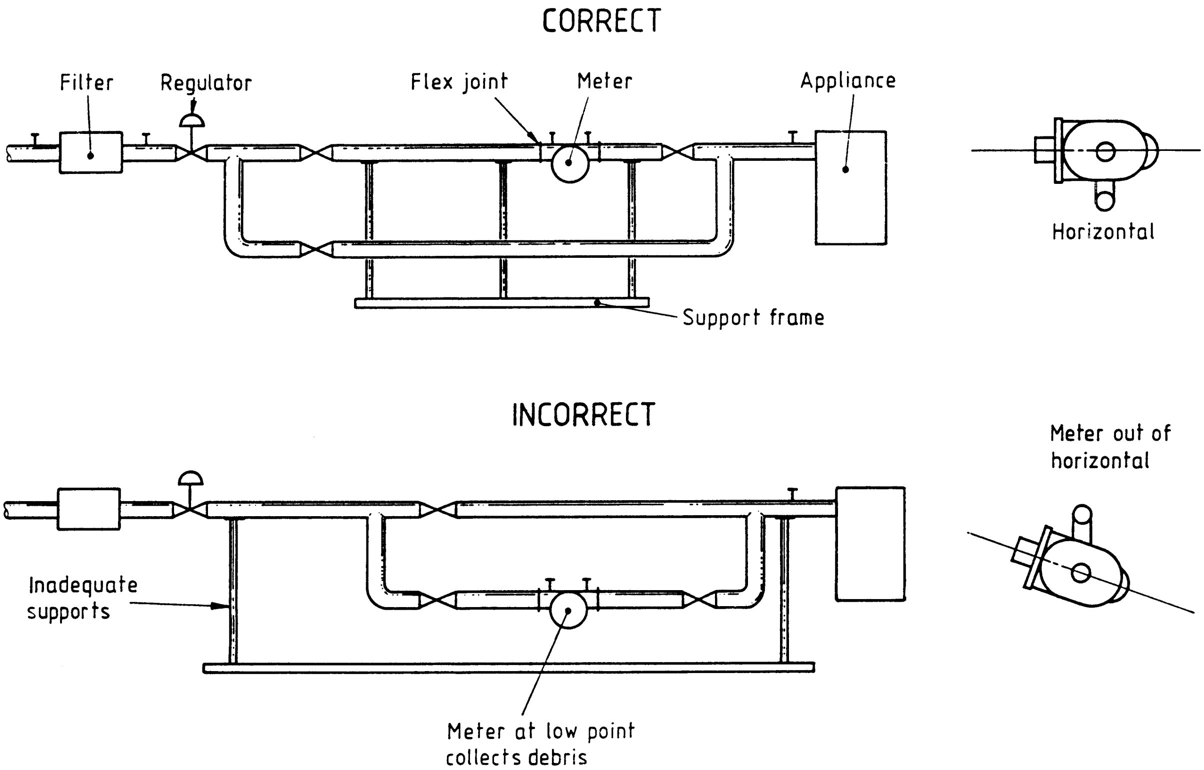


Figure 4.3.2 — Common installation pitfalls for positive displacement meters

4.3.7 Economic influences on applications

Positive displacement meters are relatively expensive when throughput of flow is considered. They do however offer very high performance and the potential user should carefully assess whether performance is a main parameter for selection. If it is, then PD meters present a good choice. With their tight tolerances they are higher in cost maintenance terms than other forms of meter. The routine changing of mechanical gears, shafts and other components located outside the body is straightforward but if sensing elements, gaskets, rollers and bearings inside the body require attention the line has to be closed down unless a bypass is provided. Most routine maintenance is best performed by skilled technicians.

Stocking of spare parts varies with design. Designs such as diaphragm meters are stocked as complete meters but the vane, rotary, oval gear and helix types require rotors, bearings, and electronics spares to be kept.

Calibration costs range from low for simple consumption meters to high for the more precise metering installations such as those on custody transfer applications. Here extra pipework connections and proving valves should be provided to enable in situ calibrators to be connected in series. Such an arrangement is shown in Figure 4.3.4.

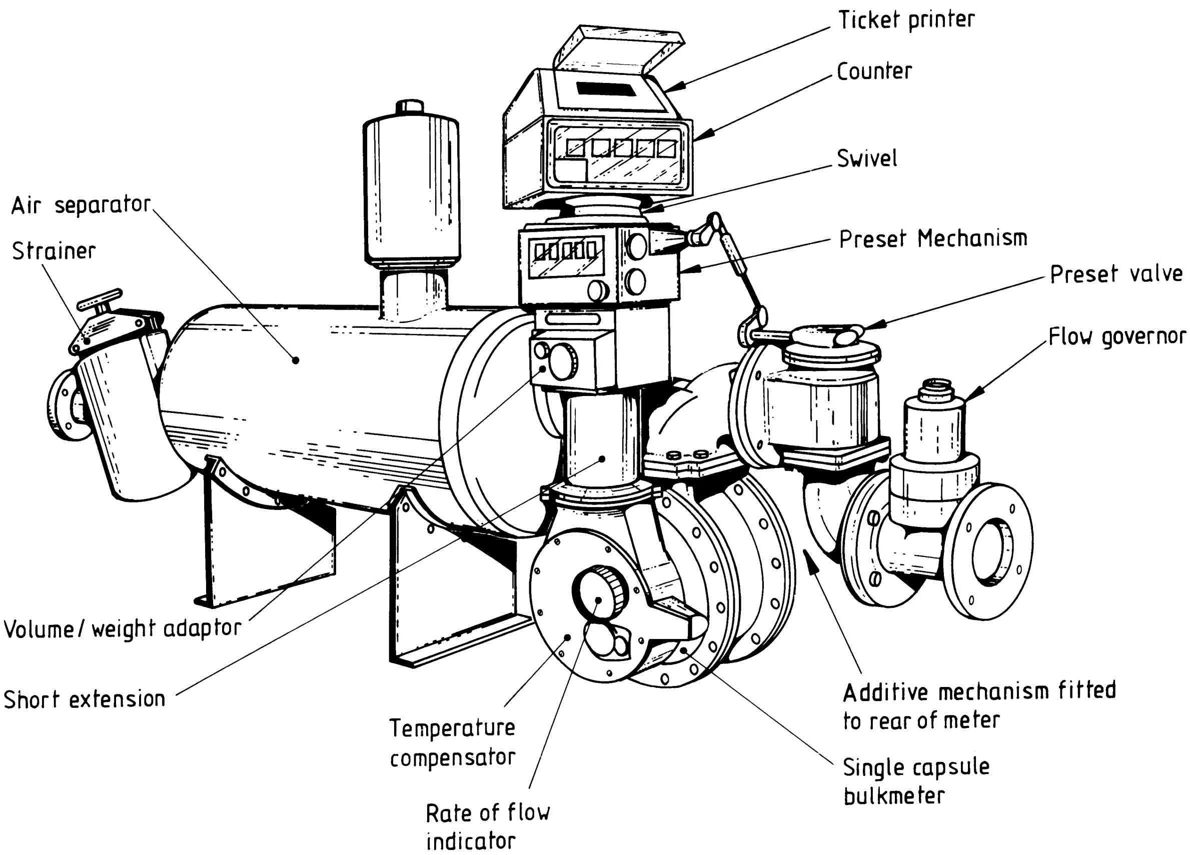


Figure 4.3.3 — Typical high performance metering installation

4.4 Group 4 meter applications: rotary turbine types

4.4.1 General

Even though the meters within this group contain moving parts and are affected by fluid properties, the group contains some of the highest performance meters currently available. The technology on which they are based has been developed over many years and as a result they have become accepted within well defined application rules. This section reviews the applications of these meters and gives details of the strengths and weaknesses which can be matched against application requirements. The more common types such as turbines have more information on basic applications and the limits are fairly well defined. Others within the group are treated but in some cases the applications are less well defined.

4.4.2 General applications

4.4.2.1 ***Applications of axial turbine meters***

Applications depend on basic characteristics which include:

a) low uncertainty and good linearity;

b) wide flow rangeability and relatively low head loss for high throughputs;

c) applicability over wide pressure and temperature range;

d) pulse output, making interfacing to modern electronics relatively straightforward;

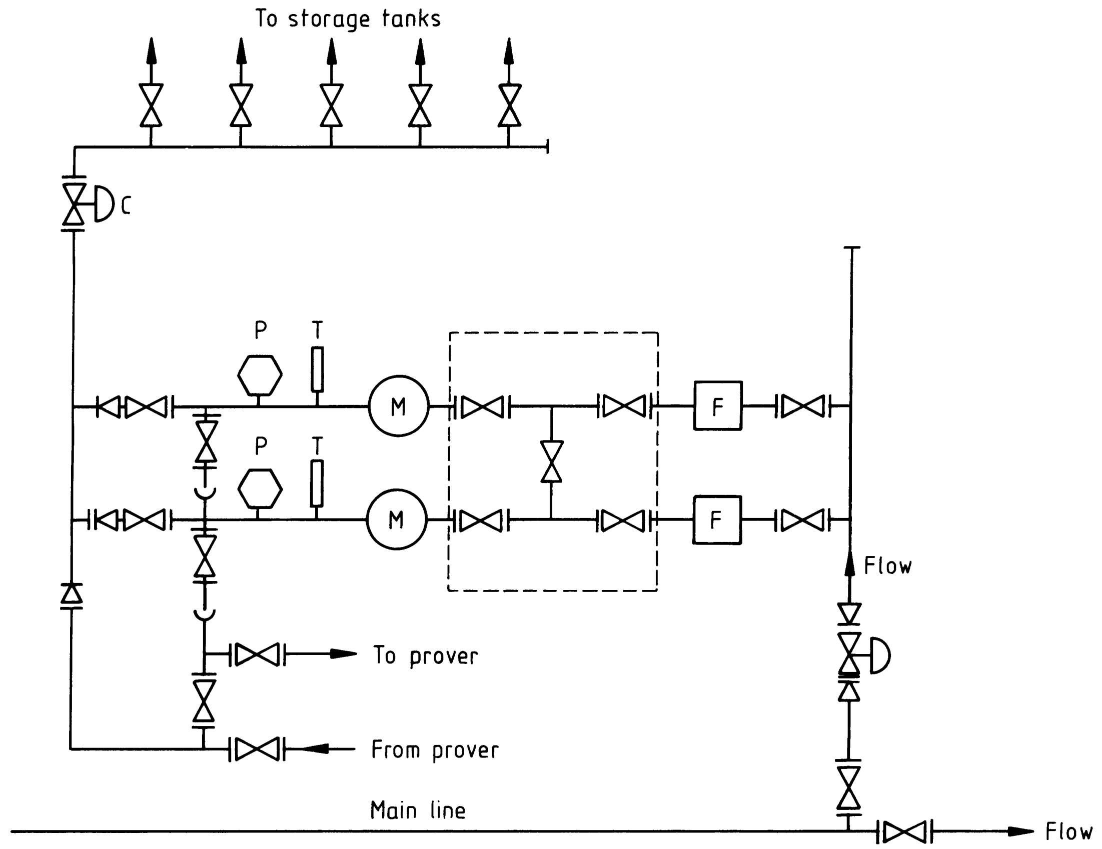
e) availability for both liquids and gases;

f) very high frequency response.

These characteristics have enabled the turbine to find general application in process and batch control. The high repeatability and pulse output makes flow rate indication and totalization very straightforward. The meter was originally developed for the aerospace industry where it was used to measure fuel consumption. This has given rise to similar applications in automotive, hydraulic, and general engineering industries for the testing of systems and components. In process applications, it is important that performance is maintained for long periods so that the quality of the product is maintained. This should involve regular checking and maintenance but sadly this is not often undertaken.

The commonest design of bearing for liquids is the journal bearing. When sealed or self-lubricating ball-bearings are used the turbine meter can be applied to natural, industrial and liquid gas measurements. The low temperatures encountered in cryogenic application require careful selection of the bearing materials.

Turbine meters are also regularly used as master meters to assess the performance of less accurate meters, since their performance is often comparable to the method used to calibrate them. A full review of applications can be found in Watson and Furness (1977).



Key:

F is the filter

M is the flowmeter

T is the temperature gauge

P is the pressure gauge

C is the flow control valve

Figure 4.3.4 — Complete pipeline metering system using displacement meters

4.4.2.2 ***Applications of mechanical helix type or Woltmann meters***

Helix type or Woltmann meters are used in large numbers and exclusively in potable water distribution networks having pipe diameters between about 2 and 12 in[3)]. In such a size range they monitor the consumption to groups of houses or a factory, at the smaller end of the range; or meter the flow passing through a small trunk mains at the larger. In combination with a self acting changeover valve and a smaller size meter (jet type, inferential or rotary piston) a helix type meter is used as a combination meter to meter flows having a flow rate range greater than can be accommodated by a single meter. Such applications occur where sudden demand may be great, e.g. water for firefighting, industrial process water or laundries and where the steady demand may be quite small.

Helix type meters are normally equipped with a mechanical counter and hence require no power but, by the addition of digital or encoded counters, they can be linked to a central computer to indicate flow rates and volumetric flows for network control purposes.

4.4.2.3 ***Applications of propeller and Pelton wheel meters***

Propeller meters are lower cost versions of either turbine or mechanical types. They can be used in similar applications to those covered but are generally preferred when economics are a major consideration. Performance and life are generally inferior to the turbine and they may not prove quite as cost effective as expected if regular attention is required. They are used in flow rate and totalization applications, particularly in water consumption.

Pelton wheel meters are worth considering when an electrical output is required for totalizing low liquid flows. Typical applications would include dosing of chemicals into larger tanks, mixing of small amounts of ingredients in pharmaceutical, food or processing industries and in fuel consumption measurements on small engines. They are generally cost effective and when used with good quality secondary electronics can prove fairly accurate. It should be remembered that head loss across the device is high when run close to the specified top of the range.

4.4.2.4 ***Applications of insertion type mechanical meters***

These are a very cost effective means of providing a pulse output in a large bore pipe. They are usually used in 150 mm diameter pipes and above, and designs are available for liquids and gases, including steam. They may be permanently installed or alternatively they can be made retractable under operating conditions. As with the conventional turbine meters they require periodic recalibration to ensure performance. Typical applications would include irrigation systems, large-bore water pipes and irregularly shaped gas or ventilation ducts and one-off investigations of flow in water distribution systems.

4.4.3 Influence of meter performance on applications

4.4.3.1 ***Axial turbine meters***

Typical performance statements for turbine meters are as follows:

Uncertainty:	0.25 % of rate over 10 : 1 flow range (liquids)
	0.5 % of rate over 10 : 1 flow range (gases)
Repeatability:	± 0.02 % of rate over 10 : 1 flow range
Linearity:	± 0.5 % of rate over 10 : 1 flow range

It is because of their good performance that they find widespread use as custody transfer meters, particularly on hydrocarbons. They are generally applicable on lubricating fluids where the Reynolds number is usually in excess of 3 000 to 4 000 but this lower operating limit can be as high as 10 000 depending on design. The low flow performance can be improved by replacement of the standard magnetic pick-off with an RF type (see **3.4.9.2**) or the addition of linearizing electronics. Ideally magnetic pick-offs should not be used below 25 mm bore size since the rangeability can be reduced to around half of that quoted. It should be remembered that turbine meters are available in a wide range of sizes, 5 mm to 600 mm, but each size has a different linearity. This fact may be important in totalization applications, where a single meter factor is set in the electronics.

[3)] 1 in = 25.4 mm.

Figure 4.4.1 shows the characteristic pressure drop for an axial turbine meter. Such a characteristic is obtained for most group 4 meters. It is clear that the majority of the loss occurs as the fluid accelerates through the rotor area, with some recovery occurring downstream of the blades. There is a maximum flow rate that can be put through the meter for a fixed inlet pressure because of the possibility of cavitation occurring within the meter. This is characterized by the sudden increase in meter output as the formation of bubbles leads to an increase in volumetric flow rate. Inferential meters should be sized to run with a pressure drop of around 0.6 bar to 0.8 bar at maximum flow. Provided the downstream pressure is maintained at a minimum of 1.5 bar then cavitation should not be present if the meter is operated within the specified range. Obviously if higher throughputs are required the system pressure must be increased accordingly.

An additional fact to be remembered is that the pressure drop varies with the specific gravity of the fluid and could be different in actual operation from the manufacturers calibration data sheet unless the same fluid is metered in both instances.

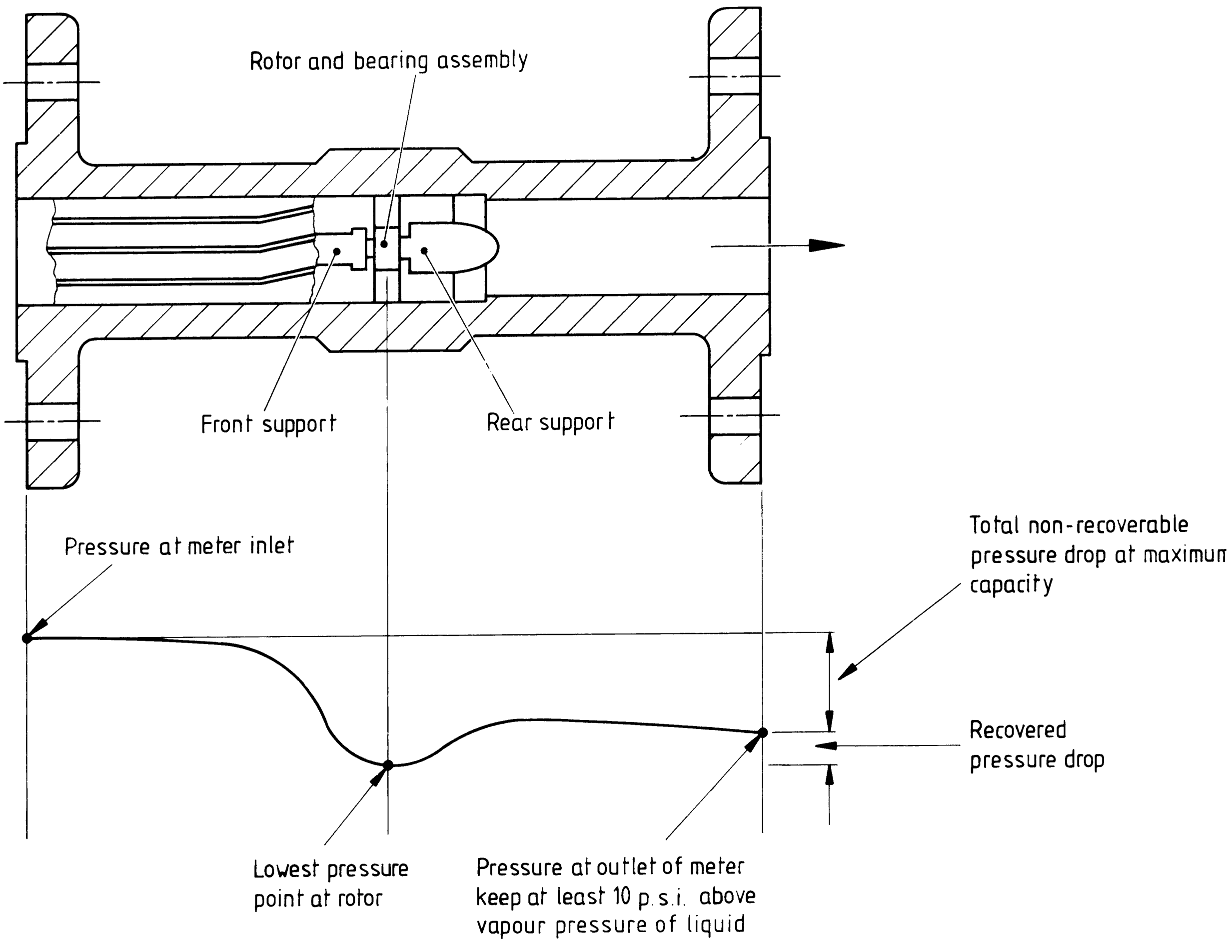


Figure 4.4.1 — Pressure drop along length of a turbine meter

4.4.3.2 ***Mechanical helix type or Woltmann meters***

The general performance of these meters is very similar in many respects to some of the commercially available turbine meters. Uncertainty and repeatability however are generally not better than 0.5 % and 0.1 % of reading respectively due to the influence of the mechanical readout system and the transmission system from rotor to readout. Sizes are generally in the range 50 mm to 300 mm and rangeability is not usually better than 10 : 1 within a linearity of ± 1 % of reading.

4.4.3.3 ***Propeller and Pelton wheel meters***

The performance of these two different types of mechanical inferential meter is different from those covered in **4.4.3.1** and **4.4.3.2**. The uncertainty of the propeller meter is typically 2 % of reading over a maximum 10 : 1 flow range. The range however does tend to be less than this and 5 : 1 or 6 : 1 is probably more realistic.

Pelton wheel meter performance is normally quoted as a percentage of full scale and not of reading. It should therefore be borne in mind that these types of meter have lower performance, particularly at the bottom of the quoted operating range. Pressure drop is also higher with 0.7 bar to 0.1 bar at maximum flow being typical. Repeatability is around ± 0.1 % and linearizing electronics can be used to improve the overall performance.

4.4.3.4 ***Insertion meters***

The major advantage of insertion meters is the negligible pressure drop and the minimum disturbance to the stream. Flow range is typically quoted at 10 : 1 with an uncertainty of ± 1 % of full scale. Repeatabilities are usually ± 0.25 % of reading.

4.4.4 Influence of fluid properties on applications

4.4.4.1 ***General***

The selection of a particular meter is influenced by the viscosity and density of the fluid to be metered.

4.4.4.2 ***Viscosity***

The effect of viscosity is one of reduced linearity relative to the same meter's performance on water. This is shown in Figure 4.4.2 for both helical and straight bladed meters. The transition from linear to non-linear portions of the curve occurs at progressively higher flow rates as viscosity increases. The smaller the meter, the greater the effect of viscosity. Manufacturers generally state that changes occur above 0.02 Pa·s and around 0.1 Pa·s the meter does not have a linear portion. It must be remembered however that although linearity is impaired, repeatability is not and these types of meter can still be used on viscous liquids if the installation is equipped with an in-line proving device (see section 6).

It should also be remembered that fluid viscosity can be highly temperature dependent and if an application has wide changes in fluid temperature the possible change in viscosity should be noted. As indicated in Figure 4.4.2, variations of several percent from a water calibration can occur with viscous fluids and the calibration supplied with the meter may not be valid for a fluid different from the calibration medium. Generally manufacturers do not specify Reynolds number criteria in their literature. The actual effect of viscosity varies between manufacturers and the potential user is advised to check these design aspects carefully.

4.4.4.3 ***Density***

The effect of density on turbine meter performance is far more important in gases than in liquids. The much lower torque from this lower density is offset by operating on line at much higher velocities. To ensure the rotor does not turn at higher speed which will reduce bearing life, the blade angles are reduced. The effect of gas density is shown in Figure 4.4.3 for a turbine meter. As density increases so linearity also improves. It has been found that, for some designs, calibrations at atmospheric pressure do not hold true in high pressure applications.

Gas applications also give rise to significant possible operating problems due to mis-sizing. Inferential flowmeters measure actual volume flowing and it is frequently necessary to convert the nominal operating conditions supplied by the vendor to actual volume flow. This can be done by application of the gas laws by the equation:

$$(q_v)_{actual} = (q_v)_r \cdot \frac{p_r}{p} \cdot \frac{T}{T_r} \cdot \frac{Z}{Z_r} \qquad (4.4.1)$$

This will ensure that the fluid velocities through the meter fall within the recommended limits laid down by the manufacturer. If in doubt it is better to have the supplier size the meter to the actual operating conditions required.

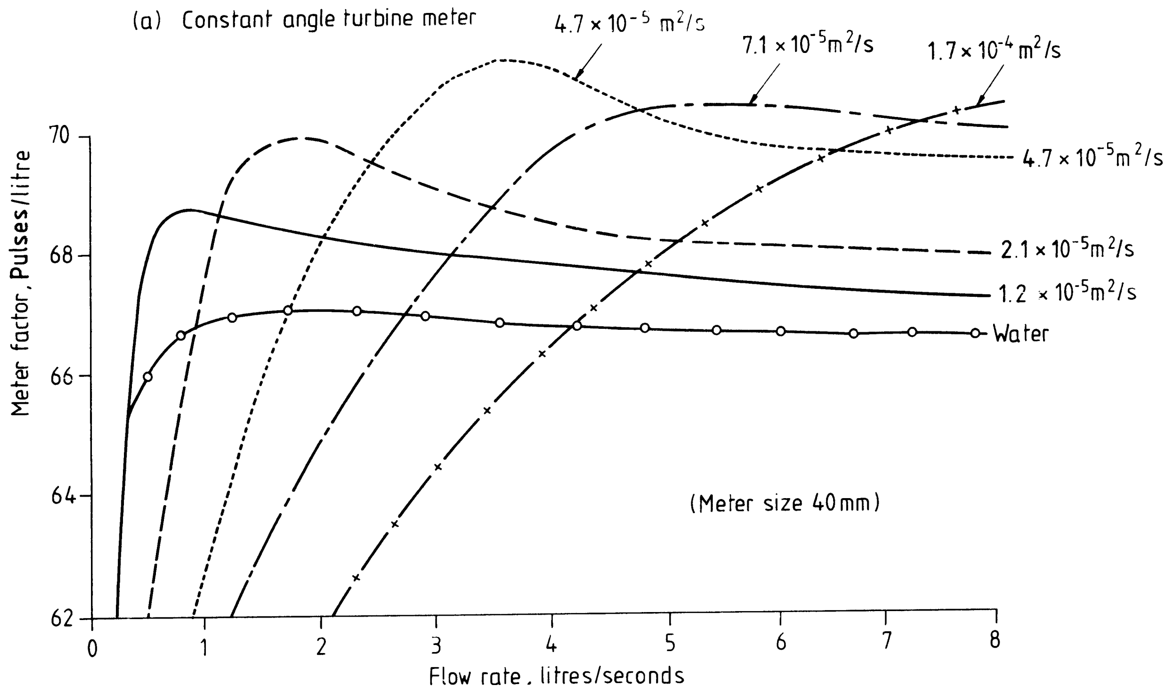


Figure 4.4.2 — Effect of viscosity on turbine meter performance

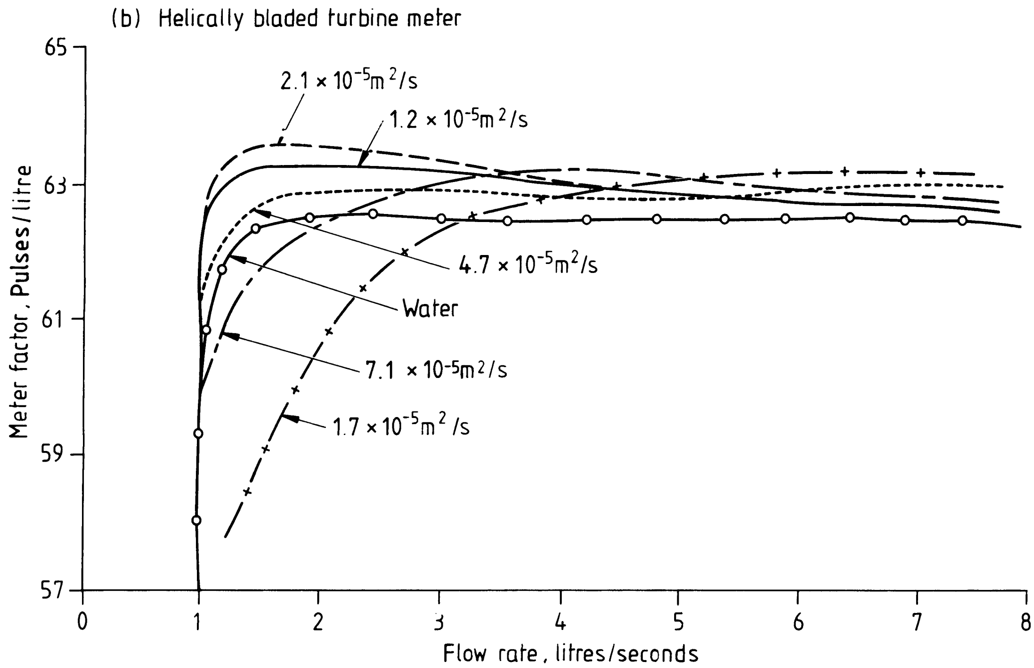


Figure 4.4.2 — Effect of viscosity on turbine meter performance *(concluded)*

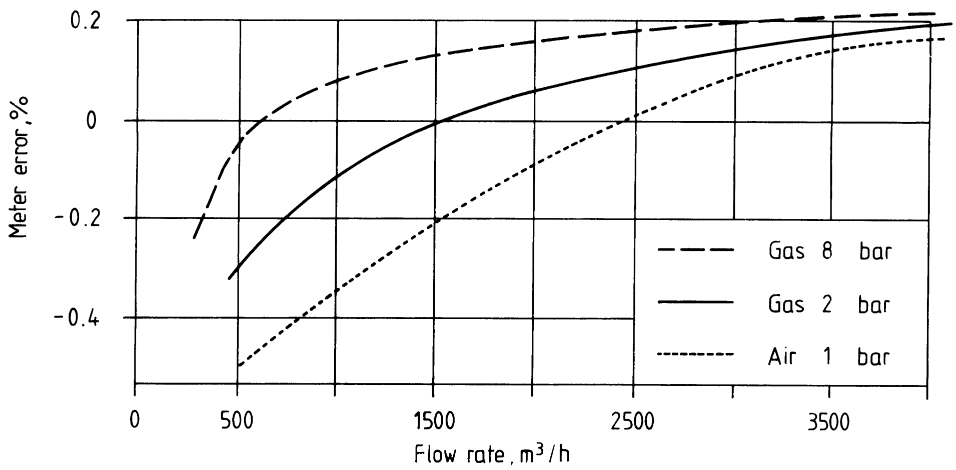


Figure 4.4.3 — Effect of gas pressure (density) on turbine meter performance

4.4.4.4 ***Pressure and temperature***

The wide temperature and pressure capabilities of this group of meters enables them to operate in extreme applications. They can be used between – 270 °C and + 400 °C with little difficulty and at pressures up to 300 bar, range being determined by the choice of materials. The flange rating needs to be correctly specified for high pressure applications and combined high temperature and high pressure applications may require special body designs. The dimensions of the meter may also be affected in these applications and small changes in performance could result if low pressure water calibration data is available.

4.4.4.5 ***Chemical considerations***

The chemical nature of the stream also requires consideration. Bearings are susceptible to corrosion or pitting with certain acids or alkalis with a rapid change in performance or even complete failure. PTFE-lined meters with special rotors or bearingless meters should be used with aggressive chemicals. Some organic fluids also cause problems, particularly solvents which are essentially non-lubricating in nature. Most manufacturers try to assess the lubricity of the fluid from the viscosity but this is insufficient. The chemical composition of the fluid flowing through the meter affects its design and the choice of materials used in its construction.

4.4.4.6 ***Bearing selection***

With the wide choice of different design of bearings, the selection depends on the properties of the fluid being metered. When the process fluid is clean, non-corrosive and possesses good lubricating characteristics, the ball bearing type should provide excellent life. Most industrial fluids are classed as dirty since they contain small particles from corrosion or erosion of the inside of the pipe. These tiny particles cause ball-bearings to fail fairly rapidly and thrust or journal bearings provide a better solution. The newer designs of ceramic bearings are beginning to be accepted in the chemical, petrochemical and food industries and do have advantages over the cheaper journal types.

If the operating characteristics are not ideal, such as contaminants or non-lubricating fluids, then bearing selection becomes a compromise between life expectancy and performance. Each application should be considered on its requirements and the manufacturer should be able to provide a suitable bearing for the stated fluid properties. If the fluid is very aggressive or totally non-lubricating, then special designs such as the Hoverflo® (see **3.4.8.2**) are the obvious answer.

Most turbine meters will accept some degree of small particulate matter for short periods but if the fluid contains larger amounts of particles, it is essential to protect the meter by installing a filter upstream. The sizing of the filter is also important, both in terms of pressure loss and mesh size. In order to safeguard filter life, the inlet velocity should be kept below 2 m/s. This then allows mesh size to be fixed. Most suppliers of group 4 meters can advise on suitable strainers or filters but Table 4.4.1 lists values adequate for most applications.

Table 4.4.1 — Recommended filter characteristics for group 4 meters

Meter size	Mesh size	Mesh opening width	
mm		mm	in.
6 to 15	150	0.1	0.0039
15 to 20	100	0.15	0.0059
25 to 80	80	0.175	0.0069
100 to 150	60	0.2	0.0079
> 150	40	0.3	0.019

4.4.4.7 ***Two-phase flows***

The measurement of two-phase flows presents special problems. Turbine meters have been used with other meters (target meters, densitometers, etc.) to assess the mass flow of two-phase water flows. The behaviour of most flowmeters in two-phase situations is not understood and the output from meters is difficult to interpret. The basic problem is the phase distribution of the gas and liquid; this changes with pipe orientation, flow velocity, design of meter and void fraction. Figure 4.4.4 shows the behaviour of a turbine meter in air/water mixtures. Errors of 20 % of reading are typical for changing fluid properties. Should the meter output become erratic, cavitation could be occurring within the meter. The system pressure should be raised or the meter should be moved to a more stable location. In two-phase applications the indicated output should be treated with extreme caution.

4.4.5 Influence of installation on applications

4.4.5.1 ***General***

All group 4 meters are affected to some extent by the velocity profile at the inlet to the rotor. They are also particularly sensitive to swirl and great care should be taken to ensure that the upstream pipework does not produce any flow distortion or swirl. Where this cannot be avoided, flow straighteners should be fitted or alternatively the meter should be sited in another location, well away from these disturbances. Meters with helical blades are generally less sensitive to profile effects as discussed in **4.4.4.2**, (see also Jepson and Bean 1969) and where variations cannot be reduced but an inferential meter is required, it is suggested that a helically bladed rotor be considered.

4.4.5.2 ***Upstream and downstream pipe lengths***

Straight lengths of pipe both upstream and downstream of the meter are required for most meters in this group. The Pelton wheel type meters are less demanding in their requirements and these will be treated separately. There is no clear agreement of what should be acceptable lengths and in industrial applications it is often not possible to position a meter of this type in pipes of sufficient length. Where short lengths of pipe are available the overall accuracy could be significantly different from the manufacturers quoted specification. Standards requirements range between 10 D and 20 D upstream and 3 D to 5 D downstream with straightening vanes to stabilize any profile effects. These are the minimum acceptable and where possible longer lengths should be used. The greater the length the lower will be the uncertainty interval.

Pelton wheel meters can have inlet lengths shorter than the other meters in the group. There is a significant reduction in area as the fluid passes into the body of the meter, and consequently profile and swirl effects are significantly attenuated. It is still suggested however that an inlet length equivalent to five body lengths be used upstream of the meter. It is important that the inlet pressure with this type of liquid applications is maintained well above the fluid vapour pressure. The head loss through these meters is much higher than the remaining meters discussed.

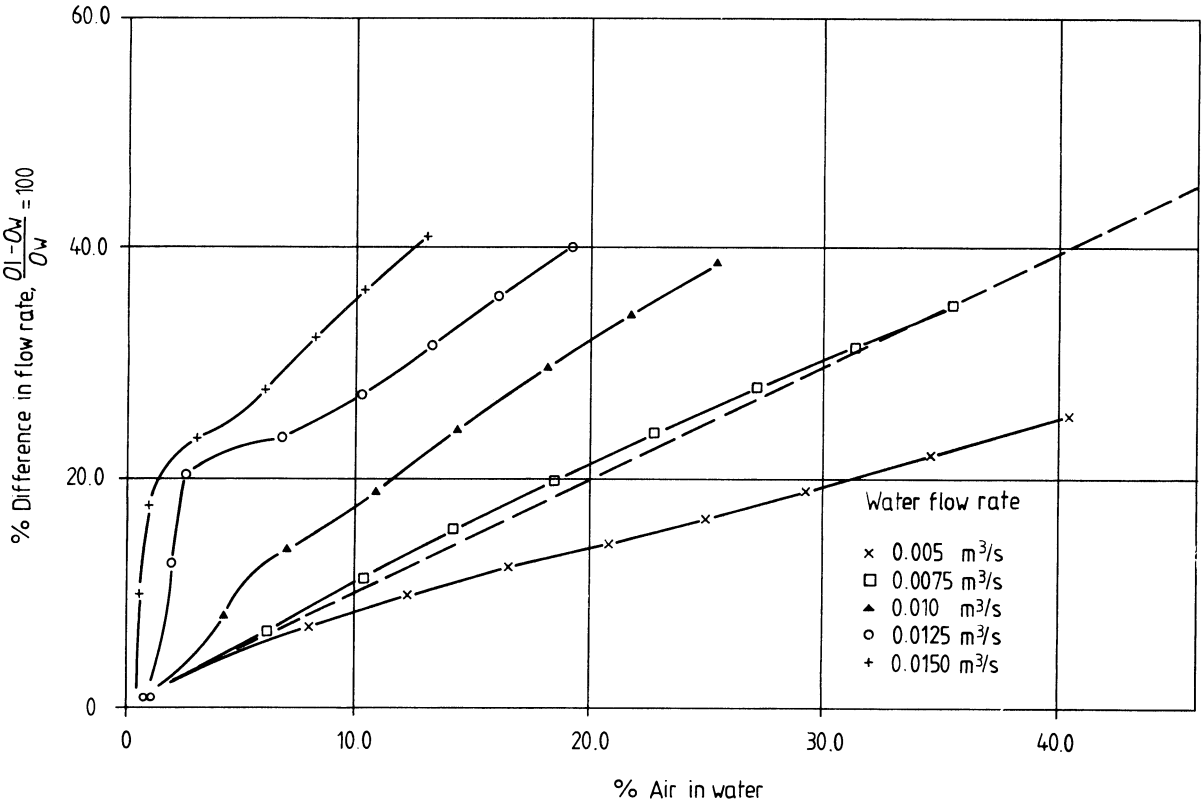


Figure 4.4.4 — Effect of two-phase flow on turbine meter performance

4.4.5.3 ***Meter installation***

The largest influence is that due to swirl, the influence on turbine meters is shown in Figure 4.4.5. The presence of bends and valves upstream of the meter can easily give a few degrees of swirl in the line and the effect on meter performance will result in deviations from the ideal case. Where the prospective user has limited space it may be advisable to select another type of flowmeter or move the installation to a location in the plant where longer lengths are available.

The piping should be in accordance with the suppliers recommendations. The internal diameters should be matched as far as possible with the bore of the meter to avoid profile effects. Empty flowmeters should not be subject to sudden surges of flow and flow should always be controlled on the downstream side of the meter to minimize flow disturbances. Any valves upstream of the meter should be of the ball valve type and be either fully open or fully closed. Where meters are required to be periodically inspected, the meter line should be fitted with a bypass. All filtration, separation and other equipment should all be located well upstream of the meter. The attitude of the pipework may also affect the choice of meter. Some types can only be installed in horizontal pipes while there are no restrictions in other designs. The rangeability of the meter may be affected in vertical downward flows. The installation should as far as possible match that in which the instrument was originally calibrated.

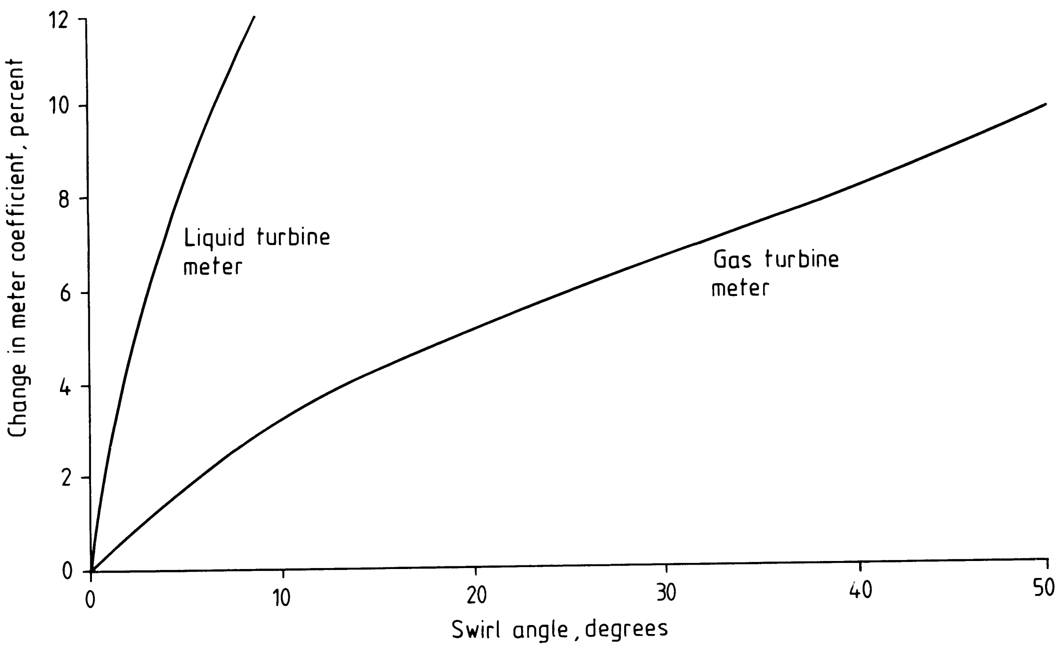


Figure 4.4.5 — Effect of swirl on turbine meters

4.4.5.4 *Pulsating flows*

In pulsating flows group 4 meters tend to over register, the magnitude being dependent on the frequency and amplitude of the pulsations. Over registration is generally worse in gas applications than for liquids. Figure 4.4.6 shows the expected response to positive and negative step changes in flow. In cases where pulsations are known to exist the application of group 4 meters should be carefully assessed.

4.4.6 Environmental influences on applications

These aspects can give rise to significant trouble if due care and attention is not taken. Temperature changes can be quite severe, with typical variations between – 20 °C and 35 °C occurring through the year. Humidity may also vary and though not directly affecting the primary element, could influence the secondary electronics associated with the meter. Mechanical devices are not affected to quite the same extent and where the environmental changes are severe, they should be considered. Large variations in temperature can cause expansion and contraction in certain components. If the tip clearance is affected this can cause major changes in the value of the meter factor and the linearity.

Power cables, motors and switchgear all produce electromagnetic radiation. With the magnetic pick-offs used by so many manufacturers, the spurious and additional pulses that can result may be picked up and counted as signal pulses. Unwanted pulses may also enter the system from the mains. In these cases where a noisy electrical environment is apparent, several options are available. Multiple but independent pick-off systems can be used and their outputs compared. Screened cables should be used wherever possible and the use of local preamplifiers on the meter will also be of benefit. Factors to be considered include:

a) use of mains filtering on instrument supplies;

b) grounding the cable sheath at one point to prevent earth loops;

c) keep signal and power cables well apart;

d) following the recommended installation guide to the letter.

In hazardous areas, all electrical equipment must be designed and certified to accepted standards. Corrosive environments such as those encountered in chemical plants, may also affect safety limits. A full knowledge of the operating environment is necessary in these applications.

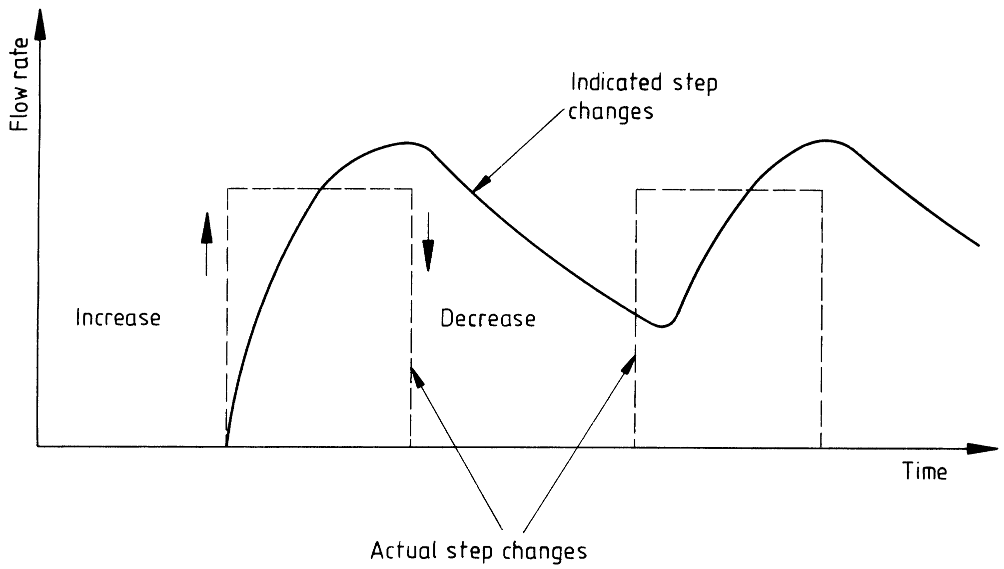


Figure 4.4.6 — Response of turbine meter to step changes in flow rate

4.4.7 Economic influences on applications

Inferential meters are generally very cost effective when comparing the purchase price with the throughput and performance. They do require periodic maintenance and recalibration to maintain their high performance. These costs may be a significant proportion of the purchase price and should be included when economics are an important influence. The price of these meters varies significantly between types and designs. For large pipe installations insertion meters are worthy of consideration.

Provided the meter is operated within its specified range on a lubricating clean fluid, then routine maintenance is not so important. Generally most failures of these meters are catastrophic in nature with the rotor ceasing to spin due to bearing seizure. Such an occurrence happens when air is blown through liquid meters or lines are started abruptly.

These meters are generally very robust and with care should be capable of many years of accurate service. As meters of most types have been produced for some time, spares availability is not usually a problem but stocks of items known to require regular replacement can conveniently be held.

Installation costs depend on the application, the desired performance and whether in situ calibration is required. The cost of flow conditioners needs to be added whenever installation in non-ideal locations is necessary.

4.5 Group 5 meter applications: fluid oscillatory types

4.5.1 General

Of the group, the vortex meter is now in common use and has substantial background data. Very little application data relating to the other meters is available at present. Therefore the majority of **4.5** is related to the vortex meter. Data for the other types is referred to the vortex meter unless there are significant differences. The insertion vortex meter relies heavily on the vortex meter data with the additional problems of profile and location effects, as discussed in **3.4.7** and **3.5.5**.

4.5.2 General applications

4.5.2.1 *Vortex shedding meters*

Vortex meters are beginning to make in-roads into areas where differential pressure meters have traditionally been applied. These include the industrial metering of water, steam, air, chemicals and other fluids. The two main advantages they have over the orifice meter are rangeability and the digital output signal, which is more compatible with modern data acquisition and control systems. Thus rate indication, totalizing, batching and utility metering are all general applications of the vortex shedding meter. The actual design of the vortex detection method, together with the fluid Reynolds number, dictate whether a particular application will be suitable for this type of meter. Useful applications reviews can be found in Miller et al. (1977) or Witlin (1979).

4.5.2.2 *Fluidic meters*

Fluidic meters are also beginning to be applied to industrial flow measurement. The attraction of no moving parts and a digital output mean that provided the materials of construction are compatible and the Reynolds number is above the minimum, then liquids can be metered to within ± 1 % of flow rate. Domestic metering of gas is one area where fluidic meters are showing promise for future developments.

4.5.2.3 *Swirlmeter®*

These can be used for the general measurement of fluids at pressures below 100 bar. There are two types of sensor, a thermistor for low pressures < 25 bar and a piezo sensor for below 100 bar. In the past this type has tended to be overlooked in favour of the vortex shedding meter but they have equivalent flow rangeability though with an increased pressure drop. Further information is given in Dijstelbergen (1970).

4.5.2.4 *Insertion meters*

Vortex insertion devices can be used in large bore liquid and gas flow applications. They are less common than insertion turbine types, see **3.4.7**, and applications experience is therefore limited. Typical applications could include stack flow metering, fume or glove box monitoring and hot tap gas metering.

4.5.3 Influence of meter performance on applications

4.5.3.1 *Vortex meters*

Vortex meter uncertainty varies with design and method of vortex sensing. Claims range from 0.5 % to 2 % of reading for liquids to between 1 % and 2 % of reading for gases. Claims on rangeability vary widely with up to 150 : 1 being quoted. A more typical industrial claim is however closer to 15 : 1 but as most industrial plants run with liquid velocities around 1 m/s to 2 m/s it is doubtful whether such performance is ever required in practice. Most vortex meters have a minimum velocity around 0.5 m/s and the upper flow limit is rarely achieved, except possibly in some gas or steam applications.

The output from vortex meters is claimed to be independent of the fluid. Thus meters of this type are calibrated on air and used on water and vice-versa. The validity of this depends on the meter design and studies have shown that for some designs there are shifts between fluids, of up to ± 1 % of reading over the flow range. There is a little concern over the long term stability of calibration with drifts of up to ± 0.2 % of reading occurring over a period of months.

The most common application problem is on the calculation of flow range. For a vortex meter this is determined by Reynolds number at the low end and cavitation and compressibility at the top end. On gases care should be taken in sizing to ensure that the correct flow units are used, actual cubic volumes not standard cubic volumes for sizing. Confusion in this area can lead to completely wrong sizing. Most vortex meter manufacturers can supply sizing charts in the form of meter size against flow rate for variations in viscosity and density. An example is given in Figure 4.5.1 for sizing liquid meters. Similar tables are available for other fluids.

When considering repeatability, there are ranging claims that are subject to resolution. The most common claim is ± 0.15 % or ± 0.2 %. Resolution is important with vortex meters as the frequency of shedding reduces as the cube of the diameter increases. For liquids, a typical frequency for a 100 mm (4 in.) vortex meter is 10 Hz. Thus to achieve a resolution of 0.1 %, the collection of 1 000 pulses is necessary. This will be achieved in 100 s, i.e. a sample time of 100 s is required in this example. For a gas, higher velocities may give minimum frequencies of around 100 Hz, still requiring 10 s to achieve 0.1 % resolution. In addition there is often up to 30 % frequency modulation on the pulse output train. Interpolation and period timing does not help the resolution, implying that a resolution of better than ± 0.1 % is difficult for a vortex meter.

The basic output from the vortex meter is pulses but often these are converted to a linear analogue output proportional to flow. This normally adds a full scale deflection error of ± 0.1 % on top of the basic linearity. A problem with the analogue output is the basic frequency. Unless long integration times are used the analogue output can appear very noisy, particularly on a chart recorder. When looking at the basic signal, the dynamic response is determined by the frequency. Because the vortex shedding is a fluid phenomenon, changes in flow rate have an immediate effect on the vortex shedding. However this will not be seen until one pair of the vortices have been shed. Thus if the frequency is 1 Hz then the true response time will be 1 s. This is not however a very accurate response and may be an explanation for the apparent lack of repeatability between individual vortices under nominally steady flow.

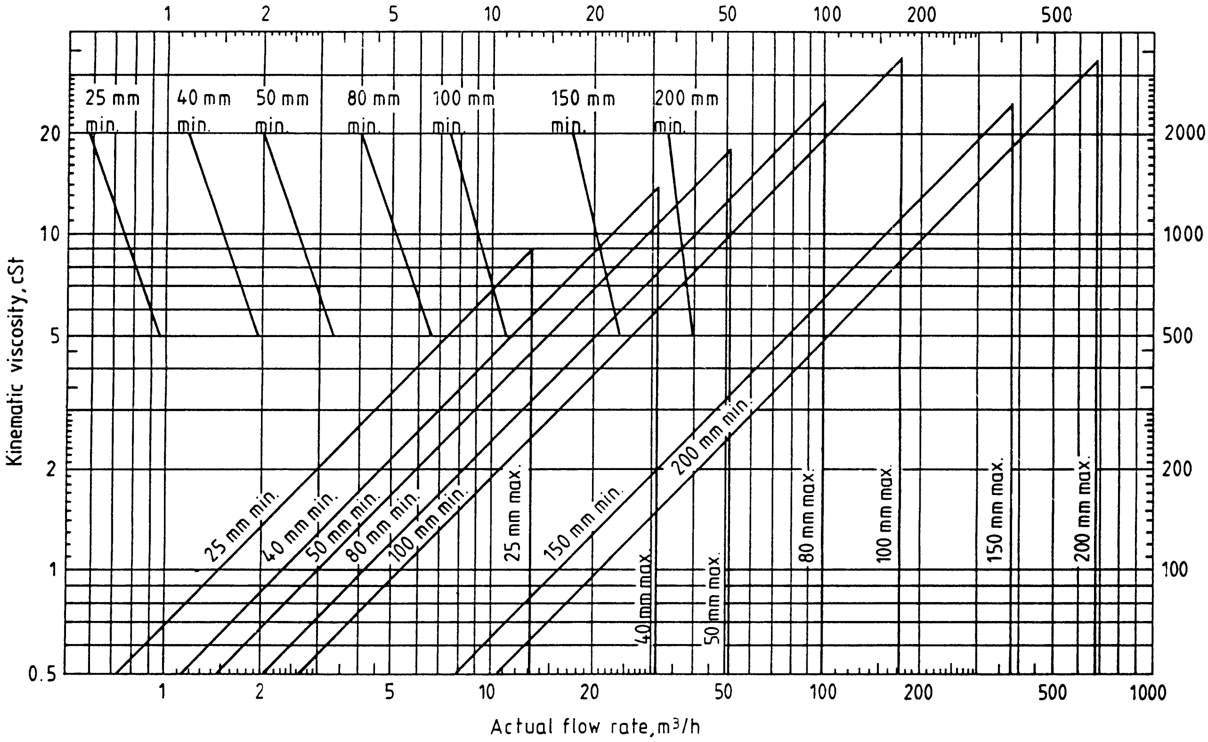


Figure 4.5.1 — Typical sizing charts for vortex meter

Vortex meters measure actual volumetric flow. This is generally acceptable for liquids as the density change due to pressure is negligible; only temperature affects the density. With gases, the meter needs density compensation to give a mass flow output. Using a mass flow computer with either pressure/temperature or direct densitometer measurement, the vortex meter can be compensated for mass flow measurement. The position of the pressure/temperature or density tapping should be approximately half pipe diameter downstream of the bluff body. If placed in any other position a correction will have to be made.

The vortex meter has a reasonable pressure drop, which must be taken into account on installation if pumping pressure is low. The usual pressure drop is around 15 kPa.

4.5.3.2 ***Fluidic meters***

Currently there are few fluidic oscillators in commercial operation, and all are of the feedback type. Application data for them is similar to a vortex meter. A review of the differences is given below, where there is no comment the vortex meter data applies.

The flow range is determined by Reynolds number at low flow and cavitation/compressibility at high flow. At the low end the Reynolds number varies according to design but is usually around 10^3 based on the pipe. Thus they are capable of operation below that of a vortex meter, see Table 4.5.1. The linearity of available meters is typically ± 1 % of flow rate although many of the experimental meters are better than ± 0.5 % of flow rate. The pressure drop for a fluidic oscillator is typically 20 kPa.

Table 4.5.1 — Typical low flow limits for vortex and fluidic meters

Size	Vortex	Fluidic	
	Water	Air[a]	Water
mm	L/m	m^3/h	L/m
25	30	20	5
40	45	30	8
50	60	40	10
75	85	50	—
100	105	62	—
150	160	100	—

[a] 1 bar.

4.5.3.3 ***Swirlmeter®***

Performance is a little more difficult to define for a swirlmeter as it can only be calibrated on gas. Uncertainty is quoted as 1 % of flow rate between 20 % and 100 % of full flow and 2 % between 10 % and 20 % of full flow. The pressure drop can be up to 60 kPa.

4.5.3.4 ***Insertion types***

As with all insertion meters two components contribute to the performance of the meter. The first is the intrinsic performance of the meter type, combined with the uncertainty of a point velocity measurement. The vortex meter performance is given in **4.5.3.1**, to which it is essential that the errors of positioning and hydraulic effects be added. This gives a total uncertainty for this type of meter of 2 % of full scale. The overall linearity of velocity measurement for an insertion meter is usually quoted as ± 1 % of full scale. Over smaller ranges (e.g. 5 : 1) a linearity of ± 2 % of actual flow is possible.

The second component is the uncertainty in estimating volumetric flow which is totally dependent on the effort put into installing the meter. If the meter is installed where the profile is unknown, then the performance is likely to be in the region of 10 % of flow rate. By careful profile measurement however, this can be as low as 2 % of flow rate at an individual flow rate. An increase in range will invariably increase the measurement uncertainty.

As the blockage is generally so small the pressure drop is very small and reduces as pipe size increases. This is particularly advantageous for large pipe lines in saving pumping costs.

4.5.4 Influence of fluid properties on applications

4.5.4.1 ***Vortex meters***

The lower limit of vortex shedding is determined by Reynolds number usually between 10^4 and 2×10^4. A typical set of low flow figures for water and air are given in Table 4.5.1. There are designs which operate to much lower Reynolds number (approximately 10^3) by using thinner bluff bodies of triangular cross section as standard, although in general they are of a different linearity.

The nature of the flow requires careful assessment. Two areas cause concern with abrasive fluids, the bluff body and the transducers. Fluid abrasion will round-off any sharp edges on the bluff body. Fortunately most bluff body designs allow a considerable degree of damage and rounding of the upstream edges before there is a significant change in the calibration constant. If there are sharp edges at the rear of the body then abrasive damage here may cause larger changes in calibration. Damage to the transducer is very dependent upon the transducer design, and the supplier should be able to give advice on his design. In general vortex meters are immune to chemical attack as they can be made from a variety of materials to ensure compatibility. The same is generally true of the transducers and any seals required for the bluff body or housing.

Temperature effects give rise to density and transducer problems. Extremes of temperature may cause failure of the transducers either by expansion of transmission liquid in pressure sensors or by exceeding the Curie temperature in ultrasonic sensors for example. The standard upper limit is around 100 °C but some transducers are designed to go up to 300 °C for steam applications. Fewer designs of transducers can operate at cryogenic temperatures, the most successful so far have been the oscillating disc transducers. The major problem is the slightly high pressure drop causing early cavitation in cryogenic liquids.

Excessive compressibility affects the relationship between frequency and flow rate. Currently there is no data for correcting the curve due to compressibility, and Mach numbers below 0.2 present no problems. Cavitation usually destroys vortex shedding. For liquids the upper flow limit is usually determined by cavitation, i.e. the boiling of the liquid due to pressure drop. To avoid this, the following condition should be followed:

$$\text{upstream pressure} = 4\,\Delta p + 1.25\,(p_{\mathrm{v}} - p_{\mathrm{A}}) \qquad (4.5.1)$$

where

Δp is the pressure drop;

p_{v} is the vapour pressure at flowing conditions;

p_{A} is the atmospheric pressure.

Vortex meters can be used on low concentration slurries. Successful application depends on the transducer and on ensuring there is no build up of slurry on the bluff body by aligning the axis of the body horizontally and not vertically as is the normal convention. Due to the composition variations with slurries, there are no definitive guidelines and the suppliers' advice should be sought. Small volumes of bubbles in slurries can cause shifts in calibration. Particles of accumulated gas travelling along the top of the pipe will be pulled into the vortices, irrespective of the bluff body orientation, causing breakdown of the vortex shedding. Dependent on the type of transducer these cause problems indirectly, either by:

a) blockage of access or porting;

b) direct interference with the operation;

c) direct physical damage.

4.5.4.2 ***Fluidic meters***

The meter can cope with both clean liquids and gases. However slurries, gas in liquid and particles in gas can cause severe problems of blockage of the feedback loops. It is difficult to orientate them to alleviate this problem, although the feedback loops should be kept horizontal if possible. The design of body and the flange rating fix the maximum temperature and pressure but a typical operating temperature range is – 20 °C to + 175 °C.

4.5.4.3 ***Swirlmeter®***

The Swirlmeter operation is quoted as being independent of density, the temperature and pressure. Particles can be a problem because of the close spacing of the inlet swirl generator.

4.5.4.4 ***Insertion meters***

These have the same fluid property limitations as vortex shedding meters as discussed in **4.5.4.1**.

4.5.5 Influence of installation on applications

4.5.5.1 ***Vortex meters***

Vortex meters are sensitive to flow profile variations. They are designed to operate under fully developed profile conditions. To maintain the stated performance a minimum length of straight pipe is required after most pipe fittings, and typical values given in Table 4.5.2. Further research is required to confirm these figures. Downstream of the meter, fittings should not be installed closer than 2 D although a minimum of 5 D is better practice.

There is some controversy regarding the removal and reinstallation of meters. Calibration shifts of the order of 1 % have occurred after reinstallation. It is agreed that the longer the meter housing the less likely any problem. Ideally as with most flowmeters, the meter should be part of a calibrated run, e.g. Figure 4.5.2 with the housing dowelled to ensure positive relocation. Dependant on the meter type (see Figure 4.5.3) the piping adjacent to the meter is important especially with the wafer design. Two important rules for siting vortex meters are as follows:

a) a smaller upstream pipe than meter bore will cause errors;

b) with wafer meters the downstream pipe is very important.

Table 4.5.2 — Recommended minimum upstream lengths for vortex flowmeter installation

Disturbance	Upstream straight pipe diameter *(D)*
Single bend (medium sweep 90°)	10
Elbow 90°	15
Double bend	15
Two or more 90° bends form in the same plane	25
Two or more 90° bends in different planes	≤ 150[a]
Reducing cone 15°	10
Expansion cone 15°	15
Butterfly valve (fully open)	15
Butterfly valve (20 % open)	25
Gate valve (fully open)	5
Gate valve (30 % open)	30
Control valves and other sources of severe flow disturbance[b]	≤ 70

[a] Depending on the bend configuration. Less if flow straighteners are used.
[b] Every effort should be made to install control valves and other sources of severe disturbance downstream of the vortex meter.

Build up of scale or rust, etc. on the inside of the pipe should be avoided because it can cause a net reduction in pipe diameter or distortion of the flow profile. Swirl can be a damaging factor during vortex shedding and therefore in such a situation a flow straightener should be sited before the required length of straight pipe.

Vortex meters like most meters are susceptible to errors due to pulsating flow conditions. Tests in pulsating gas flow have shown a high sensitivity to pulsation frequency. If the vortex shedding is in the range between a quarter and two times the pulsating frequency then it may lock-on to the pulsation frequency. Laboratory data shows the pulsation level does not have to be large to destroy the vortex shedding. Some older designs of vortex meter, i.e. pressure sensors, can be sensitive to vibration, although the latest designs have some form of compensation or are immune. Vibrating pipework may need to be braced or an alternative orientation may help.

Generally vortex meters may be orientated horizontally or vertically except with slurries and gases or in cases of excess vibration. Most meters are uni-directional and incorrect installation would lead to distorted results.

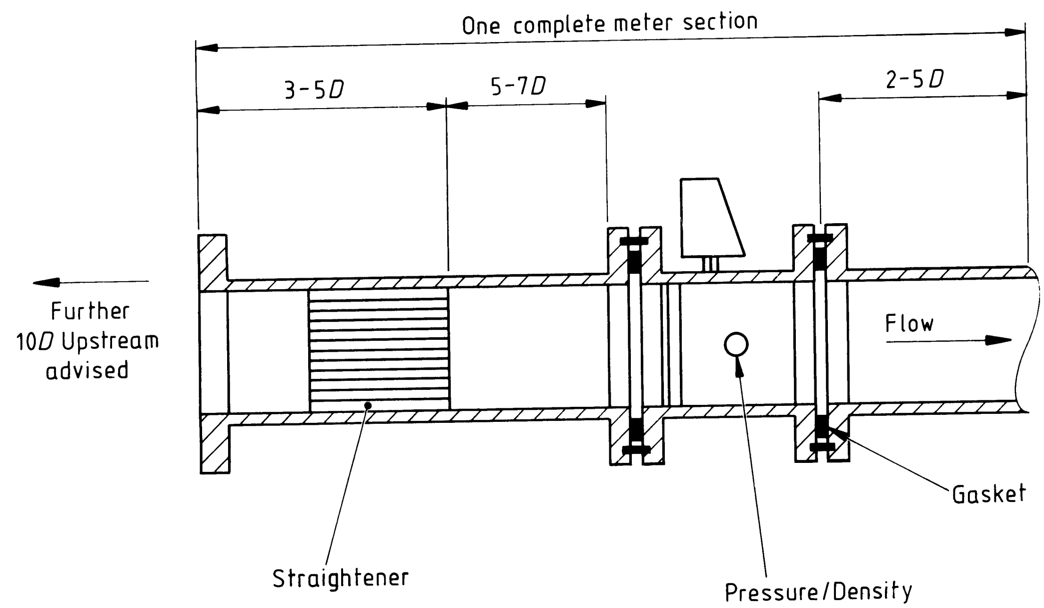


Figure 4.5.2 — Recommended vortex meter installation

4.5.5.2 ***Fluidic meters***

The available data shows the meter to be far less susceptible to upstream pipe configuration than most meters. Certainly, if the conditions stated for the vortex meter are adhered to it is likely that the specified performance will be achieved. The upstream and downstream pipework are less important than for a vortex meter, the upstream pipe can be as much as 10 % smaller or 15 % larger in diameter than the inlet. Gasket protrusion and inlet pipe offset is important, the allowable displacements are approximately twice that of a standard vortex meter.

4.5.5.3 ***Swirlmeter®***

As a result of its higher pressure loss the meter is very resilient to pipe variations. There is little data available, but inlet length requirements are shorter than for the same sized vortex meter. Tests conducted with the meter installed downstream of various bend configurations has shown that swirl has a small influence on performance. These tests showed shifts in linearity of less than ± 0.5 % of flow rate.

4.5.5.4 ***Insertion meters***

In theory insertion meters are far more prone to pipe effects. In practice if profile plotting is carried out, insertion meter performance is improved. It is very important that the insertion vortex meter is aligned with the flow. The meter is sensitive to alignment and can give large errors if this is not taken into account. As with all insertion type meters positioning is critical.

4.5.6 Environmental influences on applications

The effect of the environment is dependent upon the meter design. However there are common goals all suppliers are striving for and these are achieved with the majority of transducer designs. Almost without exception in this group of meters the transducer housings are located on or close to the meter. This gives an upper temperature limit of between 60 °C and 80 °C in the surrounding (this may be higher if military specification components are used). As electronics are involved, humidity could be a problem and care is usually taken to avoid the effects by coating the boards and sealing the enclosures. Signal interference is reduced by making the transmission, be it pulses or analogue, in the form of current. The method for converting current pulses into voltage input is shown in Figure 4.5.4.

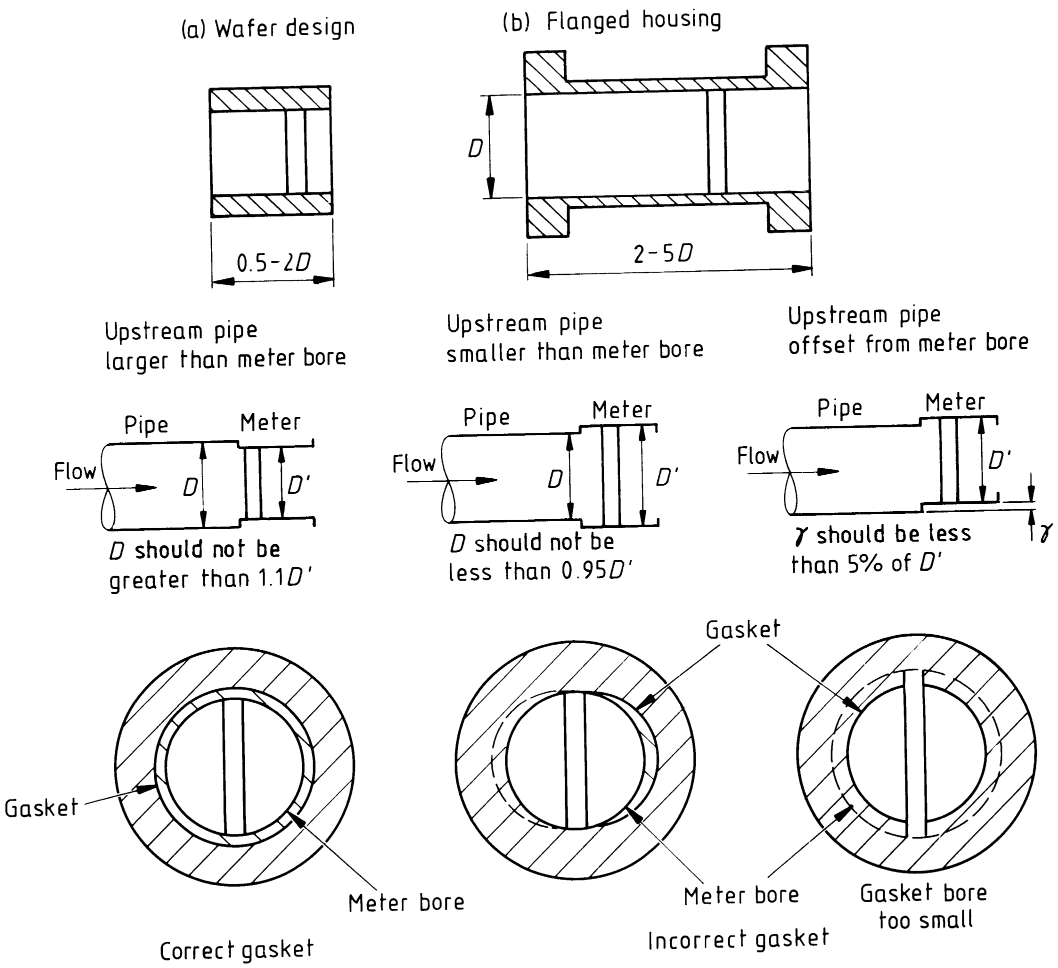


Figure 4.5.3 — Pipe connection details for vortex meter installation

Often vortex meters are sited in hazardous areas. One way in which this problem is resolved is to encase the electronics in an explosion proof housing often with inert gas purging. More commonly the electronics are designed to comply with an intrinsically safe standard, such as one published by CENELEC[4)], BASEEFA[5)], etc. Power is kept to a minimum so that in the event of a catastrophic failure there is never sufficient power generated to cause a spark. Connections between the electronics in the hazardous area and the safe area are normally through zener barriers (see **5.5.7**).

4) European Committee for Electrotechnical Standardization.
5) British Approvals Service for Electrical Equipment in Flammable Atmospheres.

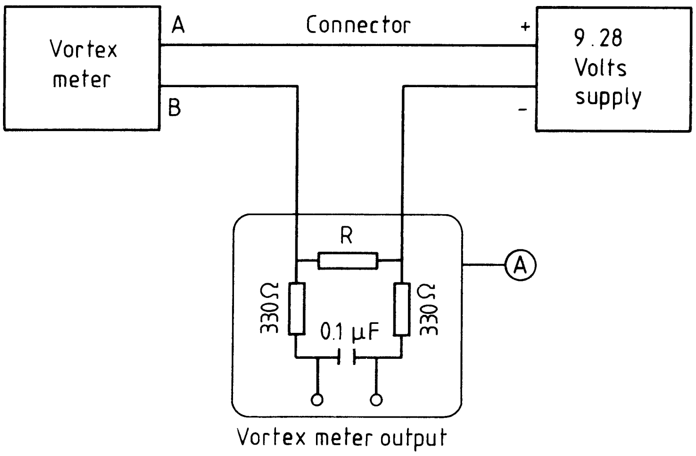


Figure 4.5.4 — Suggested circuit for voltage to current conversion for vortex flowmeter

4.5.7 Economic influences on applications

4.5.7.1 *Vortex meters*

There is a wide variation in the cost of vortex meter but the basic price compares favourably with many other types of meter, as indicated in Figure 2.6. The wafer type (clamp between flanges) have lower purchase costs than flanged meters, but installation costs may be higher.

The majority of vortex meters include a factory calibration. This is usually performed using water at five different flow rates with repeat calibrations at one point. They are relatively easy to calibrate, thus on-site or independent calibration does not involve excessive cost.

The cost of installation can vary widely dependent upon the meter design and the level of performance required. Wafer designs can be time consuming to install because the location requirements makes alignment difficult. Some manufacturers offer an alignment tool to alleviate this problem. Meters with end fittings, flanges or screw threads, are relatively easy and incur few extra costs. Electronic installation requires the minimum of cost as most designs are two-wire transmitters requiring only relatively low cost cables.

Once the meter is installed, maintenance costs are generally low. The most likely faults are damage to the bluff body or to the transducer. Repair time will depend on body design. In general both components are easily removable for repair and may not require removal of the entire body. Because the vortex meter does not usually have moving parts the life of the meter is conceptually indefinite. Minimal wear is commonly experienced and deterioration of the transducer will tend only to cause a reduction in sensitivity rather than any change in calibration. Due to this the intrinsic reliability is high once the unit is installed and working. Only direct attack on the bluff body or transducer by erosion, corrosion or build up will result in catastrophic failure.

If applied and used correctly, no maintenance other than regular routine calibration checks should be required. Operational problems such as bluff body wear, electronic failures and sensor failure are the primary sources of maintenance costs. Of these, sensor failure is by far the most common. This is due to the dirty nature of most fluids passed through vortex meters. The latest designs where the sensor is located outside the pipe are more suitable to industrial applications. Sensor location is one important design feature to check. Should the sensor fail, it can be replaced without line shutdown in these designs. Similarly, electronic failure can be overcome by board or transmitter replacement.

4.5.7.2 *Fluidic meters*

As with vortex meters, sensor or electronic failure is handled by component replacement. There has been a tendency in certain applications for the sensor to become coated by the fluid thereby giving erratic or total failure. It is prudent to stock spare sensors and signal conditioning boards to minimize downtime should failure occur.

4.5.7.3 ***Swirlmeter®***

The basic cost of the meter is high because of the complex shape of the meter. Also they are bulky in larger sizes and the material costs go up dramatically.

4.5.7.4 ***Insertion meters***

Once the pipe size is about 250 mm an insertion meter becomes very cost competitive, particularly as its cost does not increase greatly with size. As discussed in **3.5.5.2**, insertion metering is a very economic way to measure flow in large bore pipes.

The maintenance cost of an insertion vortex meter is low, not only because the vortex meter itself has long life, but also because it is simple to remove from the line and repair. Usually it is inserted into the line via a valve. This allows the meter to be replaced without stopping the process fluid. If a full traverse to find the profile of the fluid is carried out, then the on-site calibration cost is likely to be high because of the time taken to carry out the tests.

4.6 Group 6 meter applications: electromagnetic types

4.6.1 General

Electromagnetic meters are the first of the new generation of electrical meters to be accepted in industry. They are not new in the strict sense since the first meters appeared some thirty years ago. The two major limitations to their use are the conductivity of the fluid and the fact that they cannot be used on gases. Generally these meters will not operate on organic or hydrocarbon liquids, but they can measure liquid mixtures where water is the continuous phase. Thus water/oil mixtures could be metered with modest performance. Most electromagnetic meter manufacturers have extensive banks of conductivity data and can therefore assess whether a fluid can be metered or not.

4.6.2 General applications

Although electromagnetic meters have been used widely in industrial processes and plants, recent technical developments towards miniaturization and the use of new liner materials have enhanced their range of applications. Size, weight and power requirements have reduced significantly in the past decade, enabling electromagnetic meters to be installed where group 1 meters, particularly orifice meters were the only type previously considered.

Typical applications would therefore include waste water, emulsions, corrosive liquids, inorganic chemical streams, paper pulp flows, water distribution systems and sewage flows. Recent work also shows promise in the ability to handle two-phase gas-liquid flows with moderate uncertainty (5 % of reading) (see Bernier and Brennan 1983). From an operational viewpoint, the feature which differentiates electromagnetic flowmeters from most other types of flowmeter is the unobstructed passage that is presented to the flow. This makes them suitable for measurements on a whole range of difficult process fluids such as slurries and non-Newtonian liquids which cannot be handled by other types of flowmeter. With the appropriate liners, it also enables them to handle the highest fluid velocities that are likely to arise in industrial measurement practice. Generally there are no Reynolds number constraints other than a certain minimum velocity. Thus viscous fluids flowing at 1 m/s to 2 m/s can be measured easily, provided they have sufficient conductivity. The different liner types and electrode materials allow the meters to operate at a variety of temperatures with both corrosive and abrasive liquids (see Table 4.6.1).

Electromagnetic flowmeters are characterized by a linear relation between flow rate and the measurement signal. Consequently, they have wide flow rangeability (i.e. a given flowmeter can operate with upper range values which can be varied by a factor of as much as 20 and, for a given upper range value, the flowmeter should meet its performance specification for flow rates between 10 % and 100 % of the selected upper range value), although there could be uncertainty in the measurement at very low flows.

Except in the vicinity of the electrode, the flowtube is free from crevices or other areas where the product could become trapped and hence stagnate. Consequently it is suitable for many applications in the food, dairy and pharmaceutical industries. The flowtubes are available for a very wide range of pipe sizes from a few millimetres to 3 m. The smaller sizes are applied where the low flow rate and unobstructed flow are dominant considerations. The very large sizes find application in the water and waste industry.

4.6.3 Influence of performance on applications

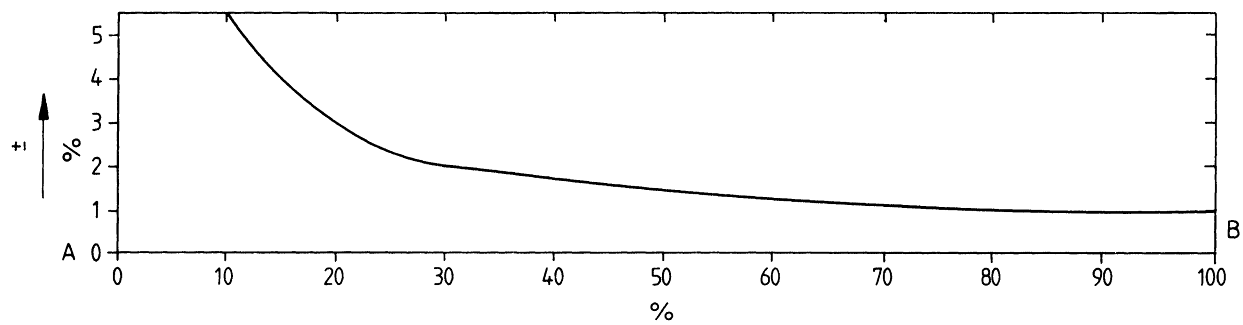
Most manufacturers do not differentiate between the errors attributable to the flowtube and those due to the measuring circuit. In general terms, meters with sinusoidal excitation of the magnetic field (a.c. types) have the performance expressed in terms of the full scale or upper range value and so the uncertainty envelope is trumpet shaped as shown in Figure 4.6.1. There are a number of suppliers and uncertainty varies from 0.5 % to around 1 % of full scale.

For systems based on pulsed excitation of the magnetic field (d.c. types) the performance is expressed in one of two ways. Some suppliers quote performance as a percentage of the flow rate from the upper range value down to 10 %, below this the error is expressed as a fixed value. Typical uncertainty can range from 0.5 % of reading or lower to 1 % of full scale depending on design. Other suppliers publish a specification which shows a uniform error from the upper range value down to approximately 20 % of maximum flow and then an error which increases progressively as a percentage of full scale over the remaining flow range. This is shown in Figure 4.6.2.

Velocities above about 5 m/s are not generally recommended unless the liner material has been selected for the duty. Accelerated pipe erosion and liner damage can result if this has not been checked.

Table 4.6.1 — Electromagnetic flowmeter liner types

Material	Temperature range	Some application properties
	°C	
Polytetrafluoroethylene (PTFE)	– 50 to + 200	Chemically inert. Wear resistant. Suitable for hygienic fluids
Ebonite	0 to + 100	Corrosion resistant (acids and alkalis). Suitable for sewage and water
Polyurethane	– 50 to + 80	Good abrasive resistance
Isoprene-based rubber	0 to + 90	Good chemical and wear resisting properties. Suitable when traces of petrochemicals
Vitreous enamel	Up to 180	Excellent chemical and wear resisting properties. Suitable for depositing fluids. (Suitable for fluids which scale pipe walls)
Ceramics	– 50 to + 220	Chemically inert, excellent corrosion abrasion, radiation resistant properties, but brittle



Key:

A is the indication error in percent, related to measured value

B is the flow rate in percentage of set range

Figure 4.6.1 — Typical a.c. electromagnetic flowmeter performance curve

4.6.4 Influence of fluid properties on applications

Electromagnetic flowmeters are not suitable for gas but they can be used with a wide range of liquids and slurries since different liner and electrode materials are available. This also allows them to be used for a relatively wide range of temperatures. Table 4.6.1 gives temperature ranges and typical applications for some different liner types. Several other liner types are also available. Typical electrode materials are non-magnetic stainless steel for non-corrosive liquids, platinum, platinum/iridium, tantalum and titanium for corrosive liquids. Others are gold, zirconium and Monel.

The main fluid property affecting these meters is conductivity. The minimum conductivity depends on the design of the meter. Minimum values are generally in the range 0.05 μS/cm to 20 μS/cm. The meter output is generally independent of the fluid conductivity when it is uniform inside the meter, errors may occur if this is not the case. Most commonly metered fluids have conductivities above 5 μS/cm and all commercial meters will operate under these conditions.

The maximum pressure is determined by the flange rating and the liner material. It is important to specify whether the meter will operate in vacuum conditions because of possible liner deformation effects. As the flow tube is protected from the process fluid by the liner, it need not be compatible with the process fluid. The suppliers' advice should be sought if necessary.

4.6.5 Influence of installation on applications

In general installation requirements for electromagnetic flowmeters are among the least critical for any type of flowmeter, except for positive displacement meters (group 3). The meters are available with the flowtube and transmitter assembled as one unit or as two separate entities. The advantage of the former arrangement is that it minimizes the stray impedance due to the connections to the electrodes and hence enables the system to function satisfactorily on liquids with conductivities down to the lower limit. On the other hand, electronic components set the upper temperature at which the system will function satisfactorily, probably 80 °C, which is appreciably less than the limit imposed by the ability of the flowtube lining to withstand the process temperature.

An important installation consideration is to ensure that the meter is always full otherwise errors will result. Also where the fluid is not in contact with the electrodes there is no output, as shown in Figure 4.6.3. Hence the ideal arrangement is for the meter to be installed in a vertical pipe, particularly if the process fluid is a slurry. In some applications it is necessary to arrange a bypass so that the flowtube can either be cleaned in situ or removed for cleaning. If none of these arrangements is possible, then it is important to orientate the flowtube so that the axis of the electrodes is horizontal. This avoids loss of signal due to bubbles of gas passing over the electrode which is probably more serious than the discrepancy between the apparent and true flow rate caused by the entrained gas. It also avoids the problem of deposits coating the bottom of the meter tube, and therefore one of the electrodes.

The ideal installation for any flowmeter is one in which the velocity flow profile is fully developed but for electromagnetic flowmeters a straight length of pipe 10 diameters long inserted immediately upstream of the flowtube is sufficient to reduce the velocity error due to a bend or elbow to less than 1 %. The configuration of the pipework downstream of the flowtube has virtually no effect on the performance of flowmeter. Installation effects are discussed in detail by de Jong (1978) and Deacon (1983).

Electrical continuity between the flowing fluid and the metal body of the flowtube is required to establish the reference potential for the measurement signal. When unlined metal pipes are connected to the flowtube continuity can be provided via the flange bolts but it is preferable to provide conducting straps between adjacent flanges, as shown in Figure 4.6.4(a), to avoid uncertainty that may arise if a gasket is installed and the bolts themselves do not make good electrical contact. If the pipework is lined or non-conducting, earthing rings have to be used at each flange as shown in Figure 4.6.4(b). These rings are circular metal plates each having a tab for the electrical connection and concentric hole slightly smaller than the bore of the flowtube but not causing disturbance of the flow or having any effect on the flow profile. In addition to providing the electrical connection, these rings also serve to protect the leading edge of the flowtube lining when measurement involves an abrasive or hostile fluid.

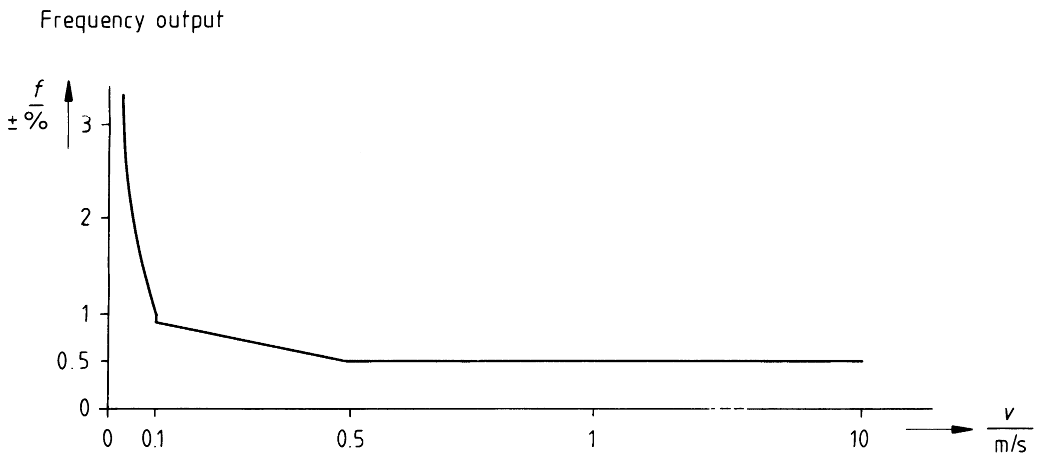
Care should also be taken to ensure that the flow tube is properly aligned to the adjoining pipework, particularly in the case of flangeless types. It is important to avoid damage to the flowtube lining during installation. For the larger sizes, lifting eyes are usually attached to the flanges but if these are not available then the lifting tackle should be attached to the sections of the flowtube adjacent to the flanges. The majority of flowtubes are fitted with standard flange connections. It should be noted that often the temperature and pressure rating of the flowtube may not match that of the flanges which are fitted.

Specially constructed flowtubes are available for operation at pressures as high as 300 bar. The short form or wafer type flowtubes in which the measuring section is formed entirely in ceramic material is not only characterized by outstanding resistance to wear and chemical erosion but also provides greatly enhanced mechanical strength particularly at high temperatures.

4.6.6 Environmental influences on applications

As with most meter types, ambient temperature and humidity, particularly where the secondary electronics are mounted on the flow tube, should always be considered. Ambient temperature limits vary but a typical range is – 10 °C to + 50 °C. Recommendations for relative humidity limits are not usually stated in the literature, therefore the manufacturer's advice should be sought. Various levels of environmental protection (i.e. IP 65, IP 67, IP 68, IP 20 and IP 51) are available. Submersible versions are available for applications where the flow tube may become submerged or even operate continuously under water. Explosion proof designs can also be obtained.

Several factors should be considered when the electrical installation of a meter is being carried out. The cables carrying the electrodes and reference signals should be of the type approved by the manufacturer (usually supplied with the meter) and their length should not exceed the maximum recommended value. This is because the minimum conductivity value is affected by the distance between the flowtube and the meter transmitter. Suppliers guidelines should be sought where necessary. The signal cables should be routed well away from power cables, motors, etc. which produce electrical radiation.



Flow velocity	Error
0.5 m/s to 10 m/s	< ±0.5 % of measured value
0.1 m/s to 0.5 m/s	$\pm\left(1 - \frac{v}{1\ \text{m/s}}\right)$ % of measured value
0 m/s to 0.1 m/s	± 0.001 m/s = ±1 mm/s

Key:

F is the error in % of measured value

v is the flow velocity

Figure 4.6.2 — Typical pulsed d.c. electromagnetic flowmeter performance curve

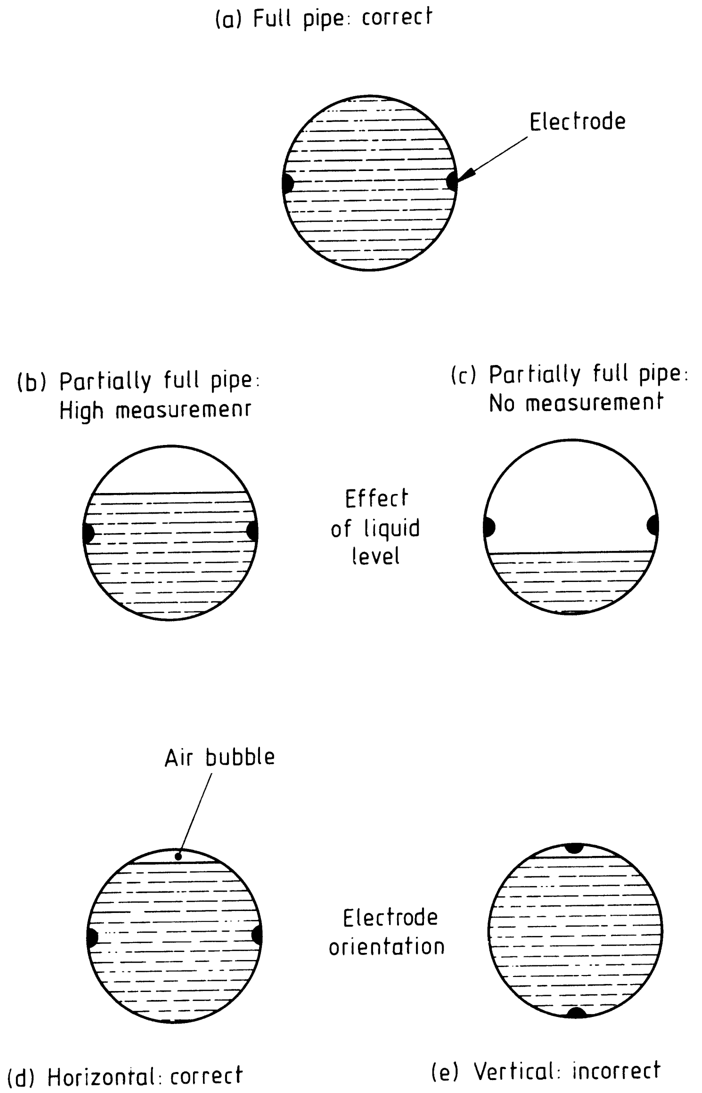
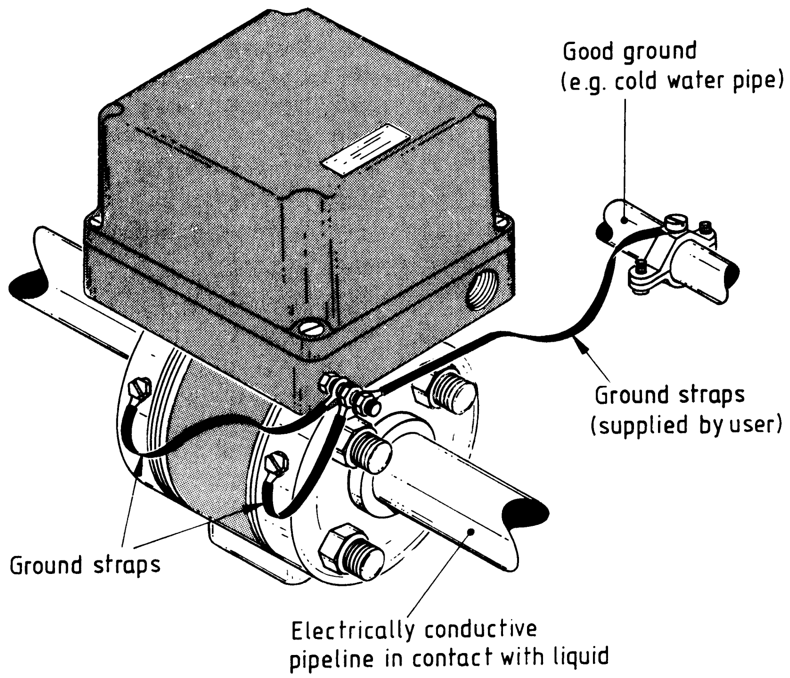


Figure 4.6.3 — Electromagnetic flowmeter installation pitfalls

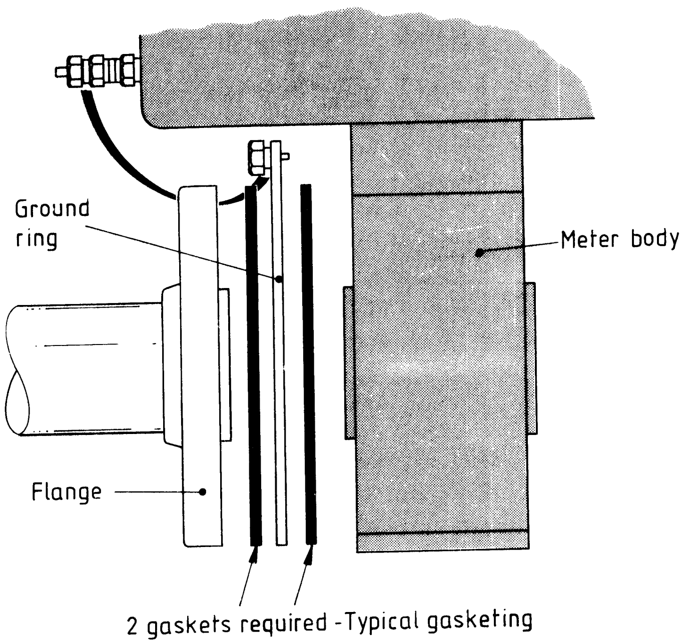
4.6.7 Economic influences on applications

The purchase price is obviously dependent on several factors, e.g. liner and electrode materials, pressure rating and size. Electromagnetic meter performance claims are high relative to many other types of meter and their purchase price is comparable to turbine meters at line sizes of 100 mm and above. Electromagnetic meters however are available in much larger sizes than are turbine meters.

Maintenance costs should be minimal if the meter matches the application since there are no moving parts. Normally no maintenance other than periodic checking or re-ranging is required. Electrode cleaning can also be carried out in-line via ultrasonic or burn-off cleaning methods. The a.c. types are susceptible to coating by non-conductive materials and the specification of the chemical nature of the stream is therefore important. Generally the newer d.c. type meters are less prone to these problems. In some designs removable electrodes are also available.



(a) Conductive pipe



NOTE Metal ring in contact with liquid (supplied by user). A quantity of four gaskets are needed for proper installation of the two grounding rings required.

(b) Non-conductive pipe

Figure 4.6.4 — Installation details for electromagnetic flowmeter installations

The meters are calibrated before delivery but at present as with most flowmeters, there are no recommendations as to when periodic recalibration should occur. Calibration checks at both zero and maximum flow are recommended to check for drift at either end of the flow range. Ideally the meter should be wet calibrated, but some meters are supplied with a simulated dry calibration only. For lowest uncertainty a comprehensive flow calibration is necessary.

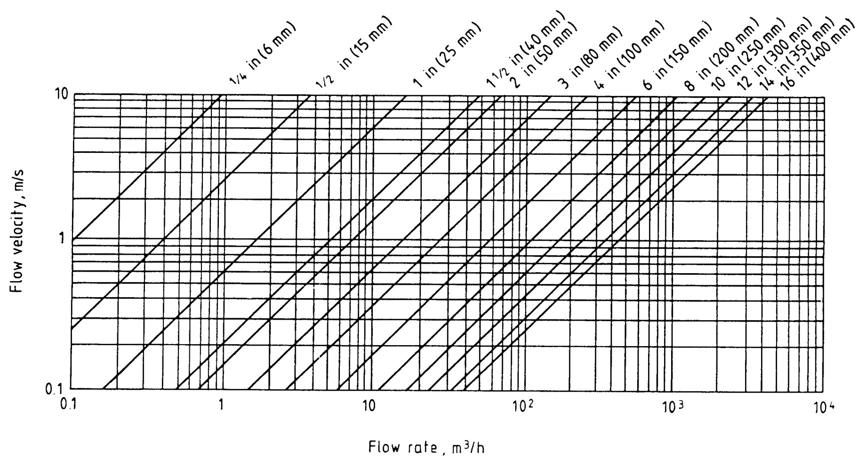
Installation costs can be relatively low compared to some other meters since the upstream straight length required is relatively short. A bypass will be necessary in some applications but the meters do not generally require the installation of filters. This, together with their obstructionless design means that they do not create any significant head loss. Usually the bore of the meter tube will be the same as that of the adjacent pipework. If, in this case, the axial velocity corresponding to the maximum flow rate is less than that recommended by the manufacturer, a primary device with a smaller bore should be used. A primary device with a bore smaller than that of the adjacent pipework may also be used for other reasons, e.g. to reduce cost or in the interests of rationalization. Information on the allowable tolerance for matching the pipe and meter tube bores is given in ISO 9104. Most manufacturers can supply the relevant sizing data in the form of a graph, an example of which is shown in Figure 4.6.5.

The secondary device of most pulsed d.c. and the latest miniature magnetic flowmeters can often be checked by injection of reference signals and it is recommended that this be undertaken at frequent intervals. Provided the flowtube and liner are acceptable for the application, spares kept may include the complete electronic unit or possibly spare circuit boards. The latest electromagnetic insertion meters require complete spare meters to be kept.

4.7 Group 7 meter applications: ultrasonic types

4.7.1 General

The applications database on both Doppler and transit time ultrasonic flowmeters is growing rapidly as these types of meter are being evaluated and used on many new applications. Until a short time ago industrial success was mixed, much of this caused by the confusion over the two types. It should be remembered that, although the Doppler and transit time types are both ultrasonic meters, their performance, application and operation is quite different. In certain applications ultrasonic meters, especially transit time types, are now giving good reliable service. This section of the guide clearly distinguishes the different characteristics of the two types in application terms.



NOTE To select the meter size:
find meter sizes within the velocity of 0.3 m/s to 10 m/s (vertical scale) for a specified full-scale flow rate (horizontal scale). Select one meter size that is less than or equal to the pipe size. When more than one meter size fits, select one that has its full-scale velocity between 1 m/s and 3 m/s.

Figure 4.6.5 — An example of a manufacturer's electromagnetic meter sizing chart

4.7.2 General applications

4.7.2.1 *Transit time meters*

Transit time meters, both single and multiple path, can be applied on a wide range of clean, single phase liquids and with modified transducers, to gases. The multiple path ultrasonic flowmeter can be used when flow conditions are relatively poor and still gives good performance. In particular, for large pipe installations with poor velocity profiles, the multiple path ultrasonic meter may be the only practical method of achieving a reasonable performance without in situ calibration. There is no upper limit on the pipe size that can be used. Several multiple path transit time meters have been installed on pipes of 10 m bore. Typical applications for transit time meters would include:

a) water flows;

b) plant effluent (reasonably clean);

c) liquid propane gas (LPG) or liquid natural gas (LNG);

d) clean chemical streams.

The main application for an ultrasonic flowmeter with clamp-on transducers is a portable instrument for measuring totalized flows or flow rates in pipes with no installed flowmeters. Adjustable scaling should be incorporated, with appropriate techniques for deriving the scaling factors, and transducer spacings to suit particular pipe geometries. The linearity is generally good and the rangeability adequate for many applications, particularly where the flow can be stopped to check the meter zero setting.

4.7.2.2 *Doppler flowmeters*

The main application of the Doppler ultrasonic flowmeter is on pipes carrying liquids containing sufficient proportions of either bubbles or solids to give strong reflected signals. Due to the uncertainty on the velocity of the particular discontinuities being monitored relative to the mean fluid velocity in the pipe, the uncalibrated performance can be very low. Consequently, these instruments are mainly used as flow rate indicators or switches, unless evaluation tests indicate that the particular fluid can give reliable and consistent signals. Performance, however, varies considerably between suppliers.

Doppler type meters work well on raw sewage, sludge, aerated fluids (not high air content) plant effluent and dirty process liquids. They are generally unsuitable for very clean liquids unless the flow is seeded or the turbulence level is high enough to obtain a signal.

4.7.3 Influence of meter performance on applications

4.7.3.1 *Transit time meters*

Single path ultrasonic flowmeters have few fundamental constraints, other than those detailed in the following subclauses. The velocity profile through the meter should be reasonable if the specified performance is to be achieved. Particular limitations relate to change of accuracy with flow rate, due to changes in velocity profile with Reynolds number, and zero drift which may necessitate periodic resetting with the pipe flow reduced to zero. The best performance is obtained by the use of a dedicated spool piece and a typical commercial design is shown in Figure 4.7.1.

The clamp-on design has a larger measurement uncertainty than either the single or multiple beam designs where the transducer is in contact with the fluid. Due to uncertainties in clamping the transducers to the pipe, variations in acoustic coupling, condition of the internal pipe bore and actual path length, the overall uncertainty is around 3 % of reading over flow ranges of 20 : 1. One such commercial design is shown in Figure 4.7.2. It should also be noted that the user is often required to specify the pipe materials and dimensions for clamp-on meters. Use on unspecified pipes could severely affect performance. This may restrict their use as a flexible, portable instrument.

The uncertainty of wetted transit time meters varies between 0.5 % of reading for the large multiple beam systems and up to 3 % of reading for the smaller single beam design. Experience has shown that the application governs the performance to a large extent.

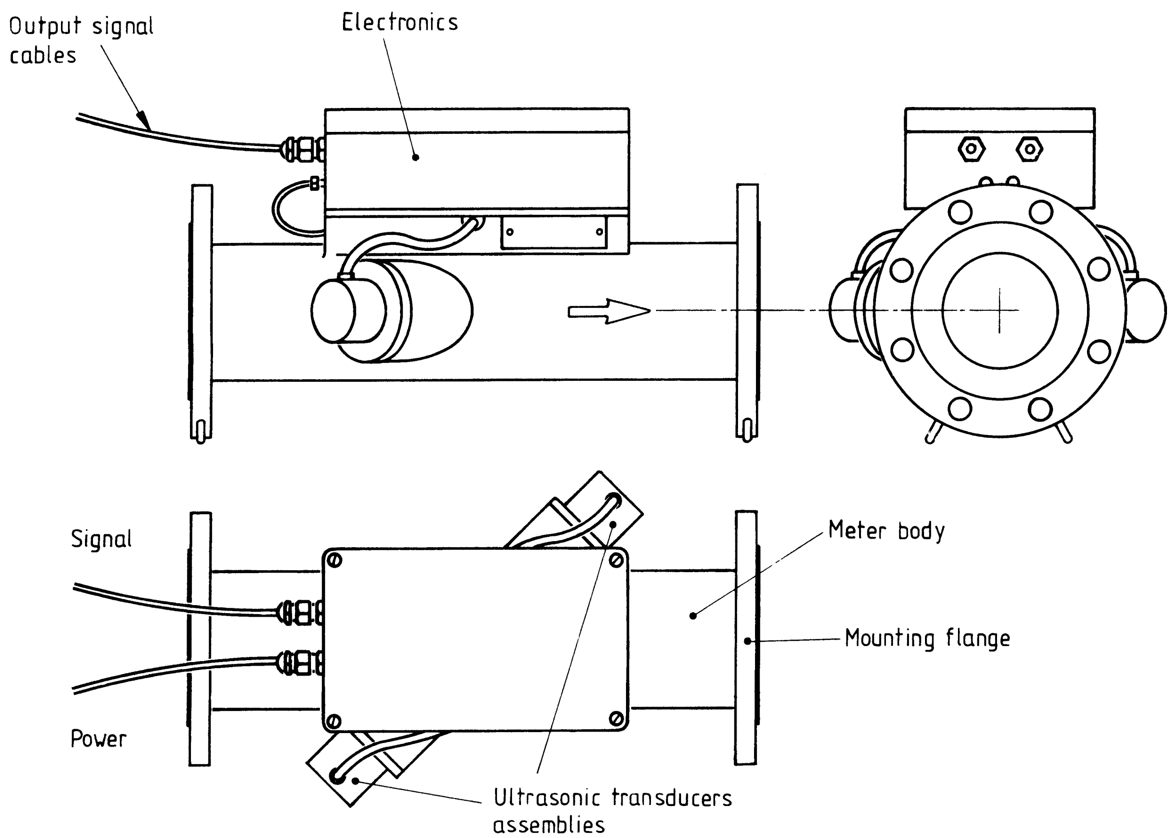


Figure 4.7.1 — Typical transit time ultrasonic flowmeter spool piece

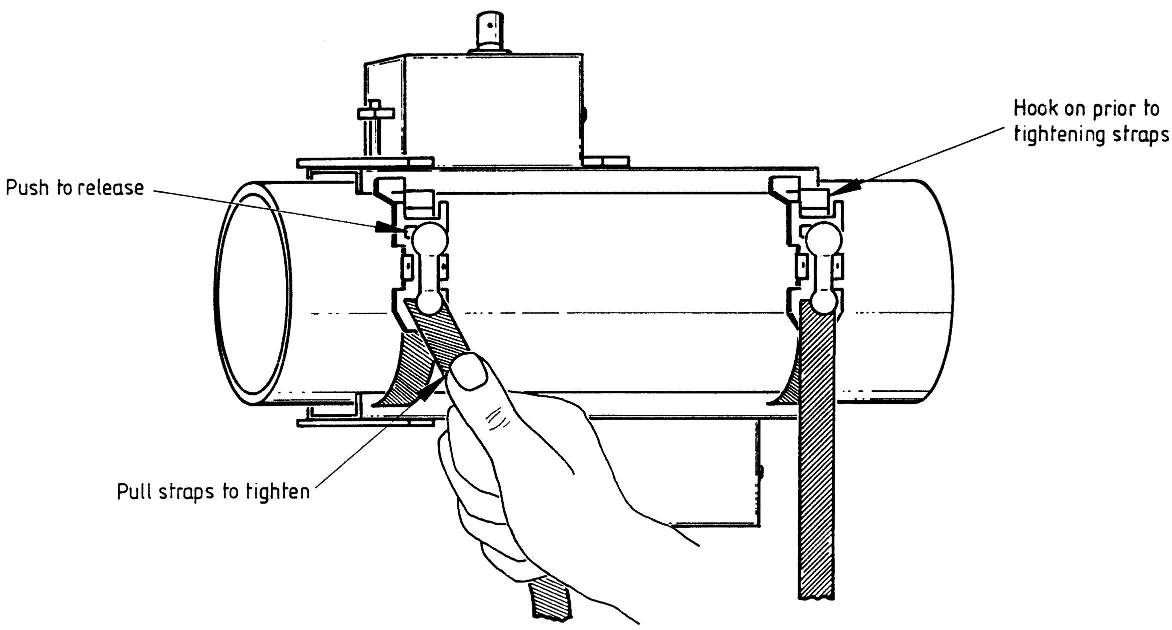


Figure 4.7.2 — Clamp-on transit time ultrasonic flowmeter

4.7.3.2 ***Doppler meters***

Because of their potential as clamp-on non-intrusive flowmeters, Doppler type instruments tend to be used on unsuitable applications. This is particularly true where high performance claims are made. Consequently they have achieved a rather poor reputation apart from simple applications such as flow indicators or switches. Modern equipment, when used correctly on suitable liquids, can give satisfactory results over a wider range of applications, but care is still required in matching the equipment to each particular situation. Typical performance claims range from 0.5 % to 10 % of full scale for measurement uncertainty with repeatabilities of ± 0.2 % of full scale. In some cases the region of flow interrogated, and so the velocity measured, may change with the concentration of charged particles. Again many of the claims cannot be substantiated, but it is clear that the Doppler based technology does not give the same overall performance as the transit time meters.

4.7.4 Influence of fluid properties on applications

4.7.4.1 ***Transit time meters***

The main consideration for transit time devices is that the fluid should be a homogeneous single-phase, as quantities of other phases can interfere with the transmission of acoustic energy along the path. For liquids, considerable successful experience has been obtained on water and hydrocarbon applications, and for gases, good results have been demonstrated on high pressure natural gas. If the quantity of the second phase present is low then it may be possible by using sophisticated electronic techniques, such as flywheel circuits, to reduce the effects of lost signals.

Fluid pressure is not normally a problem provided the transducer assemblies are suitably designed. Fluid temperature can offer constraints depending on the particular type of piezo-electric material used in the transducer, and the presence of temperature sensitive material, such as plastics, in the transducers. One particular design has been used at temperatures up to 300 °C but such specialized transducers tend to be expensive. Temperature stratification in the fluid can also be a problem, giving reduced performance, but the stratification present in most industrial situations is unlikely to be a major constraint.

The acoustic properties of the fluid can be important and, for some types of ultrasonic flowmeter, the velocity-of-sound characteristics at operating conditions are required for compensation purposes. It is difficult to achieve satisfactory acoustic coupling in low pressure gases, and this leads to poor signal-to-noise ratios.

Flow velocity should be turbulent for the lower measurement uncertainty. Laboratory data indicates a shift in meter factor between laminar and turbulent flow and most manufacturers specify a minimum flow velocity above which the instrument performs within the stated specification. Sizing data is often supplied in the form of tables and an example is shown in Figure 4.7.3. Chemicals may present problems if corrosion, crystallization or fouling of the transducer occurs. This will affect the efficiency of acoustic transmission and could introduce systematic errors. The supplier should be aware of the end application especially in a new or untried installation. This is not so much of a problem with clamp-on or Doppler meters but inside pipe characteristics may be affected in a similar manner.

Gas applications are generally not recommended for ultrasonic meters with clamp-on transducers due to the difficulty in transferring sufficient acoustic energy through the pipe wall. Non-Newtonian fluids also present problems since their velocity profile development is different than for Newtonian fluids. Applications experience in this area is very limited.

4.7.4.2 ***Doppler flowmeters***

For Doppler flowmeters some fluid discontinuities are necessary. These could be gas bubbles, dirt particles or even a second immiscible liquid. Typical minimum concentrations are around 0.5 % for a sensitive meter but signal attenuation will occur at high void fractions.

Attempts have been made to use Doppler type ultrasonic flowmeters on clean liquids such as water without significant gas or solids content, relying on turbulence eddies to reflect the acoustic energy. Results have been variable and potential purchasers should ask for a practical demonstration on their particular application to show if acceptable results can be obtained. With current advances in transducers and electronic circuitry it is probable that improved success rates will be obtained.

4.7.5 Influence of installation on applications

4.7.5.1 *Orientation*

In general, ultrasonic flowmeters can be mounted in horizontal, inclined or vertical pipes. In horizontal and inclined installations the transducers should not be positioned in a vertical plane, otherwise the transducer faces can be affected by solids or gases in liquid flows, or solids or liquids in gas flow.

4.7.5.2 *Direction of flow*

By suitable design, ultrasonic flowmeters can be used in bi-directional flows although this may require more complex electronic circuitry.

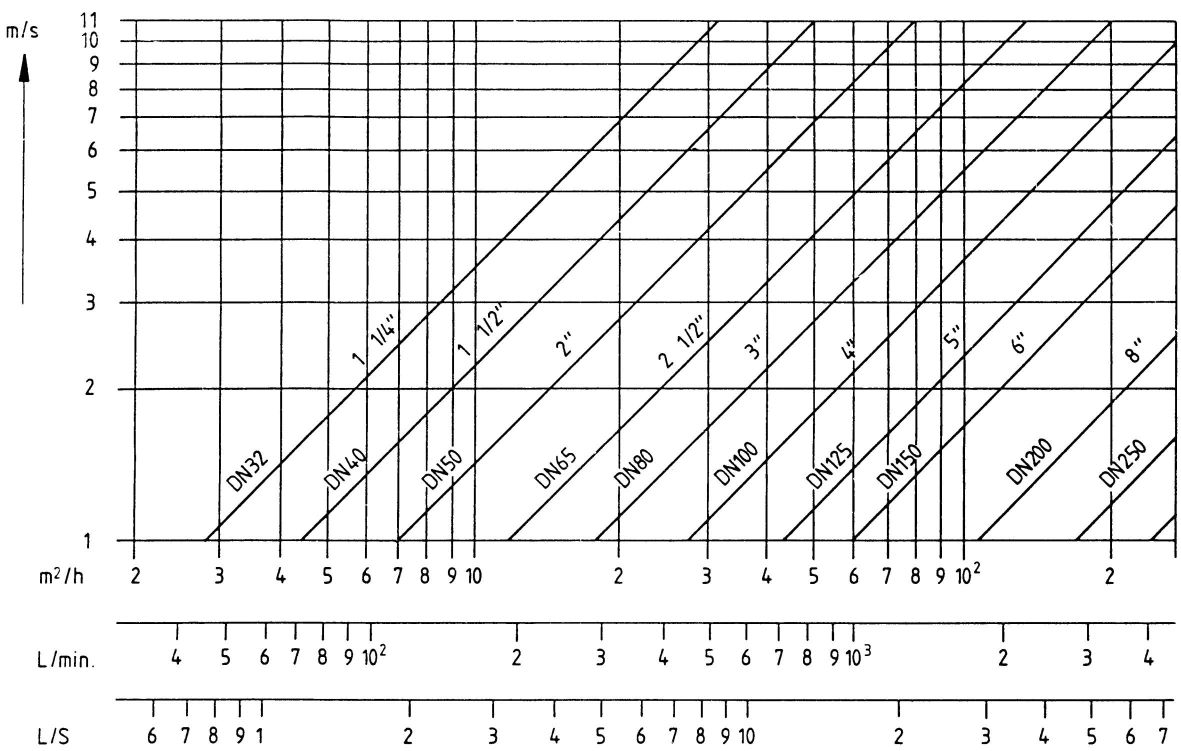


Figure 4.7.3 — Part of sizing table for transit time ultrasonic flowmeters

4.7.5.3 *Upstream flow disturbances*

Like most other flowmeters, the acoustic flowmeter is sensitive to the velocity profile of the fluid through the meter. The upstream and downstream straight pipe length requirements for orifice plates, as quoted in BS 1042-1.1 can be used as a general guide for ultrasonic flowmeters. Most suppliers quote requirements of at least 10 *D* of straight pipe upstream and 5 *D* downstream, but this minimum upstream length is certainly inadequate for single beam systems. Recent experimental work (see Hϕjholt 1986) has shown that shifts of between 3 % and 10 % of rate have been observed for common upstream disturbances (e.g. 90° bend) at a spacing of 10.4 *D* between the disturbance and mid beam plane.

The multi-beam meter is much less sensitive to upstream disturbances and as a result can operate in more disturbed flow profile applications with little or no change in overall performance. Hϕjholt (1986) shows that two-beam systems installed downstream of various disturbances showed shifts of up to 2 % of rate for a spacing of 10.4 *D* between the disturbance and mid beam plane. This data casts doubt on some manufacturers' claims. Generally, twin beam meters require approximately 15 *D* to 20 *D* upstream and single beam meters require at least twice this (i.e. 30 *D* to 40 *D*). The multiple path meters require less upstream length than two-beam meters.

The considerations given also apply to the clamp-on designs.

4.7.5.4 ***Pipe conditions***

Deposits on the inside surface can create poor acoustic transmission or deflection from the expected path length. The outer surfaces are less critical, as paint or light corrosion do not normally affect acoustic transmission provided a suitable couplant is used between the transducer and the pipe surface. It should also be noted that pipes manufactured with a granular structure (e.g. concrete and cast iron) are likely to cause ultrasound dispersion and consequently most of the sound will not be transmitted into the fluid and performance will be poor.

4.7.5.5 ***Doppler meter installation***

Due to the lower inherent performance of these meters, the constraints on upstream lengths can often be relaxed to some extent without significantly worsening the overall uncertainty. The comments made in **4.7.5.4** about pipe materials and conditions also apply to Doppler meters.

4.7.6 Environmental influences on applications

Environmental conditions around the spool piece and transducers are not generally a problem. If the electronics are mounted with the spool piece then there may well be constraints on temperature and humidity. Particular care is required for intrinsically safe operation and sensitive fluids, and certain designs may well be unsuitable.

4.7.7 Economic influences on applications

Ultrasonic flowmeters tend to be more expensive than many alternative types in small pipe sizes. However, costs do not rise appreciably with an increase in pipe size, so that they become more cost effective as size increases. Further details are found in Figure 2.5(b). The multiple beam systems are generally much more expensive due to the need for computational electronics to central multiplex and operate the multiple beams. This may prohibit their use on the smaller sizes to those applications where low head loss, non-intrusive but relatively low uncertainty metering is required. Where pipe layout is a problem, the multiple beam system may be the only sensible solution.

Due to the flexibility of the clamp-on ultrasonic flowmeter, the purchase cost can often be spread over a number of applications making it a viable proposition, provided the problems of use on pipes of different dimensions and materials are taken into consideration.

Ultrasonic flowmeters are generally calibrated by the manufacturers so this item is included in the price. When high performance it required, in situ calibrations are desirable, but in many cases such calibrations are impractical due to lack of suitable techniques. In some cases the method used to calibrate the meters has an inferior uncertainty to the meter being calibrated. For example, tracer methods on large bore pipes are approximately twice the uncertainty of the meter they are intended to calibrate.

Additional pumping or fan power requirements and costs are almost zero due to the virtual obstruction-free construction of the spool piece. Electrical running costs are low owing to the use of modern electronic digital circuits. A large amount of modern semi-conductor electronics is used in their manufacture and this should make them reliable. However, if they do fail, then maintenance can be more difficult and expensive than for some of the alternative types of meter. Plug-in replacement circuit boards offer one solution which may be cost effective in particular circumstances, although this may involve a calibration check if certain of the boards have been replaced.

4.8 Group 8 meter applications: direct and indirect mass types

4.8.1 General

As discussed in **3.8**, mass may be measured by direct or indirect means. Where volumetric flowmeters are used together with densitometers (see **5.3**) or pressure and temperature elements (see **5.1** and **5.2**), the application constraints are discussed in section 4 for the relevant meter selected. In this section discussion and comments are therefore confined to the direct type mass meters.

4.8.2 General applications

Mass metering is growing significantly in many industries. Petroleum, chemical, food and energy related industries have an increasing need to improve plant or process efficiency. Direct mass flowmeters (in particular Coriolis types) are finding increasing applications where plant processes are highly variable and where fluids being metered are beyond the range of indirect mass types. Those industries metering on a mass basis include the following:

a) petroleum, both offshore/onshore and in pipeline product allocation;

b) chemical, in batching, blending and process;

c) food, in batching, blending and process;

d) energy, in engine testing and turbine monitoring;

e) distribution, in truck, rail and tanker loading;

f) cryogenics, truck loading and process.

Some success has been reported where aggressive chemicals need to be metered. If the tube materials are chosen carefully, the same meter can be used for a number of fluids, for example in the same batch reactor. This will reduce uncertainty where different fluids are mixed to a precise recipe, and eliminates multiple flowmeters on the individual lines.

The frequency of vibration of the tube also varies with the density of the fluid in the tube. Therefore, in addition to a mass flow output signal, most suppliers are also able to offer a signal output proportional to density. It should be stressed however that the output signal frequency is a non-linear function of density and may not be directly usable unless conditioning electronics are also provided.

4.8.3 Influence of performance on applications

4.8.3.1 *Indirect mass meters*

Indirect mass systems have a typical rangeability of 10 : 1. This may be reduced significantly by the effects of fluid properties on the performance of the type of meter used (see **3.8** for individual meter characteristics). Techniques to extend the flow range by electronic methods (linearization) are possible providing the flowmeter is repeatable. Restrictions on flow range are limited by the desired performance and mechanical constraints of the equipment chosen.

4.8.3.2 *Coriolis types*

Direct mass meters can have rangeabilities up to 100 : 1. Rangeability is normally dictated by the overall performance requirements and maximum allowable pressure drop. The quoted uncertainty varies considerably between manufacturers, with claims as high as 0.15 % of reading being made, although 0.4 % to 0.5 % of reading is more easily demonstrated. These meters are available up to 6 in. nominal bore and flow rates up to 9 000 kg/m. However larger sizes are rather cumbersome and heavy, and installation may present problems.

Overall performance of mass measurement systems are generally governed by uncertainties associated with the system design. There are several examples where comparisons between weighbridges, volumetric flowmeters with associated densitometers and Coriolis mass meters have been made. These show that the uncertainties of using a single mass meter are lower than the flowmeter/densitometer combination. Indirect mass systems comprising of volumetric flowmeter and densitometer will have uncertainties given by:

$$U_{ind} = \sqrt{(U_{vl}^2 + U_{den}^2)} \qquad (4.8.1)$$

where

U_{ind} is the total uncertainty of indirect mass measurement (in %);

U_{vl} is the total uncertainty of volumetric measurement (in %);

U_{den} is the total uncertainty of density measurement (in %).

It should be noted that U_{vl} and U_{den} should include the uncertainties associated with calibration devices and any temperature correction made. Furthermore U_{den} refers only to the transducers and not the representative nature of the sample taken. Total system uncertainty is therefore given by the root sum square of all the individual component uncertainties, as shown in Appendix B.

Direct systems have outputs directly related to mass and therefore can be calibrated directly against weigh scales. System uncertainties would be:

$$U_{dir} = \sqrt{(U_{dm}^2 + U_{ws}^2)} \qquad (4.8.2)$$

where

U_{dir} is the total uncertainty of direct mass measurement (in %);

U_{dm} is the total uncertainty of direct mass meter (in %);

U_{ws} is the total uncertainty of weigh scale (in %).

It is important to note the traceability of any calibration methods used. Direct systems can have a much shorter traceability to national standards than volumetric-based indirect mass systems, thus reducing overall systems uncertainties significantly.

Excessive pressure drop in any system is expensive and in addition may cause damage to mechanical flowmeters. The Coriolis direct mass meter is restricted on pressure drop only by the maximum pressure rating of the meter itself. Typical pressure drop for all types of flowmeter is 0.2 bar to 0.3 bar when the meter is operating in the middle of its quoted range. At maximum flow however this could easily rise to 3 bar or more as shown in Figure 4.8.1 for one commercial design. This may limit applications unless a meter larger than the line size is installed. The suppliers can assist in sizing the meter for optimum pressure drop if head loss in the system is critical. Most publish specifications giving the user sizing charts and procedures to select the correct meter.

With additional losses occurring across strainers, air or gas eliminators, straighteners and valving, the total system loss should be carefully assessed to avoid significant amounts of cavitation which will affect meter performance. Recent experimental work suggests the meter is sensitive to high void fraction two-phase air-water flows. Data also indicates that slugs of gas in the liquid also affects output and performance.

The dynamic response is dependent on the type of primary metering element chosen and method of signal transmission. With correctly sized flowmeters response times are typically:

indirect, less than 100 ms

direct (Coriolis), 100 ms to 10 s (adjustable).

Response times are often increased to smooth out unwanted fluid noise, for example that caused by positive displacement pumps.

4.8.3.3 ***Wheatstone bridge meters***

The hydraulic Wheatstone bridge meter can measure flows from 0.05 kg/h to 280 kg/h. Sizing of the meter is best performed by the supplier since each meter is custom-built for a particular application. Meter uncertainty is around 0.5 % of rate with repeatabilities of approximately half of this value. Operating pressure is limited to 70 bar and temperatures range from – 30 °C to + 150 °C.

4.8.4 Influence of fluid properties on applications

4.8.4.1 ***General***

In general, indirect systems are designed and sized to handle one fluid over a given flow range. Meter calibration is best performed using the actual process fluid, since many volumetric flowmeters are affected by changing fluid properties and hence the factory calibration on standard fluids may not be transferable.

Coriolis type mass meters generally have no such constraints and are claimed to be relatively unaffected by viscosity, density, temperature and pulsations. Some evaluation data taken recently tends to cast some doubt on the total validity of these claims, with shifts of the order of 0.1 % of reading being observed between ethylene and water. Generally however, the factory calibration can be transferred to another process fluid with a small increase in uncertainty. The zero stability however should be checked periodically for possible drift effects.

The hydraulic Wheatstone bridge types should be used at viscosities below 50 cP, because of limitations of the pump. Large shifts in performance have been reported at high viscosity and these will be unknown unless the meter is calibrated in situ.

4.8.4.2 ***Density and compressibility***

Density determination in indirect systems can be made by in-line transducers or by sampling methods. Care must be taken to ensure that any density measurement is representative of the metered density.

Compressibility effects can induce errors on indirect systems using volume meters in conjunction with temperature and pressure measurement. This type of problem is typically associated with the petroleum industry.

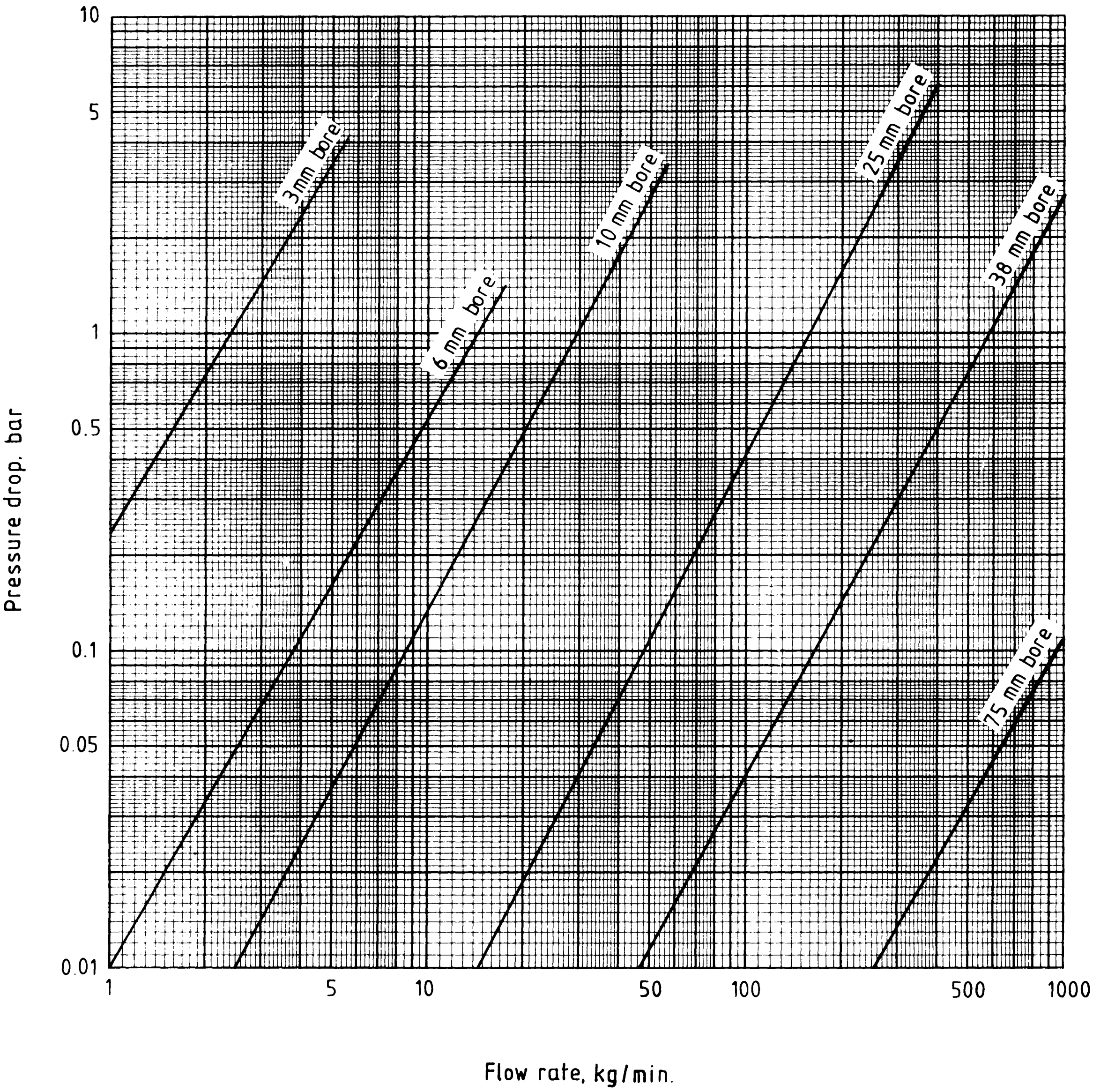


Figure 4.8.1 — Typical pressure drop characteristics for Coriolis mass flowmeters

4.8.4.3 ***Two-phase flows***

Measurement of two-phase flow is not yet viable for present day indirect systems. Evaluation of Coriolis meters have shown some promise (up to 15 % gas-in-liquid by volume) providing the gas is finely dispersed throughout the liquid and slug/plug flow is not present. Preliminary experiments have also shown that all meters of this type can have high errors, either positive or negative at higher void fractions, depending on the mounting attitude of the flowmeter. This may be due to a change in flow regime through the flowmeter introducing variable Coriolis force distributions.

4.8.4.4 ***Temperature and pressure***

Limitations are a function of the measuring transducers, and system design. The smaller multiple orifice systems have maximum operating pressures and temperatures as stated in **4.8.3.3**. At low mass flow rates, it is necessary to control the flow to within ± 1 °C to maintain the claimed performance. The Coriolis types can withstand temperatures up to 245 °C and flanged units are available up to ANSI 600. These meters should not however be used at elevated pressures and temperatures unless the supplier has checked the application. This could result in tube failure if the instrument is used outside the prescribed limits.

4.8.4.5 ***Lubricity and abrasiveness***

When metering low lubricity and abrasive fluids it is advisable to keep fluid velocities as low as practicable. High velocity not only causes premature component failure and wear but also degrades the system performance.

4.8.5 Influence of installation on applications

4.8.5.1 ***Orientation***

All standard mass systems can be mounted in horizontal or vertical pipes. It is important to ensure that pipes remain full as significant errors may result from partially full lines. The hydraulic Wheatstone bridge types should be mounted on a solid base, as should the older versions of Coriolis meters but the new designs of Coriolis meters can be directly mounted in-line.

4.8.5.2 ***Direction of flow***

In general, mass systems are configured to measure flow in one direction only. The exception is the Coriolis meter. When reverse flow is required this is accomplished by suitable valving and changeover piping, or in the case of Coriolis meters, by calibration in both directions to determine any difference in meter factor. In this case no changeover valving is required.

4.8.5.3 ***Pipe configuration***

Upstream and downstream straight pipe length requirements are dictated by the choice of individual flowmeter. If insufficient space is available, flow straighteners may be utilized. For the hydraulic Wheatstone bridge types, it may be necessary to install upstream filters to protect the pump, if dirty fluids are being metered.

Direct mass meters of the Coriolis and differential pressure type have no requirements for upstream/downstream pipe configuration and this is one of the most attractive industrial features of these meters. Care should be taken to avoid cavitation induced by partially open valves or mismatched pipe diameters.

4.8.5.4 ***Electrical connections***

It is good practice to avoid combining signal and power cables. Signal cable specifications are usually given by the manufacturer to ensure transmission integrity.

4.8.5.5 ***Pulsation effects***

Fluid pulsations can be generated by pumps, etc. These pulsations may show up in the flowmeter signal output in the form of a beat frequency superimposed on the flowmeter frequency output. Where this frequency is close to the natural frequency the meter, large errors in performance can arise. In general pulsations and plant vibrations within 30 % of the natural frequency or a harmonic will cause errors in Coriolis type meters.

4.8.5.6 ***Accessories***

The requirements for filters, air eliminators and valving, etc. is dependent upon the type of mass flowmeter, system accuracy requirements and serviceability. Figure 4.8.2 details typical arrangements for direct and indirect systems.

4.8.6 Environmental influences on applications

The primary sensing equipment of most types is not normally affected by environmental conditions. Radio frequencies from local portable radio transceivers can affect some secondary and electronic equipment, most manufacturers supply equipment which is RFI free. Electronic equipment may be adapted for use in tropical environments if required.

Many flowmeters give low level millivolt pulse signals. It is advisable to preamplify these signals before transmissions to the receiving equipment, thus minimizing the risk of picking up interference from power cable, transformer and rotating machinery. Where a high level of security on signal transmission is required, for example in custody transfer applications, the system should be in accordance with IP 252/76-13.1.

4.8.7 Economic influences on applications

Initial purchase price is only one factor when considering the total cost of a mass metering system. In the case of Coriolis meters this is higher than for inferential meters but there is no need to purchase additional temperature and pressure transducers with a flow computer to perform the calculation. Therefore although Figure 2.6 shows the cost of these meters to be high, this is because they are specialized instruments which simplify total mass measurement installations. Coriolis mass meters require no maintenance other than periodic checking of the zero and span adjustments in the electronics. It is however prudent to assess the flowtubes for wear at quarterly intervals if particulate streams are being metered as this may pre-empt sudden unexpected tube failure. Where aggressive fluids are involved, the use of plastics-coated tubes is recommended. Wear and corrosion may also cause long term steady drift in output due to changes in the effective mechanical properties of the vibrating system.

Direct mass meters are no more expensive to install than many other types of meter and they have the added advantage that long inlet and outlet pipe lengths are not required. Spares to be stocked include circuit boards and other secondary electronic components. The latest designs have the sensing tubes sealed inside stainless steel castings to protect the tubes from external corrosion. If sense coil or tube failure occurs then the complete unit will have to be returned to the supplier. Meters installed in critical applications may require a complete spare meter to be kept for these rare eventualities. The cost of stocking certain key electronic components is not high. Electronic equipment tends to be updated frequently; however most manufacturers support their products with spare parts for a minimum of 10 years.

For the Wheatstone bridge designs, maintenance is usually limited to attention to the pump. Spare seals are normally all that is required. There is the possibility of damage to the small orifices in the system from the fluid, and regular checking (twice each year) is recommended. The manufacturers advice on the stocking of spare parts should be sought to minimize possible downtime in the event of failure.

Consideration should be given in the installations to allow for in situ calibration. Calibration can be performed by companies specializing in this field who use master meters, vessels, provers or weigh scales, or by the transducer supplier.

4.9 Group 9 meter applications: thermal types

4.9.1 General

Thermal meters are normally used to measure the flow of clean gases. As discussed in **3.9** they use the thermal properties of the fluid to measure flow velocity or mass flow. They are beginning to find use in small scale industrial gas applications where other types of meter cannot handle the low gas density applications, where other types of meter cannot handle the low gas densities and, in some cases, the low fluid velocities. Applications are limited to those fluids where the heat capacity is known. This infers that gas mixtures of changing and unknown composition cannot be measured with the claimed uncertainty of the meter.

Liquid applications are generally rare. The presence of bubbles or dirt on the sensor can affect heat transfer rate and hence performance. There is also the problem of corrosion to the wire probes and life tends to be limited.

4.9.2 General applications

There are two basic types of flowmeters in this group:

a) heat loss type or the hot wire anemometer and its variants;

b) stream temperature rise or heat transfer type usually referred to in the literature as the Hastings® meter (see Widmer et al. 1982).

They have applications across most industrial and scientific requirements which tend to be restricted to gas flows from very small, less than 1 mL/min to modestly large, up to 28 000 L/min, although when combined with orifice plates have been extended to millions of L/min. The heat loss types are almost always flow velocity instruments and because most have exposed filaments, are susceptible to contamination. Consequently their usefulness is limited to clean fluids unless special precautions are taken. The filament may also have a high surface temperature and so may be considered to be unsafe with certain gases. The second type is a mass flowmeter which, because of its small size, independence from temperature and pressure effects, lack of delicate filaments and moving parts, is used in the so-called high technology industries (such as semiconductor processing) where multi-gas flows are required in controlled proportions.

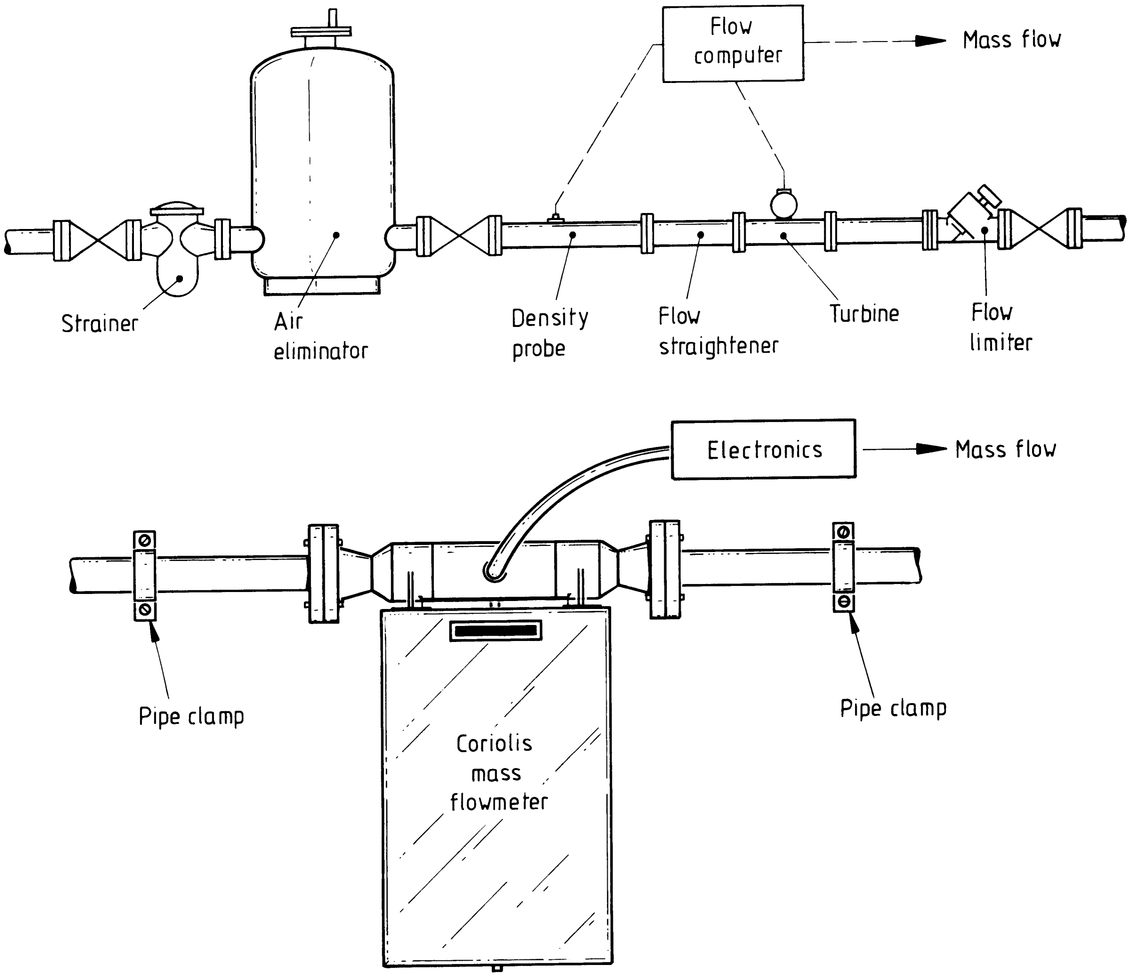


Figure 4.8.2 — Typical installation arrangements for indirect and direct systems

The range of applications for both types is diverse, with respiratory research, environmental studies, missile testing, pneumatic gauging, semiconductor doping, flare stack monitoring, ventilation and air conditioning being just a few examples of fields in which these versatile devices are found. Typical gases with known applications include oxygen, nitrogen, hydrogen, helium, carbon dioxide, ammonia, argon as well as air and refrigerants. Most manufacturers carry extensive data banks of the density, specific heats and other thermodynamic gas properties to enable correction factors to be applied when the gas is calibrated on one fluid (usually air) and used on another.

4.9.3 Influence of performance on applications

4.9.3.1 *Heat loss types*

This group includes hot-wire and hot-film probes, thermocouples both self-heated and externally heated, thermistors and thermopiles, exposed and protected. The majority however offer a simple, easy to use hand-held probe type measurement of air velocity of limited performance, total system uncertainty being of the order of a few per cent, (2 % of flow rate plus 0.2 % of full scale being typical). The repeatability of these meters is around ± 1 % of reading. They are usually capable of high sensitivity to low velocity flows, from about 0.025 m/s, particularly the exposed filament type. For wind speed measurement applications they can be made non-directional and can have the sensors (usually thermocouples) sealed inside corrosion resistant tubes to provide weatherproofing.

Most suffer from contamination and consequent drift, but drift with temperature can be made surprisingly small with compensation and control. Unless protected, exposed filaments are susceptible to damage, however it is usually this type which offers best dynamic response.

The relationship of output with velocity is not a simple square-law but many offer a quasi-logarithmic scaling for both-end range expansion. It is usually the associated electronics which provide linearization as none are inherently linear. A typical output characteristic for an air transducer is shown in Figure 4.9.1.

4.9.3.2 ***Heat transfer types***

Within their available flow range, thermal flowmeters of this type have the great advantage of measuring gas mass flow directly. No secondary electronics are required to compute mass flow from temperature, pressure and velocity. The signal conditioning simply applies scaling and amplification to produce a standardized signal, i.e. 0 V d.c. to 5 V d.c. or 4 mA to 20 mA, etc., the output from the transducer (Hastings type) being inherently linear. Over-range flows will produce an output signal which is useful though non-linear.

Uncertainty is typically 1 % full scale though the latest designs offer 0.5 % full scale which includes non-linearity. Generally linearity is of the order of ± 0.2 % full scale. Stability of performance is high with recalibration periods of 12 months being normal but rarely adhered to by most users.

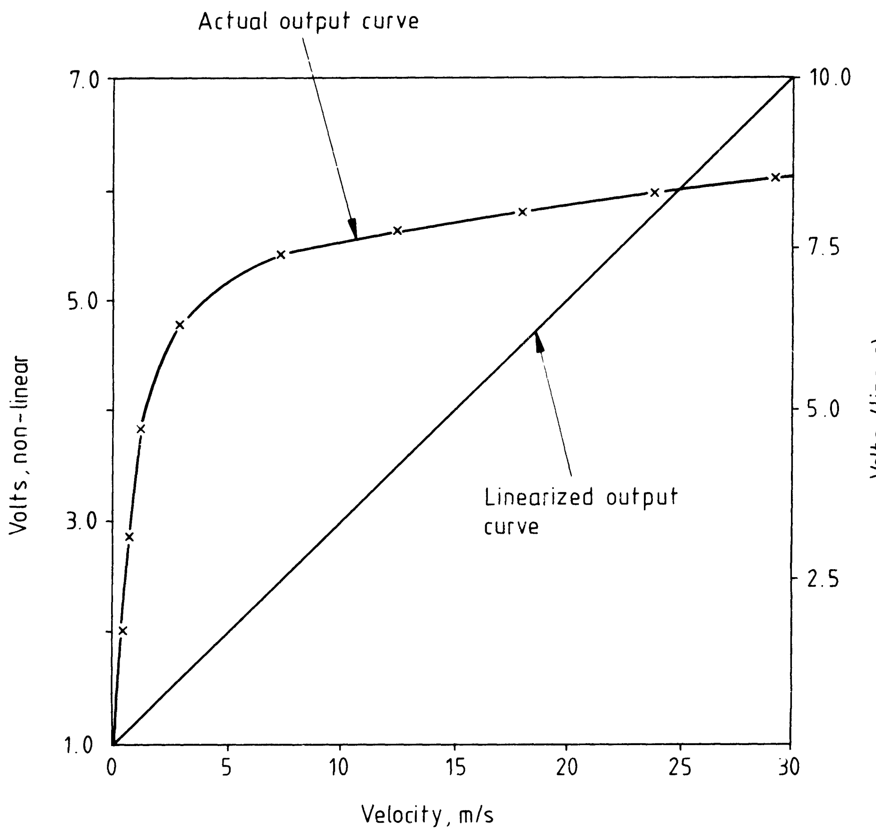


Figure 4.9.1 — Output characteristic of a thermal anemometer

Measurement repeatability of 0.2 % full scale or better is common among the better designs and although comparable performance is often claimed with cheaper types it is seldom achieved.

A typical output curve for a thermal meter of this type is shown in Figure 4.9.2. Rangeability and resolution are usually at least 1 in 10^3 but some types have poor signal-to-noise ratios which will limit the useable measurement range of any one transducer. Pressure drop or head loss can be low, from about 0.1 mm Hg (1.3×10^{-4} bar) to 760 mm Hg (1 bar) although it is more usually 10 mm Hg to 12 mm Hg, this value decreases with increasing line pressure.

High level signal outputs of the usual industry standards, i.e. 0 V d.c. to 5 V d.c. or 4 mA to 20 mA, are nearly always provided, either directly from the transducer or from its remote but matched electronics/display unit. Associated secondary electronics usually includes a totalizer for gas consumption audits, e.g. for factory special gas supplies, hydrogen, argon, etc. Adverse factors on performance include relatively large size for the higher flow ranges, availability limited to comparatively low flows, below 28 000 L/min and dynamic response ranging from 300 ms to 500 ms to as much as 15 s to within 2 % of final value. This last factor renders the technique unsuitable for pulsed flows. As with all transducers, calibration against a primary or transfer standard is periodically necessary.

4.9.4 Influence of fluid properties on applications

4.9.4.1 ***Heat loss types***

These can be used for gases or liquids but the majority are for gases because the power considerations make all but the smallest liquid measurements costly. They cannot be used for mixed phase flows or flows where a change of state may occur, and they are also gas species dependent. As these meters usually make a point measurement, they are affected by Reynolds number, velocity profiles, viscosity and density. Pressure is limited to the range from about 0.5 atm. to about 2 atm. In the case of the exposed hot-wire type, safety factors have to be a consideration if explosive gases are involved. Corrosion gases cannot be measured except by special sealed element types.

A particular design used in automotive engine testing for monitoring air intake flow, consists of a venturi tube with a ring of hot-wire elements, automatically passing a heating current through them at frequent intervals in order to raise their temperature sufficiently to burn off the accumulated contamination which exists in normal atmospheric air.

4.9.4.2 ***Heat transfer types***

These devices are almost invariably used for gas and vapour flow measurements as their output is a function of specific heat capacity which is greatly different for liquids and gases, the input power requirements being much lower for gases. For this reason, it is not possible to measure two-phase flows nor gases with composition variations.

As heat capacity for most gases remains approximately constant over a wide range of temperature and pressure, these meters retain good performance for a considerable variation in operation conditions. Typically 0.07 bar to 17 bar but capable of up to 400 bar and – 20 °C to 100 °C. Care has to be taken to avoid gas instability by operating close to critical points. Independence from viscosity and density effects is another valuable feature. The design and sizing are such that the gas velocity is reduced to laminar flow conditions so that the temperature is approximately constant across the stream thus avoiding the boundary errors of the large tube types known as boundary layer flowmeters.

When used for general purpose measurements, the meter is usually calibrated on air and a correction is applied for application on the process gas. Gases with highly corrosive properties or vapours with low vapour pressure can be measured by choosing appropriate materials of construction and design, e.g. stainless steel, Monel and low pressure drop types. The flow sensing tube is often of small size, i.e. 0.1 mm diameter, so it is essential to ensure that the stream is free from particulates and fouling contamination. Even for large size flowmeters the sensing tube is still of such small dimensions that any blocking may cause gross errors due to change of the flow division ratio between it and the laminar flow bypass element. However, solvent flushing and reverse air blast can often produce a complete cure and, as there are no delicate internal parts, elements, etc., it is perfectly safe to do so, even in unskilled hands.

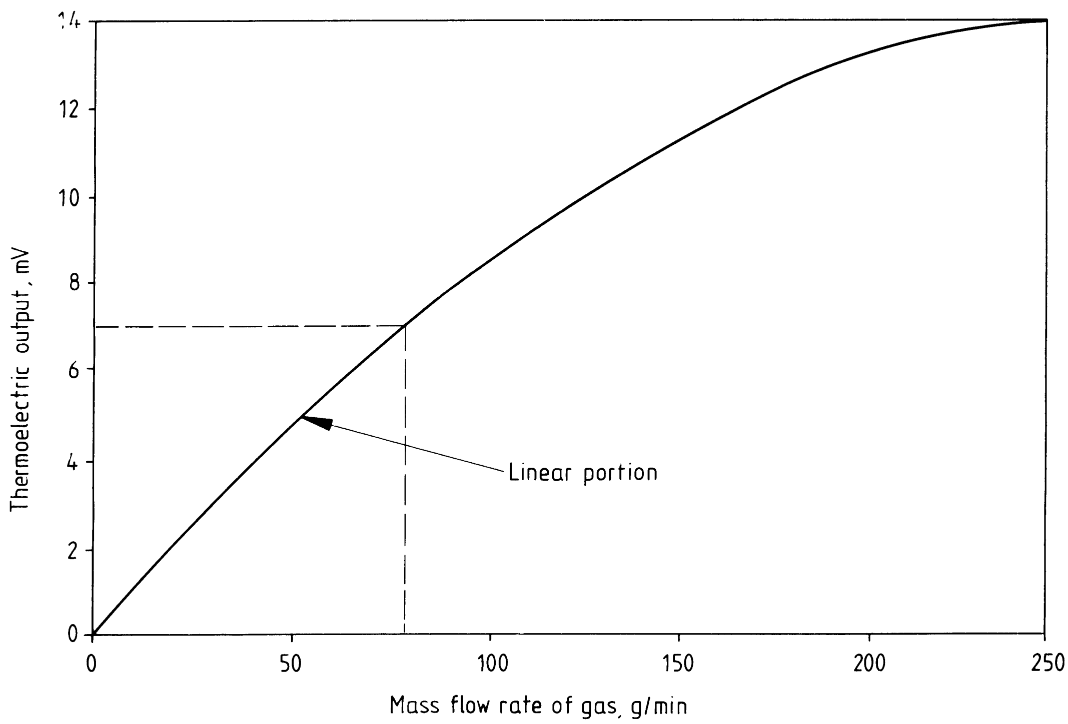


Figure 4.9.2 — Typical output from a thermal profile meter

4.9.5 Influence of installations on applications

4.9.5.1 *Heat loss types*

Meters for air velocity measurement are available for closed-pipe, duct, room and wind configurations. Hand-held types are usually simple indicators not intended (nor able) to provide highly accurate results. More accurate versions are available with provision for gland mounting into tubes or ducts, where an initial investigation will have been made to determine its suitability for the application.

The high spatial resolution and fast response for the fine-wire probe type makes it highly appropriate for use in boundary layer and turbulence studies. For the same reasons performance can be grossly affected by inappropriate siting in streams adjacent to obstructions, bends or changes of section likely to induce swirl or turbulence.

Hot-wire anemometers usually require 8 D to 10 D upstream and 3 D to 5 D downstream to set up reasonable profiles in the pipe. The greater the installation lengths the lower will be the uncertainty of measurement. An upstream filter is recommended to minimize the possibility of contamination of the element by the stream. The cable length between sensor and transmitter is normally restricted to about 6 m. This means that ideally they should be installed as four wire systems since the transmitter is inside the industrial environment.

4.9.5.2 *Heat transfer types*

Since the flow velocity is low in the laminar flow element (LFE) measuring section, it is important that transition for small lines into the larger bore of the meter is minimized. This avoids jetting affects whereby the stream impinges onto the central area of the LFE with greater energy than onto the outer area. Such an installation could result in unequal distribution of flow and consequent errors. This type is not as sensitive to the piping configuration as, for example, the orifice plate types, and the entry and exit straight lengths may be as little as 2 D though where possible 10 D are recommended. Alternatively an upstream gauze baffle can be very effective in obtaining an even gas distribution when space is restricted.

Connection arrangements vary from compression fittings to pipe threads and flanges. Upstream filters are essential unless particulate-free gases are being metered. Traditionally, the sensor tubes have been curved as horse-shoe shaped capillaries, but recent designs for the smaller flow ranges, of up to about 50 L/min, have straight tubes of relatively large bore, (i.e. 0.6 mm diameter), with sealed access plugs at each end permitting rapid and easy removal of any fouling.

Some designs suffer from attitude sensitivity and need to be calibrated in the required attitude. Most, however, will allow for any attitude with only slight readjustment of zero (electrical). Some very low flow types, i.e. less than 10 mL/min, may be susceptible to convection effects. As with most flowmeters, the direction of flow has to be complied with.

Some types have separate but matched transducer and electronic/display units. Usually this means that the cable specification is included in the calibration and has to be used with the cable supplied. In others the signal conditioning is built into the transducer assembly and no special considerations need be given to the cabling. For long distance signal paths it is recommended that the output be of the current-loop type, such as the 4 mA to 20 mA, two-wire system.

4.9.6 Environmental influences on performance

4.9.6.1 *Heat loss types*

Generally all the usual precautions for environmental protection which apply to other flowmeters apply to this type. However, the free air meters are also subject to the effects of atmospheric humidity variation and, if not adequately compensated, to temperature variation also.

Hazardous area operation imposes special constraints and no meter without appropriate certification is permitted.

4.9.6.2 *Heat transfer types*

Except for those types designed for well controlled environments (and therefore not suitable for adverse climatic conditions), most thermal mass flowmeters can perform to specification over an extremely wide range of temperature, typically – 20 °C to + 100 °C, with some capable of 200 °C. Efforts should be taken to ensure that those with laminar flow elements LFE are at a uniform temperature so that both LFE and transducer are in equilibrium. Failure to do so can introduce unpredictable errors. Hermetic sealing reduces humidity effects on electronic components to a minimum, although full weatherproofing is rarely available.

Harsh electrical environments are seldom a problem with well designed units where attention has been given to RF shielding, bonding, signal and power line separation. However, the Hastings® type in which a high-cycle transformer is the heating source, operation in strong magnetic fields such as in the vicinity of large superconducting magnets should be avoided to minimize the risk of transformer core saturation. Similarly, operation in high ionizing radiations with the attendant risk of electronics and insulation materials failure should be avoided. Very few models have any intrinsic safety certification, although most of the large multi-national petrochemical companies provide their own certification.

4.9.7 Economic influences on applications

4.9.7.1 *General*

Thermal meters require periodic attention, particularly to the thermally conductive surfaces. Sensor failure and wear, leaks and electronic problems are also areas where maintenance is sometimes needed.

4.9.7.2 *Heat loss types*

The purchase cost for these meters varies considerably from the low price, simple, hand held, wind-speed type to the fixed installation insertion probe type. Even so, the total installed cost is comparable with or lower than other probes, e.g. pitot tubes with associated DP transducers.

The meters most delicate component, the fine-wire filament, is the most likely failure point and probe replacement is the greatest spares cost. This is largely eliminated by the film thermocouple and enclosed thermocouple types. Long design life is typical and spares are readily available.

Recalibration should be included in cost estimation and may be significant as few appropriate calibration centres exist. All variants in the group are subject to contamination drift unless additional precautions are taken such as continuous purge technique. This cost should also be taken into consideration.

4.9.7.3 *Heat transfer types*

The Hastings type of thermal meter is a most cost effective gas mass flowmeter which eliminates the need to monitor separately temperature and pressure to provide an accurate direct mass flow output. The initial purchase price is modest and only increases significantly at the highest flow ranges due to the large flange and construction costs associated with the LFE.

Spares stocking is minimal and limited to common, readily available electronic components. Some designs allow for field replaceable sensor tubes and shunt elements. The long service life which can be expected from operation in reasonably clean conditions means that running costs are low.

Most installation costs are comparable with any other closed-pipe fitted device. For large sizes conical adapters may be required and, if shut-off valves are to be employed for service withdrawal, should be included in the costing. Calibration costs can be as much as 15 % of the purchase price for the smaller sizes and are ongoing.

Reference has been made to the low pressure drop and, although not applicable to all types, any extra pumping power requirements are likely to be insignificant.

4.10 Group 10 meter applications: miscellaneous types

4.10.1 General

The diversity of flowmeters in this group makes application generalization difficult. Only the tracer and velocity area integration methods have fairly well defined operational procedures and guidelines. Of the other types in this group, laser anemometry is more suitable to research applications, although there are instances of these instruments being installed in industrial and process plants. Cross correlation meters have only just become commercially available and applications experience is limited and mixed. There are very few examples of the use of NMR or gas ionization meters, as these are still basically at the research stage. The bulk of this section therefore concentrates on tracer techniques.

4.10.2 General applications

4.10.2.1 *Tracer methods*

Tracer methods are applicable to a broad spectrum of industrial applications. Though research studies of installed flowmeters have been reported, there is relatively little data on the industrial applications of such instruments. However, tracer methods are used to provide spot measurements of flow rate on a discontinuous basis. Relevant publications include Edmonds and Charlton (1985) and Johnson (1986).

Situations in which tracer methods have been used include the following:

a) on-line calibration of installed flowmeters;

NOTE In this situation tracer methods are applicable to practically all types of fluid over the widest range of flow rates and line sizes.

b) measurement of open channel flows (not covered by this guide);

c) investigations of systems and plants not provided with installed flowmeters and where a knowledge of flow rate assumes special importance;

d) diagnosis of plant malfunction.

NOTE The movements of materials around process plants are complex and frequently interactive. The use of tracers at critical points has demonstrated rapid fault identification, with associated production savings.

A further important though little known application is the measurement of steam flow rates, particularly those associated with power generation equipment. Steam metering, especially at low pressures, is often so difficult that even if an installed meter is provided there may be considerable doubt as to its actual performance. The ability to measure steam flows in such circumstances can often point the way to efficiency improvements (see Kendrick 1986).

The most common tracers are the radioactive types. They are chosen because of the following factors:

1) external detectors can be used;

2) radioactive elements are rarely present naturally and so can quickly be identified;

3) they are highly sensitive;

4) those with short half lives are quickly and naturally lost.

4.10.2.2 ***Cross correlation flowmeter***

This expensive, potentially attractive newcomer to the flowmeter market has given good performance in laboratory tests on multi-phase flows. If the phases are tagged with different radioactive tracers, phase velocities, phase slip and bulk mean velocity have all been determined in laboratory evaluations. There have also been prototype installations on flare stacks and first indications are of measurement uncertainty of around 3 % of reading. Successful trials have also been reported from sand/water dredging operations and oil wellhead installations where water, oil and gas, flow as a complex mixture. No levels of performance have been reported for these trials. This meter is also applicable on corrosive and hostile fluids, both liquids and gases. As more instruments are sold and used, basic applications guidelines will be expanded. It is a technique to bear in mind for the more difficult applications.

4.10.2.3 ***Velocity area methods***

These have been used with tracer techniques to measure flow in very large bore pipes. There are standards available which indicate locations of the point velocity sensors and there are many instances where arrays of pitot tubes, insertion turbine meters and current anemometers have been installed and used satisfactorily. Reference to ISO 3354 and ISO 3966 will give further data.

4.10.3 Influence of performance on applications

4.10.3.1 ***Tracer methods***

Tracer based methods are capable of measuring flow rates over a very wide range, extending at one extreme from river flows to small scale laboratory systems at the other extreme. In an industrial context, this is best exemplified by the use of tracers to measure flare stack flows on oil production platforms. Gas flows ranging from 1 000 kg/h under normal conditions to 150 000 kg/h under heavy flaring can be readily measured using a pulsed velocity radiotracer method.

Under favourable conditions, the performance achievable is between 0.5 % and 1 % of reading. The actual performance is clearly an important factor in determining the circumstances and applications where tracer methods are useful. Generally, the methods are unsuitable for the calibration of high performance meters (groups 3 and 4) in custody transfer applications. It is however one of the few methods that is available to calibrate the very large ultrasonic meters that are being installed in several parts of the world. Meters in excess of 3 m nominal bore are frequently checked using tracers. Such methods are also appropriate for checking the majority of flowmeters installed on process plants, particularly where access is poor. One major advantage is that these techniques introduce no disturbance to the flow and hence no pressure drop in the system.

4.10.3.2 ***Cross correlation meters***

Very little definitive data has been published on the performance of cross correlation meters. Even laboratory evaluations rarely mention performance, rangeability and linearity. The actual performance will depend on what property is being correlated. Indications are that the multi-channel ultrasonic types are capable of ± 2 % of reading over 15 : 1 flow range.

4.10.3.3 ***Velocity area methods***

The performance that can be obtained from this method depends largely on the type of velocity sensor chosen. Insertion turbine meters, for example, have quoted performance of ± 0.5 % FSD over a 10 : 1 turndown. Pitot tubes are not capable of rangeabilities in excess of 4 : 1 unless larger levels of uncertainty can be accepted. It is important to ensure that the range of velocities existing in the pipe falls within the usable range of the point velocity sensor. It is unlikely that uncertainties of better than 1 % of reading can be realized and this will worsen as rangeability increases.

4.10.4 Influence of fluid properties on applications

4.10.4.1 ***Tracer methods***

Tracers are used for all types of fluids, provided the flow is turbulent. Clearly the prime consideration has to be that the tracer is compatible with the flowing material. Caution has to be exercised if phase changes are likely to occur. Radioactive tracers chemically identical to the flowing material except for the radioactive tag are recommended for these applications. An example is the use of tritiated water in steam flow measurement using the dilution technique (see **3.10.3**). This is one of the few effective methods of measuring wet steam flows (see Fries 1965).

Care should also be taken to ensure that fluid interaction does not occur. Particularly adsorption, absorption and chemical effects are to be avoided. For example, problems of absorption have been reported when certain chemical tracers are used with flows which contain suspended particulate matter.

4.10.4.2 ***Cross correlation meters***

Provided the materials of construction are chosen to suit the application and there is no deposition, scaling, corrosion or crystallization on the sensors to degrade performance, the correlation meter performance is essentially independent of density, conductivity, temperature, humidity, viscosity and pressure. The performance is also claimed to be independent of mixture composition in liquid/liquid flows and also of the velocity of sound.

4.10.4.3 ***Velocity area methods***

The type of sensor chosen will determine the effect of fluid properties. Reference should be made to **3.2** and **4.2** for pitot type sensors, **3.4** and **4.4** for turbine and inferential type probes, and **3.6** and **4.6** for electromagnetic probes.

4.10.5 Influence of installation on applications

4.10.5.1 ***Tracer methods***

Because tracers are used for spot-checks rather than as installed systems, it is frequently necessary to apply them in non-ideal metering runs. In such circumstances certain key features need to be critically examined to decide whether or not the desired performance can be achieved, or indeed whether such measurements are feasible.

The tracer injection point should be positioned to ensure direct injection into the bulk stream. This will avoid poor mixing and so improve performance. This is critical for the pulse injection method, because loss of pulse sharpness or pulse distortion will occur at the measuring stations. The problem can sometimes be overcome by inserting an injection gland through regions of stagnant fluid and into the flowing stream. The problem is not so severe with the dilution method, and injection into side streams is often used. If this procedure is adopted it is necessary to ensure there are no fluid take-offs between the injection point and the main stream as this will affect the concentration and quantity of tracer injected. Further, if a constant rate dilution method is used under these circumstances, allowance should be made for the fact that the tracer concentration will come to equilibrium more slowly compared with direct injection. The period of time over which sampling takes place has to be long enough to ensure that a representative selection of samples is obtained from the tracer plateau.

All tracer methods require complete lateral mixing of the tracer before the detection stations are reached. Failure to achieve this is a common source of error. The distance between the detector stations has to be sufficiently large to ensure that the time separation between the two response curves is large compared to the accuracy with which the time of arrival of the tracer pulse at each detector can be determined. It is not necessary for the mixing length to be of uniform cross section, but, if it is not, the volume has to be capable of accurate determination. Fluid feeds or take-offs in this section should be avoided.

4.10.5.2 ***Cross correlation meters***

The arrangement of the transducers can be varied to suit the pipework configuration. The supplier should therefore be consulted to check whether series, parallel or series and parallel configurations are the most appropriate for the application.

4.10.5.3 ***Velocity area methods***

The influence of the installation will be governed by the type of probe selected. In general, point velocity sensors should operate in fully developed turbulent flow for the lowest levels of uncertainty to be achieved. In those cases where the installation inlet length does not allow the velocity profile to develop, lower levels of measurement uncertainty can be expected. Reference should be made to **3.2** for pitot probes, **3.4** for inferential type probes, and **3.6** for electromagnetic probes.

4.10.6 Environmental influences on applications

4.10.6.1 ***Tracer methods***

The equipment used for tracer applications is not generally affected by environmental conditions, being portable and designed for field use. However, caution in the choice of tracer has to be exercised. The use of certain radioactive tracers is restricted by law in some countries and care must be taken to comply with any national legislation.

At a more fundamental level, it is essential that the concentration of the tracer in the flow is not at such a level as to present any environmental hazard. It is rare that this condition cannot easily be met. Nevertheless a safety analysis should be carried out prior to each application. Consideration should be given to all possible routes where a tracer may enter the natural environment and the user has to be able to demonstrate that the environmental impact will be negligible.

4.10.6.2 ***Correlation meters***

Being essentially an electronic flowmeter, the application is essentially limited by the effect of the environment on the signal processor. This is certified to IP 65 and can be used between – 20 °C and + 70 °C. Neither low nor high humidity affects the performance.

4.10.7 Economic influences on applications

4.10.7.1 ***Tracer methods***

The costs of performing flow rate measurements by tracer methods are not readily definable. Clearly, if an organization is equipped with an appropriate injection system and associated assay equipment, then costs are reduced to that of the tracer (usually modest) plus labour costs. If equipment needs to be purchased, then initial investment costs will be high.

In many cases it is more cost effective to employ a contract organization offering the service required. Such services are readily available world-wide from both the public and private sectors. Costs range from a few hundred to a few thousand pounds, depending upon the complexity of the measurements being made. This line of approach also reduces the uncertainty of measurement, since the contractor is highly skilled in both the measurement and the analysis of results. For in-plant problems, this approach is very cost effective.

4.10.7.2 ***Correlation meter***

This is an expensive instrument to purchase and the need to use the meter should be critically examined. The cost of spares and maintenance is not yet determined as industrial experience is limited. In those instances where no other flowmeter will perform the duty, the high purchase price is then irrelevant. Operating and calibration costs are also not yet fully known.

4.10.7.3 ***Velocity area methods***

These represent a very cost effective method of determining flow in pipes of large bore. The initial design, purchase and installation of the array of probes may be high, but once installed operating costs are low and head loss is almost negligible. There may be the need to stock complete spare probes and in those instances where failure occurs, the line may require shutdown to effect repair. In very large pipes (> 3 m bore) the provision of bypass lines is not practical. Provided the individual probes are regularly checked and maintained they should give good reliability.

Section 5. Auxiliary instrumentation

5.0 Introduction

5.0.1 General

This section of the guide looks briefly at auxiliary measurements often required in flow measurement systems. Pressure, temperature and/or density measurement are frequently required, sometimes to calculate mass flow, and sometimes to apply pressure, temperature or specific gravity corrections to volume flow measurements where the ambient or process conditions vary considerably. Such measurements are very common in gas metering systems, where the performance and rangeability of many flowmeters is affected by fluid property variations. Humidity measurement is also important in gas metering as this may affect the meter reading. Fluid property affects are also important for calculations of Reynolds number variations, and to estimate possible expansion and correction factors that should be applied to process data. Our knowledge of the behaviour of liquids is greater than for gases. For fluid mixtures, however, the data base and physical understanding are both poor and larger errors should be expected from most flowmeters compared to the measurement uncertainty when metering pure fluids.

5.0.2 Layout

The various clauses discuss the relevance of the measurements to flow metering systems. The operating principles of the common transducers are listed and operational and installation guidelines for their use are also given. The subjects covered are as follows:

a) pressure and differential pressure measurement (see **5.1**);

b) temperature measurement (see **5.2**);

c) density measurement (see **5.3**);

d) humidity measurement (see **5.4**);

e) ancillary electrical equipment (to be used with flowmeters) (see **5.5**).

5.1 Pressure and differential pressure measurement

5.1.1 General

The majority of flow measurements in the process industries are made using orifice plates, which require both pressure and differential pressure to be measured to enable the flow rate to be calculated. In addition, particularly where the fluid is compressible, pressure is frequently needed to be measured to enable pressure compensation factors to be applied, so that indicated volumes can be reduced to reference conditions.

5.1.2 Concepts and units

A primary calibration standard used for pressure measurement is the deadweight piston tester whereas precision Bourdon gauges and manometers are often used as working calibration standards.

Pressure cannot be measured directly, and all instruments purporting to measure pressure in fact indicate a pressure difference. The two most common reference pressures are that measured in vacuum and atmospheric pressure.

Absolute pressure, p_{abs} (in Pa) is measured relative to pressure measured in vacuum. Gauge pressure, p_{gau} (in Pa), is that measured relative to atmospheric pressure p_{ats} (in Pa). We then have the following relationship.

$$p_{abs} = p_{gau} + p_{ats} \tag{5.1.1}$$

This gives rise to the two types of pressure transducer, absolute and gauge.

Where calculations are made which involve application of the gas laws, absolute pressures are required. However, in the process and chemical industries, it is often more important to measure the pressure difference between the inside of the pipe and the atmosphere because it is that difference which directly relates to stress on the pipe.

5.1.3 Pressure measurement in moving fluids

In the case of steadily flowing fluids, there is a departure from the basic equilibrium condition. The kinetic energy of the flow is superimposed on the random kinetic energy of the fluid molecules that is present even when the fluid is at rest. To cover the fluid flow situation, three additional pressure definitions are required, i.e. static, p_s; dynamic, p_k; and total, p_o.

The relation between these three pressures at a point within the flow field is given by:

$$p_o = p_s + p_k \quad (5.1.2)$$

For incompressible fluids, the dynamic pressure, p_k, is given by the basic equation:

$$p_k = ½ \rho U^2 \quad (5.1.3)$$

Hence

$$p_o = p_s + ½ \rho U^2 \quad (5.1.4)$$

5.1.4 Ideal transducers

With an ideal transducer, the output signal is affected only by the input signal. However no transducer is ideal and in the case of pressure sensors, changes in temperature, humidity, local vibration and high static pressure can affect the output signal. The degree to which any variable affects the output signal is the sensitivity to that factor. A simple operating expression may be of the form:

$$O = \mathrm{A} \cdot p + \mathrm{B} \cdot T \quad (5.1.5)$$

where

O is the output;

p is the applied pressure;

T the ambient temperature;

A and B are transducer constants.

Sensitivity is defined as the change in output for a change in pressure with all other factors constant. A high quality pressure transducer will therefore have a high value of A and a low value of B. In addition, A should ideally be independent of temperature (temperature stability) and the direction of pressure changes (hysteresis). Other parameters such as immunity to electrical noise, dynamic response and tolerance to over-pressure may also be important in some applications. Most suppliers publish or will release sensitivity data and these are an indication of the expected measurement uncertainty of the instrument.

5.1.5 Review of pressure and differential pressure sensors

5.1.5.1 *Manometers*

The U tube manometer was the earliest device used for measuring differential pressure but it is now uncommon in industrial applications. Nevertheless, it is still an important laboratory instrument. In many designs of commercial manometer one limb of the U is replaced by a reservoir having a very large surface area relative to that of the other. The tube is partially filled with a suitable liquid (mercury, water or oil are commonly used). The unknown pressure is applied to one side while the reference pressure is applied to the other. The difference between the two is balanced by the mass per unit area of the displaced manometer liquid column. Various corrections need to be applied to the reading, i.e. for variations of density as a function of temperature and pressure, and to allow for capillary effects.

5.1.5.2 *Mechanical instruments*

The most common pressure instrument is the simple Bourdon gauge, an example of which is shown in Figure 5.1.1. General industrial gauges, class 1, have a certified uncertainty of 1 % of full scale between 10 % to 90 % of span. Class 2 gauges are inferior in uncertainty at 3 % of full scale over the entire range. There are, in addition, reference test gauges which are calibrated to give an uncertainty of 0.25 % of full scale over the entire range on both rising and falling pressure.

The diaphragm and bellows types are two further forms of mechanical instruments. These often form the basis for electrical output transducers discussed in **5.1.5.3**, but otherwise are frequently used to give a visual indication of pressure and not for compensation purposes. A wide variety of materials is used, enabling them to be compatible with almost every fluid. Materials include brass, bronze, Monel, Hastelloy, beryllium copper, stainless steel, titanium, Ni-span-C, etc. For high pressure applications, stiff diaphragms should be used. They are most commonly used in applications below 500 kPa (5 bar) and temperature ranges between – 20 °C and + 100 °C.

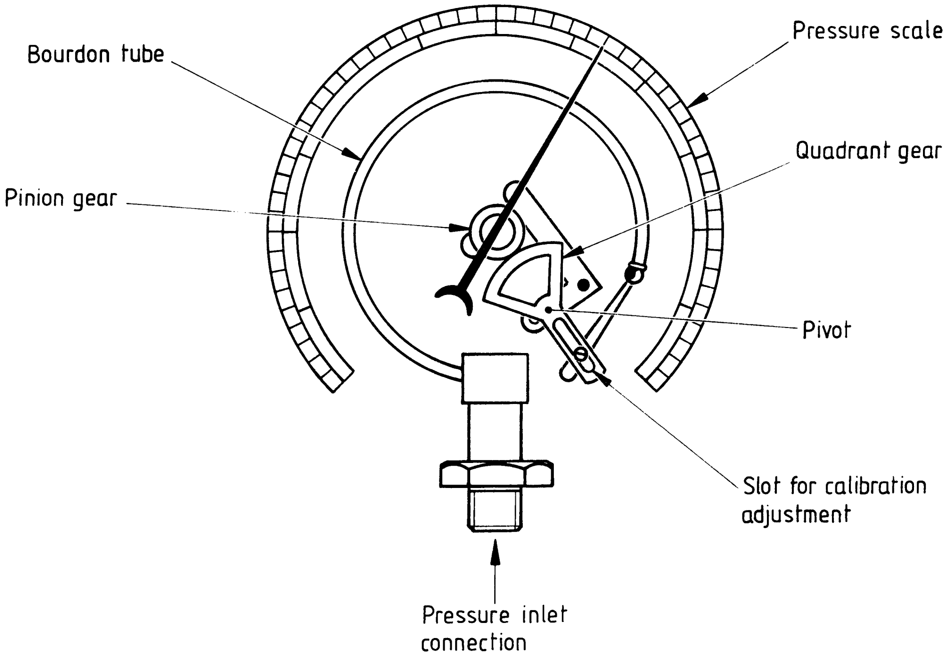


Figure 5.1.1 — Simple Bourdon gauge

5.1.5.3 ***Electrical pressure transducers***

Transducer elements can be divided into two main classifications, active or passive. Active elements are self-contained energy sources and require no electrical input when subjected to pressure variations. The output signal is a property of the transducer element itself. The so-called active transducers cannot be used to measure the unvarying or slowly varying pressure encountered in flow measurement. Examples are piezo-electric (differential pressure only) or magnetic induction transducers. The passive type of element is more commonly found in flow measurement systems. They may use mechanical elements as described in **5.1.5.2** and exploit changes in capacitance, resistance or inductance of an attached electrical element to measure pressure and provide an output. Each design has advantages and disadvantages and the more important basic characteristics are listed in Table 5.1.1. This shows a qualitative comparison of response, hysteresis, resolution, linearity and other properties of the ten major types of pressure sensor. Some have two ports, one of which can be connected to atmosphere to measure static line pressure or alternatively the ports can be connected across a contraction such as an orifice to sense differential pressure.

Table 5.1.1 is intended only to indicate the most important parameters when selecting pressure sensors for the required application. Table 5.1.2 gives more details of pressure range, output characteristics and applicable temperature range of the common types to further aid selection. As with flowmeters, the final choice should be made in direct consultation with a number of suppliers.

The type of electrical transducer most commonly used in flow metering is the capacitance cell, widely used in the process and chemical industries, being capable of high performance. A capacitor is formed by separating two metal plates with an insulating material called a dielectric. A typical design is shown in Figure 5.1.2. The pressure is transmitted via an isolating diaphragm to the high pressure side by means of the silicon oil filling fluid. As a result the sensing diaphragm in the centre moves away from one plate and towards the other. The change in capacitance is proportional to flow. The relationship is non-linear but this presents no problem to modern electronic linearizing networks.

This type of instrument has a typical uncertainty of 0.25 % of calibrated span. This includes the combined effects of linearity, hysteresis and repeatability. It is very stable and capable of withstanding high over-pressure with little or no zero shift. For those instruments used in high static pressure applications, there are relationships which enable the static shift to be estimated as a function of inlet pressure. Practical operating temperature limits are – 40 °C to + 100 °C, the limits being determined by mechanical and electrical property changes of the dielectric fluid. Ambient temperature effects are of the order of ± 0.002 % of span per °C.

Another common type of pressure sensor is the strain gauge cell, of which there are four versions:

a) unbonded gauges;

b) bonded gauges;

c) vapour sputtered gauges;

d) semi-conductor gauges.

A typical unit is shown in Figure 5.1.3 and it consists of a single crystal silicon diaphragm with strain gauge diffuser directly into the crystal. This allows a complete Wheatstone bridge arrangement to be deposited. It is rugged with high resistance to shock and vibration. An output level of 20 mV/V is typical and it can be powered by low power d.c. circuits and still give higher outputs than a conventional strain gauge. It is also characterized by good dynamic response.

5.1.6 Smart pressure sensors

One area where the impact of microprocessors has been felt is in the development of smart sensors, particularly pressure. Many physical effects respond directly or indirectly to pressure and as a result the first generation of smart process transducers appeared on the market some four years ago. Surprisingly however market penetration has been slow until recently, possibly because hand picked conventional pressure and differential pressure cells perform almost as well over the limited range often required. There is virtually no limit to the amount of intelligence and diagnostics that can be incorporated into pressure transducers but so far only those which are reasonably linear or which have well defined characteristics have been commercially exploited. There is no longer need for linearity because all signal processing is digital and algorithms can be written to cope with any signal/pressure curve, provided it is repeatable. Thus rangeability can be increased and even hysteresis can be taken into account.

Table 5.1.1 — Relative pressure and differential pressure transducer performance characteristics

Element	Resolution	Hysteresis	Response and dynamic characteristics	Temperature characteristics	Vibration and environmental sensitivity	Linearity	Mechanical overload capabilities	Life
Capacitance	E	E	G	E	E	E	E	E
Strain gauge								
Semiconductor	F	F	E	F	F	G	G	E
Vapour deposited	G	G	E	E	E	G	G	E
Bonded	G	G	E	E	E	G	G	E
Piezoelectric	G	G	E	F	F	—	P	G
Resonant sensing type	E	E	E	E	E	E	G	E
LVDT	F	F	G	G	G	E	E	E
Variable reluctance	G	F	G	E	P	—	E	E
Film potentiometer	G	F	P	G	F	G	P	F

Key:
E excellent;
G good;
F fair;
P poor.

Table 5.1.2 — Typical pressure and differential pressure transducer application characteristics

Element	Pressure range	Temperature range	Output signal	Frequency response
U-tube	5 mm to 2 m water or mercury	ambient, Note 2	visual	static
Inclined manometer	1 mm to 300 mm water or mercury	ambient, Note 2	visual	static
Bourdon tube	Up to 5 000 bar	Note 3	visual/4 mA to 20 mA	low, Note 5
Diaphragm	Up to 200 bar see Note 1	Note 3	4 mA to 20 mA Note 4	low, Note 5
Strain gauge				
Bonded	Up to 500 bar	Note 3	4 mA to 20 mA, Note 4	Notes 5 and 6
Vapour deposited	Up to 2 000 bar	Note 3	4 mA to 20 mA, Note 4	Notes 5 and 6
Semiconductor	Up to 700 bar normal 50 mbar miniature	Note 3	4 mA to 20 mA, Note 4	Notes 5 and 6
Piezoelectric	Up to 5 000 bar	Note 3	4 mA to 20 mA, Note 4	Notes 5 and 6
Resonant element	Up to 700 bar	Note 3	4 mA to 20 mA, Note 4	Notes 5 and 6
Capacitance	Up to 500 bar	Note 3	4 mA to 20 mA, Note 4	Notes 5 and 6
Variable reluctance and LVDT	Up to 200 bar	Note 3	4 mA to 20 mA, Note 4	Notes 5 and 6

NOTE 1 Widely used for the measurement of very low pressures and differential pressures.
NOTE 2 Calibration normally referenced to 20 °C.
NOTE 3 – 40 °C to + 120 °C, typical.
NOTE 4 Transmitters are also available with frequency or pulse output signals.
NOTE 5 In 4 mA to 20 mA transmitters the signal conditioning circuits usually incorporate a low pass filter which restricts the response to less than 1 Hz.
NOTE 6 If signals are taken direct from the sensing element, the frequency response is determined by the mechanical properties of the sensing element and may extend beyond 5 kHz.
NOTE 7 For industrial applications, the construction of the transmitter usually restricts the response of the sensing element to about 40 Hz, but the signal conditioning circuits usually restrict this further to less than 1 Hz.

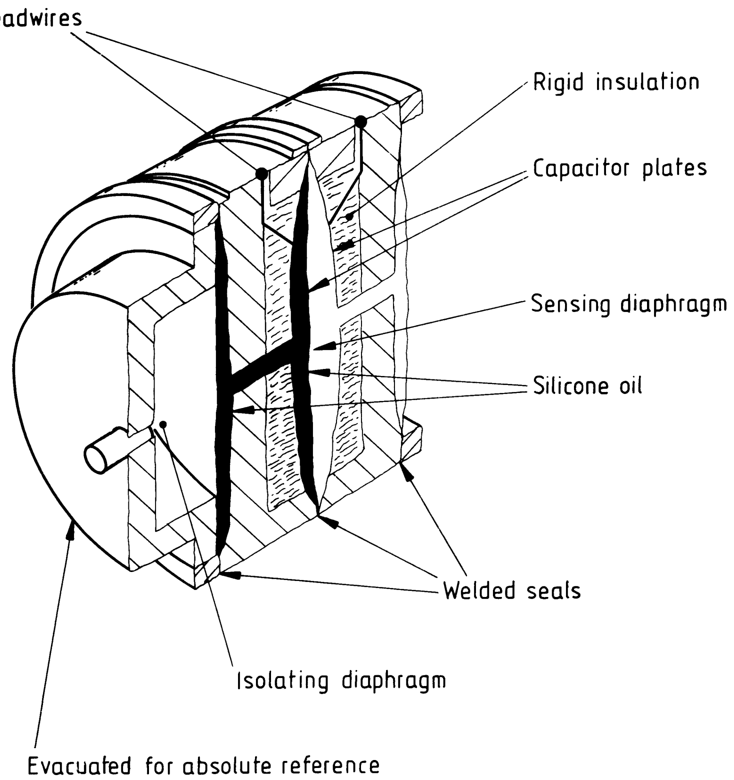
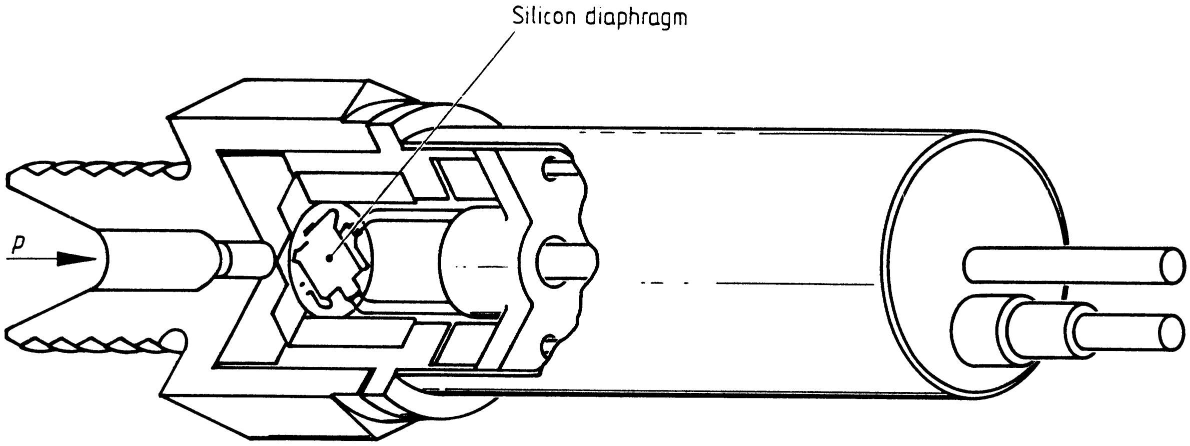
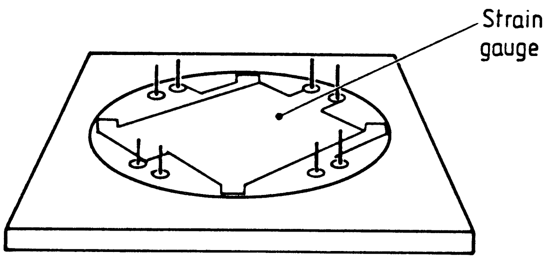


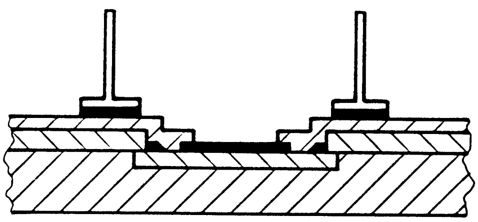
Figure 5.1.2 — Capacitance pressure cell



(a) Cross section



(b) Silicon diaphragm



(c) Strain gauge

Figure 5.1.3 — Semi-conductor strain gauge pressure gauge

It is in the remote control area that the full potential of intelligent transducers is likely to be felt. Portable instrumentation controllers enable the user to re-range, configure and display process output values without the need to be close to the transmitter. On-line re-ranging is very useful when the pressure transducer is located in an inaccessible place. It is possible to use two-way communication links to transfer the outputs from a variety of intelligent transducers located at remote outstations but the cost of such a feature should be carefully considered as this is likely to be expensive. Intelligent transducers are more expensive than conventional instrumentation but in certain applications cost is not a major consideration.

The general features of the new generation of smart sensors, in addition to those already mentioned, include the following:

a) on-line temperature compensation;

b) built in diagnostics;

c) claimed uncertainty of 0.1 % of span.

Most of the transducers use silicon as sensing elements and are generally of similar construction to that of strain gauges (see **5.1.5.3**) with the addition of micro-electronic circuits to provide the control functions. The micro-electronic circuit is usually diffused onto the sensing diaphragm at the same time as the sensing element.

5.1.7 Installation of pressure transducers in flow measurement systems

To obtain the best performance from pressure and differential pressure transducers, they should be correctly installed and regularly maintained. The zero and span adjustments should be routinely checked and for the lowest uncertainty, the device should be recalibrated periodically using standards such as deadweight testers. The orientation of the pressure tappings and the design of the connecting leads is dependent on the fluid being metered. Ideally the tappings positions for all measurements should not be located at the top or bottom of the pipe. Figure 5.1.4 shows a typical installation for gases. Positioning the tappings at the 10 o'clock and 2 o'clock points will enable sedimentation and gas bubble effects to be avoided in the impulse lines. Such a design also gives good accessibility for routine maintenance.

It is vitally important to have the pressure connections of the transducer at the same level to ensure equal static head on both sides of the transmitter as shown in Figure 5.1.4 and sometimes a balancing valve and line is installed to check for any offsets at zero flow. For flow measurement in vertical pipes, the same rules apply and Figure 5.1.5 shows typical installations for an orifice meter and differential pressure transmitter combination for a variety of applications. The secondary instruments can be located above or below the primary metering element. The general rule is that they are mounted below the pipe run for liquids and above the pipe run for gases and vapours. This is to permit gas bubbles to rise back into the flow and droplets to fall back into the stream for the two cases respectively. The connecting leads should be kept as short as possible and should not be less than 6 mm bore generally and not less than 10 mm for condensible vapour flows. There should be a slope of 1 in 20 to allow any bubbles or droplets to flow back into the line. This slope should be increased as fluid viscosity increases.

Where troublesome fluids are being metered, the use of seal pots, condensation chambers, sediment traps and occasionally purge flows may be required. Most modern pressure and differential pressure transmitters have simplified such installations and the manufacturers of orifice runs are particularly experienced in the detailed aspects of secondary meter installation.

Where there are ambient temperature variations, lagging of the leads is strongly recommended to reduce the possibility of phase change in the impulse lines. Such an occurrence will show up as a systematic error in flow measurement.

The sensing element of most modern electronic transmitters will not operate reliably when exposed to operating temperatures above 90 °C. In these cases, the length of both impulse lines can be increased by the same amount. Alternatively the flowing fluid can be isolated from the measuring element with a diaphragm and a suitable liquid can then fill the connecting leads between diaphragm and transmitter Such an arrangement is also useful where large amounts of condensation, sedimentation, corrosion or dirt exist in the main flow line. This arrangement can also guard against freezing in cold weather since the impulse line can be filled with ethylene glycol or glycol/water mixtures.

5.1.8 Effect of errors on flow measurement uncertainty

Any static pressure and differential errors will affect the uncertainty of density measurement, the correct compensation factor for volume flow and the actual computation of mass flow. A good guideline is to chose instruments that limit the density uncertainty to 1 % of reading or less. For group 1 and 2 meters (DP types) the uncertainty in mass flow varies as the square root of the density, as shown in Appendix B. When combined with ambient effects and the basic uncertainty in the discharge coefficient of 0.6 %, this criterion will allow flow measurement to be made with a total uncertainty of 1 %. Temperature measurement (see **5.2**) uncertainty should be limited to 0.75 % and if there are no further large sources of uncertainty, again a 1 % total uncertainty of flow measurement is possible. If there are both pressure and temperature uncertainties, limiting the pressure effect squared plus the temperature effect squared to 2.5 % will guarantee overall uncertainty to within 1 % on flow. Figure B.1, shows an example of a calculation of the density uncertainty for ethylene. The density values are taken from reference tables. In this figure a pressure uncertainty of 60 bar in measuring a line pressure of 70 mbar and a temperature uncertainty of 0.25 °C is additionally assumed. The calculation shows that these combined uncertainties produce a contribution to the total flow measurement uncertainty by the density of 1.153 %. If this is then combined with the primary element uncertainty plus any other uncertainties as listed in Appendix B, then the total flow measurement uncertainty can be calculated.

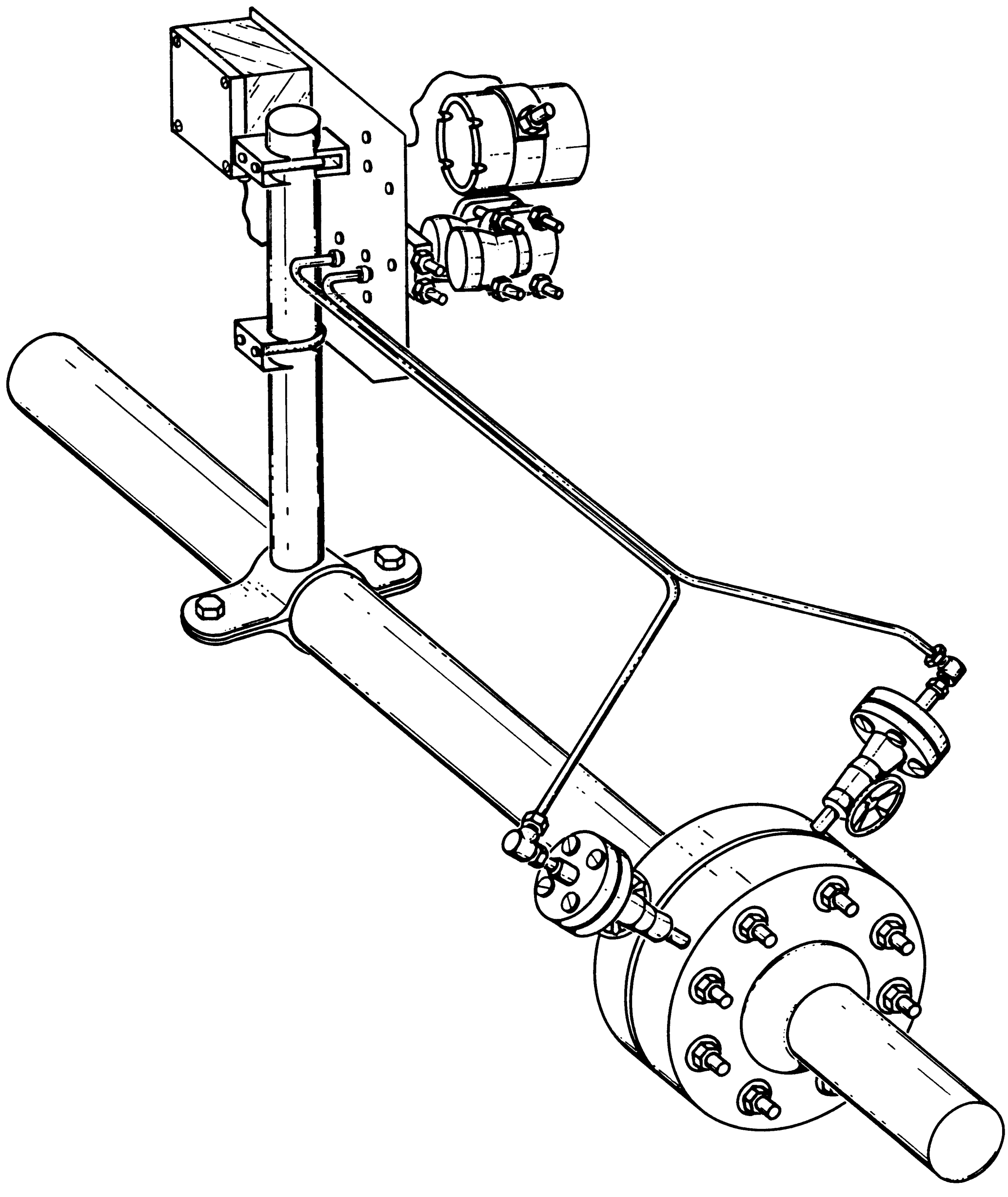


Figure 5.1.4 — Example of pressure transducer installation for gases

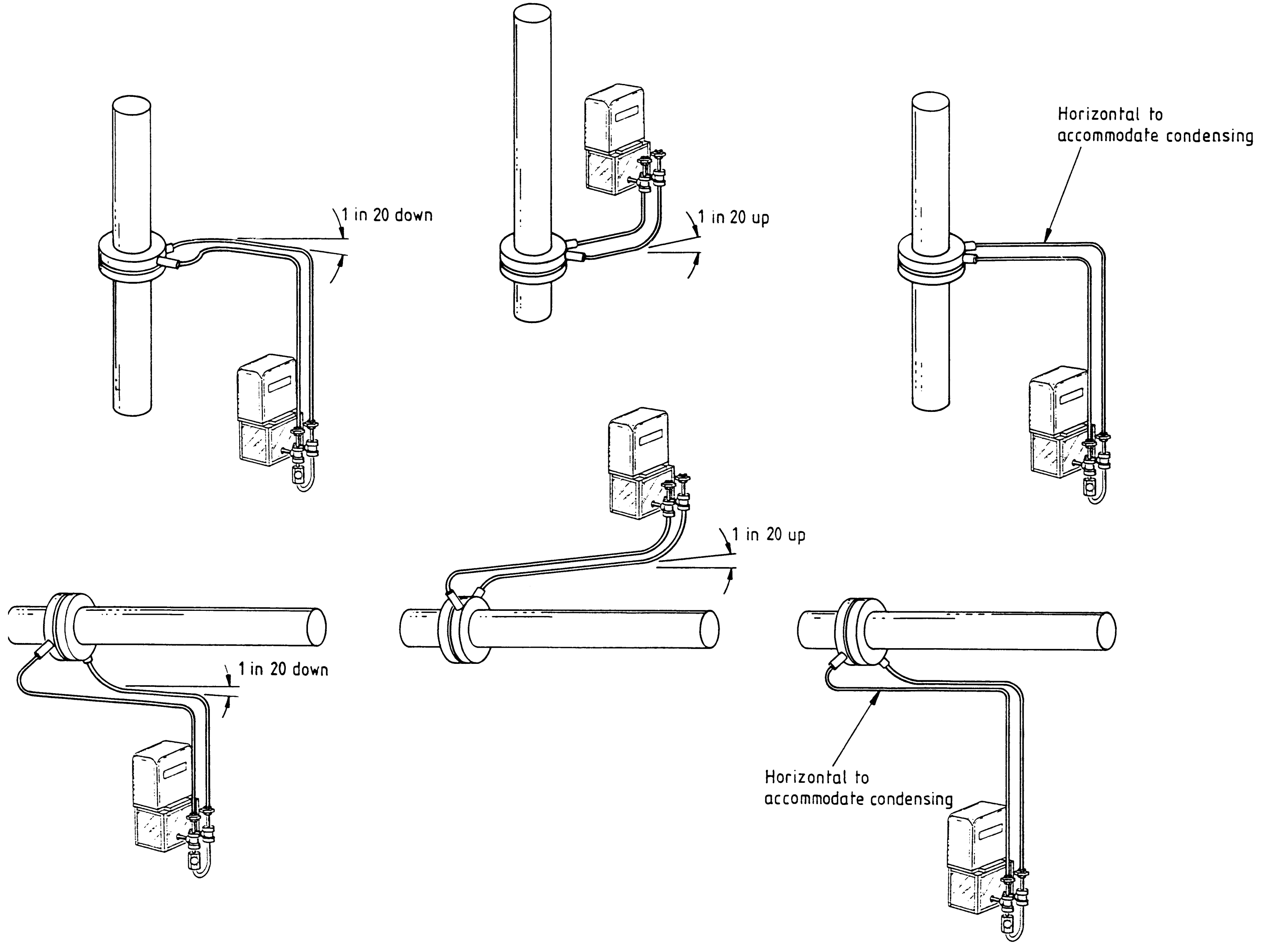


Figure 5.1.5 — Typical pressure transducer installations for fluids

For other types of flowmeter, the density affects the mass flow calculation directly. Errors of the same assumed magnitude will give higher values of total uncertainty than that calculated in Figure B.1. This simple example shows the importance of choosing the correct instruments, mounting them correctly and regularly checking them. The calculation assumed no ambient effects, no other transmitter errors and no additional uncertainties due to impulse line effects. Such a calculation serves to indicate how difficult it is to demonstrate that a metering run, whatever type of meter is used, can give a total measurement uncertainty of 1 % or better without a great deal of effort. Certainly manufacturers' claimed performance for flowmeters can bear no relation to the true total uncertainty of the measurement.

5.2 Temperature measurement

5.2.1 General

Temperature measurement is often required in association with flow measurement because fluid density and viscosity are functions of temperature. In many cases it is necessary to convert the primary measurement of fluid volume flow to a mass flow using density. Less often it may be required to correct for a temperature effect in the meter itself.

Internationally accredited laboratories hold standards of and means of calibrating temperature measuring devices.

5.2.2 Types of temperature measuring devices

5.2.2.1 *General*

Temperature cannot be measured directly but should be measured by observing the effect which temperature exerts on different materials.

The following three main methods are discussed:

a) electrical;

b) non-electrical;

c) use of pyrometers.

Of these three main methods, electrical devices are the ones most commonly applied to flow measurement. The main types are:

1) thermocouples;

2) resistance thermometers;

3) thermistors.

NOTE A comprehensive treatment of temperature measuring devices is given in BS 1041.

5.2.2.2 *Thermocouples*

The thermocouple consists of an arrangement of any two of a wide range of dissimilar wires in a common cable, joined together at a one reference end in a zone of known temperature, and also joined at the other end in the zone whose temperature is to be determined. An e.m.f. (voltage), being a function of the temperature difference, is generated between the two ends of the cable (see Figure 5.2.1 and Figure 5.2.2).

A number of specific materials for thermocouple wire have been studied and developed, and internationally accepted tabulations of their temperature/e.m.f. relationship established (see BS 4937-1 to BS 4937-8, and BS 4937-20). These are illustrated in Figure 5.2.3 and Table 5.2.1. The choice of thermocouple material for an application is dependent on a number of considerations and reference should be made to manufacturers' literature and recognized textbooks.

Literature should include advice regarding the ageing of thermocouple wire when used at higher temperatures, and the best methods of installation having regard to potential errors. An accuracy of measurement of 1 °C can be obtained with installations of good quality.

Table 5.2.1 — Thermocouple types

Letter designation	Description	Range of temperatures for which tolerances are quoted in BS 4937-20
		°C
E	Nickel-chromium/copper-nickel	– 200 to + 900
J	Iron/copper-nickel	– 40 to + 750
K	Nickel-chromium/nickel-aluminium	– 200 to + 1 200
N	Nickel-chromium-silicon/nickel-silicon	– 200 to + 1 200
T	Copper/copper-nickel	– 200 to + 350
B	Platinum - 30 % rhodium/platinum - 06 % rhodium	+ 600 to + 1 700
R	Platinum - 13 % rhodium/platinum	0 to + 1 600
S	Platinum - 10 % rhodium/platinum	0 to + 1 600

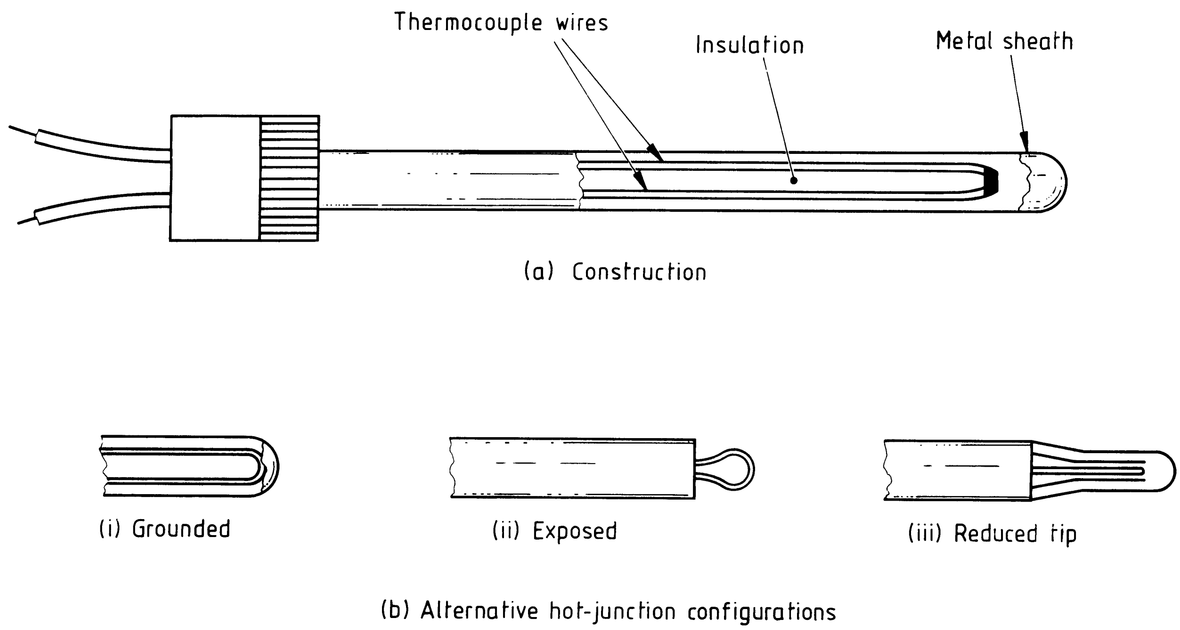


Figure 5.2.1 — Typical thermocouple construction

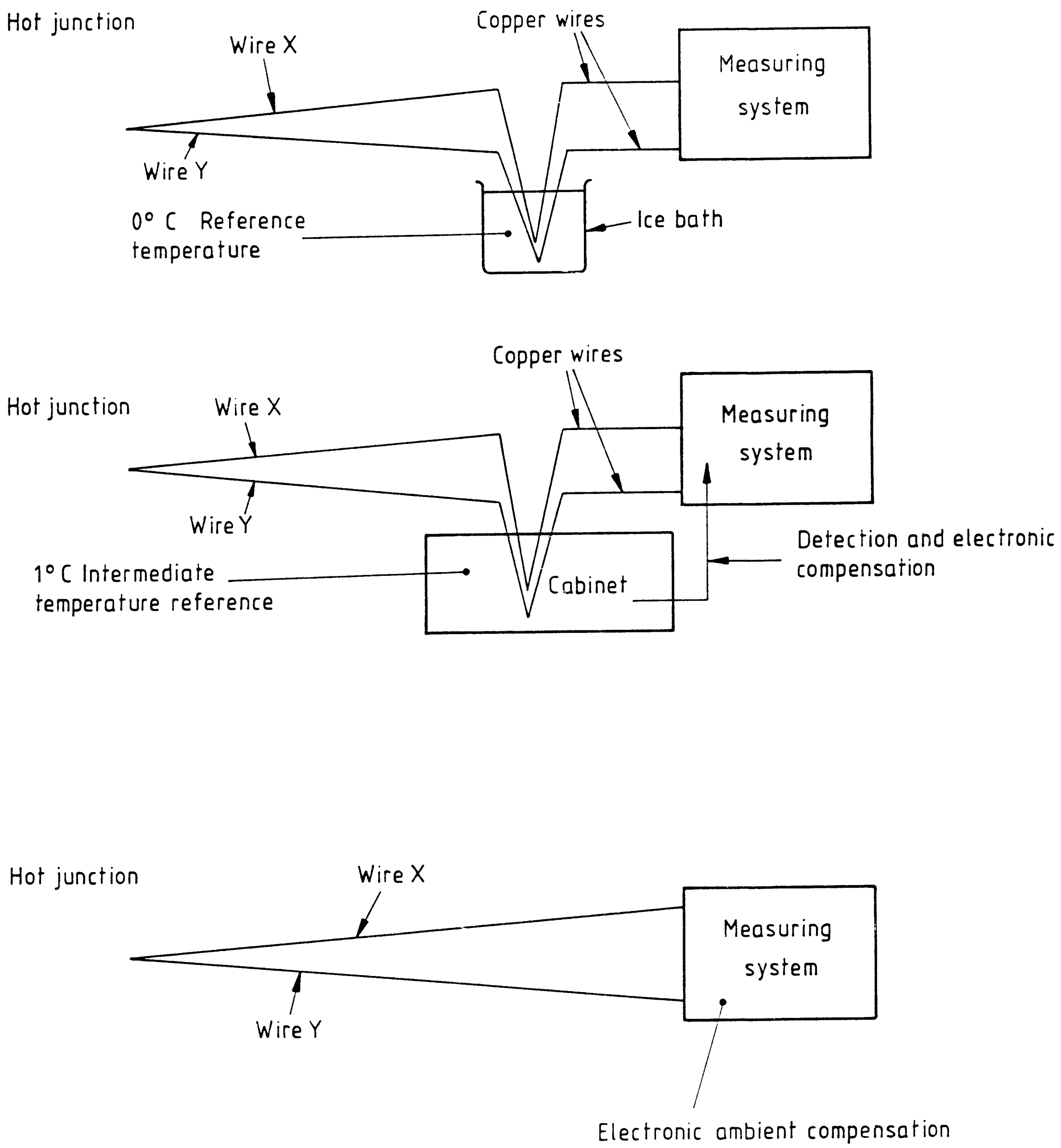
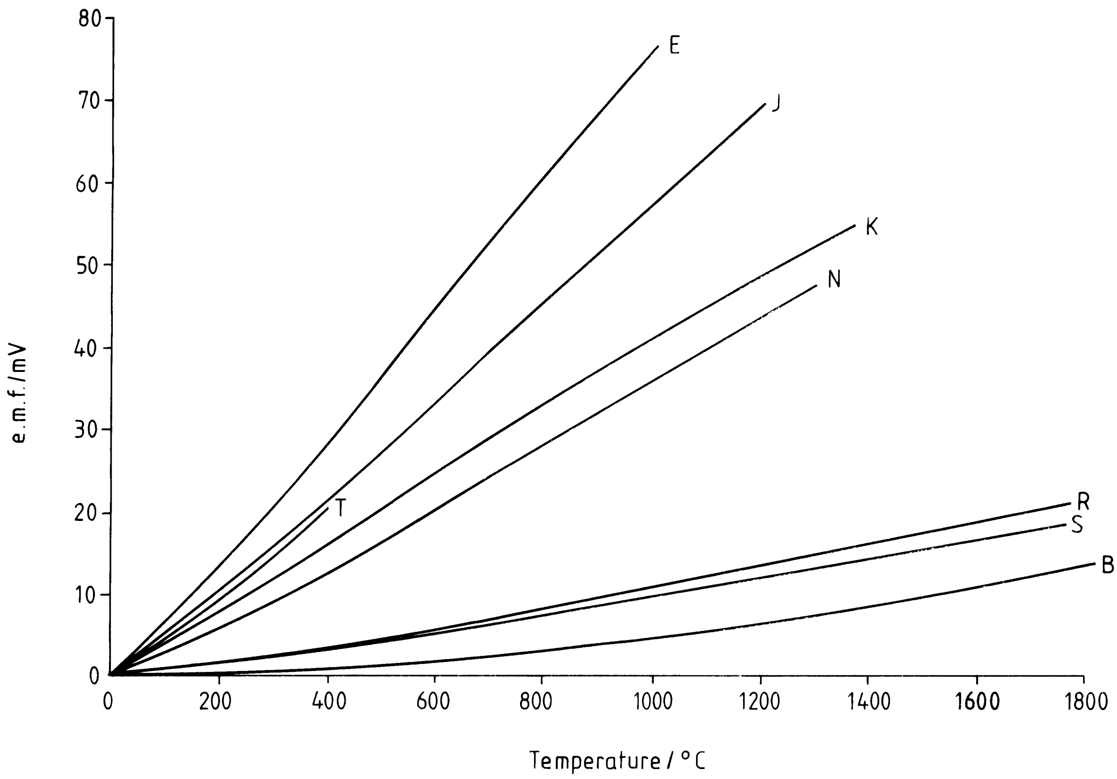


Figure 5.2.2 — Cold junction compensation



NOTE The letter designations of thermocouple types are given in Table 5.2.1.

Figure 5.2.3 — Thermocouple characteristics

5.2.2.3 *Resistance thermometers*

The resistance thermometer utilizes the principle that the resistance of an electrical conductor changes with temperature. This is characterized for temperatures above 0 °C by the relationship.

$$R_t = R_o (1 + \mathrm{A}t + \mathrm{B}t^2) \qquad (5.2.1)$$

where

$\mathrm{R_o}$ is the resistance at reference point (normally 0 °C) (in ohms);

R_t is the thermistor resistance at temperature t °C (in ohms);

t is the temperature (in k);

A, B are constants, a function of the material.

The sensing resistance elements are normally sealed into a stainless steel sheath (see Figure 5.2.4).

Reference should be made to literature for details of available materials and characteristics. BS 1904 refers to the characteristics of the platinum resistance thermometer (PRT), the most commonly used device of this type. With suitable calibration, an accuracy of 0.30 °C is achievable provided installation is of appropriate quality.

5.2.2.4 ***Thermistors***

These devices utilize the resistance variation, with temperature, of a semi-conducting material (e.g. oxides of manganese, cobalt and nickel, blended to give required characteristics). The relationship between resistance and temperature is an exponential function of absolute temperature.

$$R_t = R_{20} \exp (B/t - B/293.15) \qquad (5.2.2)$$

where

R_{20} is the resistance at 20 °C (in ohms);

B is the characteristic temperature for device (in K).

Thermistors can be very sensitive but manufacturing tolerances are normally wider than for platinum resistance thermometers. A key advantage is their availability in a variety of shapes, some as small as 1 mm. Their nominally high resistance also minimizes the effect of any changes in resistance in connection leads (see Figure 5.2.4).

5.2.2.5 ***Non electrical devices***

These generally depend on the thermal expansion properties of either liquid, gas or solid when exposed to changes in temperature. An example is the common liquid-in-glass thermometer, where the liquid may be mercury, alcohol or toluene. Examples of the characteristics of liquid-in-glass thermometers are given in Table 5.2.2.

Table 5.2.2 — Characteristics of liquid-in-glass thermometers

Liquid	Range	Uncertainty
	°C	°C
Mercury	– 39 to + 600	0.01
Mercury-thallium	– 55 to 0	0.02
Alcohol, toluene	– 100 to + 50	0.1
		1

5.2.2.6 ***Pyrometers***

These are instruments which determine temperature by measurement of the thermal radiation emitted by a hot body. They operate at ranges above the limit of thermocouples and are of two types based on two principles:

a) the optical pyrometer based on the measurement of the intensity of radiation at a particular wavelength;

b) the radiation thermometer based on the measurement of the total radiation emitted from a hot body.

A law formulated by Planck shows that the intensity of radiation of any given wavelength is a complex relation between the wavelength and the absolute temperature. The total radiant energy emitted from a body is proportional to the fourth power of the absolute temperature.

Pyrometers are generally used to measure temperatures above 500 °C and are unlikely to find application in normal gas flow metering systems. However, some types of pyrometers based on infra-red wavelength radiation have been developed to measure temperature as low as 50 °C.

5.2.3 Performance

The uncertainty required in the flow measurement will influence the type of temperature measurement system selected as will other factors such as line temperature and the required response time.

If very fast response is required, a bare wire thermocouple inserted directly in the flow may be capable of time constants of a few milliseconds in liquids or 1 s or more in air. In any permanent installation, or one in which there is a risk of damage to the sensor, a metal sheathed resistance thermometer, or thermocouple element, would normally be used. A typical time constant for a 6 mm diameter sensor might be 5 s to 10 s in water and a few minutes in air.

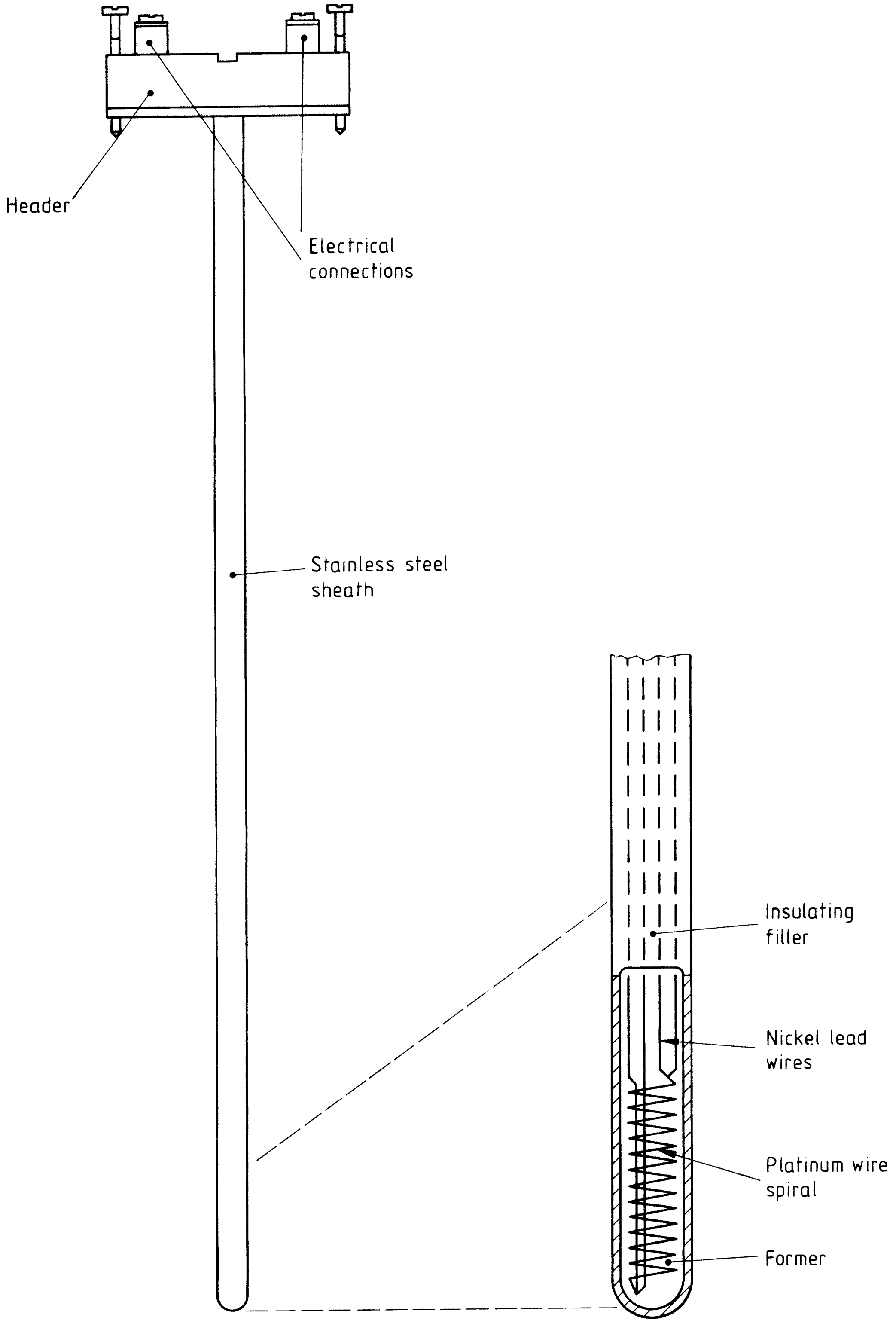


Figure 5.2.4 — Construction of a platinum resistance thermometer (PRT)

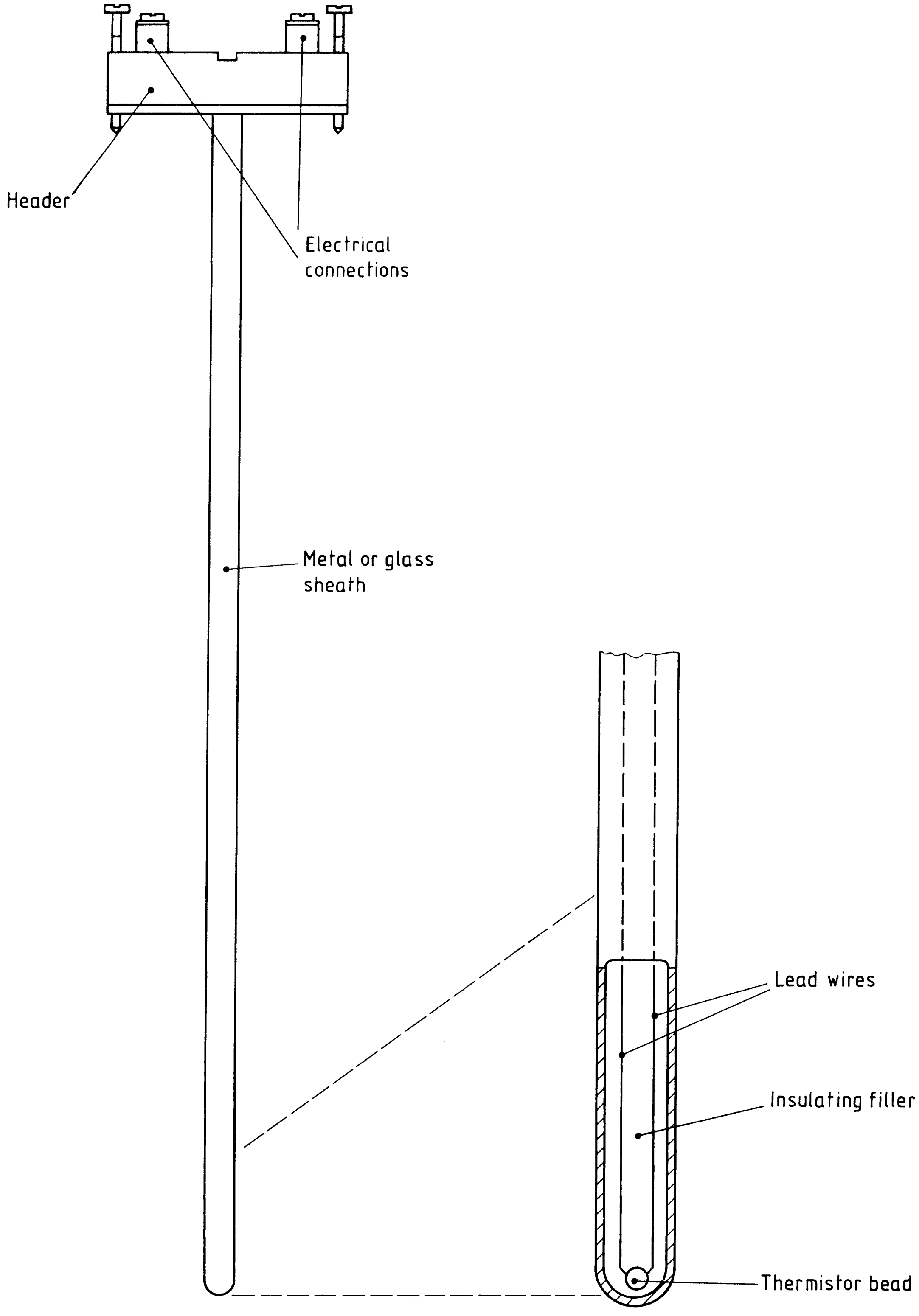


Figure 5.2.5 — Construction of a thermistor probe

5.2.4 Installation requirements

5.2.4.1 ***General mechanical features***

High pressure pipe installations should be such as to prevent leakage and enable the withdrawal of the sensor under load, as required. In these circumstances a re-entrant pocket or thermowell is necessary. BS 2765 gives details of such designs having regard to structural integrity. The response time and uncertainty for temperature measurement will be increased by using such a system and may be minimized with a low clearance between temperature sensor and pocket-bore at the sensing point.

It is essential that the sensor (or its pocket) be designed to withstand the flow conditions within the pipe, including the sideways load of the flow dynamic pressure.

The vibration conditions of the installation are to be considered in applications where fatigue of a probe or pocket may be induced.

5.2.4.2 ***Positioning***

To avoid ingress of debris and condensation into a probe or pocket, the device has to be located in the lower section of a pipe. Electrical connections between probe and connecting cable has to be protected against spray or condensation.

Probes have to be inserted into pipework downstream (typically 4*D* to 8*D*) of flowmeters to avoid possible interference with flow conditions.

5.2.4.3 ***Electrical connections***

Thermocouples and other temperature probes will often require extension cables to connect to the measuring instrument. Such connections have to be made in the appropriate materials to avoid interference or stray voltages. In the case of thermocouples, such connection have to be made so that junctions in both leads are at identical temperatures.

5.2.5 Calibration

Temperature devices may be calibrated either by the user, by comparison with a reference device, or by an accredited laboratory. The application of the temperature measurement in the flow calculation will determine the appropriate uncertainty for the calibration and hence the high precision of calibration required.

5.3 Density measurement

5.3.1 General

The measurement of fluid density is often required in industrial situations. Most plants are run by material balance and large amounts of raw materials are purchased by mass. When volumetric flowmeters are used in these applications, the meter output should be supplemented by density measurement to give the mass flow. Also density is often required to confirm fluid composition, or to determine the concentration of chemicals or the quality of mixtures.

Liquid density decreases with increasing temperature and to a lesser degree increases with pressure. Liquid density is relatively easy to measure and for most fluids a determination at one temperature is often adequate. Gas density is more difficult to measure but there are now established laboratory and industrial techniques to enable gas density to be determined with high accuracy. With mixed fluids, density determination is rather more uncertain. There are correlations to enable the density of liquid mixtures to be calculated but the determination of the flowing density of gas/liquid mixtures cannot be made with high confidence levels.

Density is defined as mass per unit volume and has SI units of kg/m^3. It is frequently confused with specific gravity, which, in the case of liquids, is relative density. Relative density is the ratio of the density at flowing conditions to a standardized density (usually water at 4 °C or air at 20 °C). Density is sensitive to temperature and usually a correction needs to be applied for the highest precision. For gases, the specific gravity and relative density differ when the flowing fluid is not air since its compressibility and that of air are different.

General techniques include the use of weighing systems, the measurement of static head or deducing the value from temperature and pressure measurements, but the majority of current process instruments are based on vibrating element methods or radioactive sources. These measure density by detecting amplitude or frequency modulation or by the amount of radiation absorption respectively.

5.3.2 Hydrometry for liquid density measurement

The simplest method to determine liquid density is using a device with a float immersed in the fluid so that a calibrated scale on the float will indicate liquid specific gravity directly. This device, the hydrometer, is very frequently used to measure the density of transparent liquids. The indicating scale is graduated in units to suit the particular industry. Commonly encountered scales include the following:

a) API[6], standard scale for low vapour pressure hydrocarbons;

b) Baume, widely used in acid and heavy liquid applications;

c) Brix, exclusively used in the sugar industry;

d) Quevenne, used in milk processing.

The hydrometer, if carefully calibrated in the laboratory using fluids of high purity and known properties, can give very high performance levels.

5.3.3 Weighing methods

One of the basic ways to measure density is to weigh a sample of known volume. For industrial measurement purposes, a continuous sampling and weighing method is necessary rather than taking samples at regular intervals. This latter method is more precise but does not easily lend itself to process plant needs. Various methods for continuous weighing have been devised, but one of the more successful for liquids is shown in Figure 5.3.1. This instrument has a U-shaped tube which is supported at the curved end by force-balance mechanism. In operation, a counter balance weight is positioned to balance the weight of the tube plus the process fluid within it. A balance is achieved when the force applied by the feedback bellows to the weigh beam equals the pressure generated from a flapper nozzle and relay, acting as a feedback loop in the system. An increase in density causes the flapper to be brought closer to the nozzle, thereby increasing the back pressure and applying more force to the weigh beam to re-balance the system. Both pneumatic and electronic force balance designs are available.

All such weighing instruments require calibration to determine the basic constants. Weights are added with the tube empty to set the scale for the instrument. Once the range of fluid densities to be measured is known, the position of the counter-balance weight is adjusted with the addition of calibrated weights, simulating the range of weights of fluid in the tube. In the pneumatic version the typical output range is 20 kPa to 100 kPa, with a basic 4 mA to 20 mA output for the electronic version. The density meter can be adjusted to operate over spans of 0.02 kg/m^3 to 0.5 kg/m^3, and for fluid densities up to 1.6 kg/m^3. The instrument is more suitable for clean fluids but can be used on low concentration slurries. It is not suitable for two-phase gas/liquid flows. For clean fluids a minimum velocity of around 1 m/s is recommended, increasing to a minimum of 2 m/s for slurry applications to avoid deposition in the tube.

A commonly encountered variation of weighing is the pyknometer bottle shown in Figure 5.3.2. This consists of a bottle of precisely known volume. The bottle and its stopper are weighed twice, firstly empty and then filled with distilled water. This determines the actual volume at reference conditions. The bottle is then emptied and refilled with the fluid whose density is to be determined and a third weighing is performed. The fluid density is then the ratio of the fluid mass to the bottle volume and the specific gravity is the ratio of the weight of fluid to the weight of distilled water. Measurement uncertainties approaching four decimal places (approximately 0.01 %) are possible under carefully controlled conditions.

[6] American Petroleum Institute.

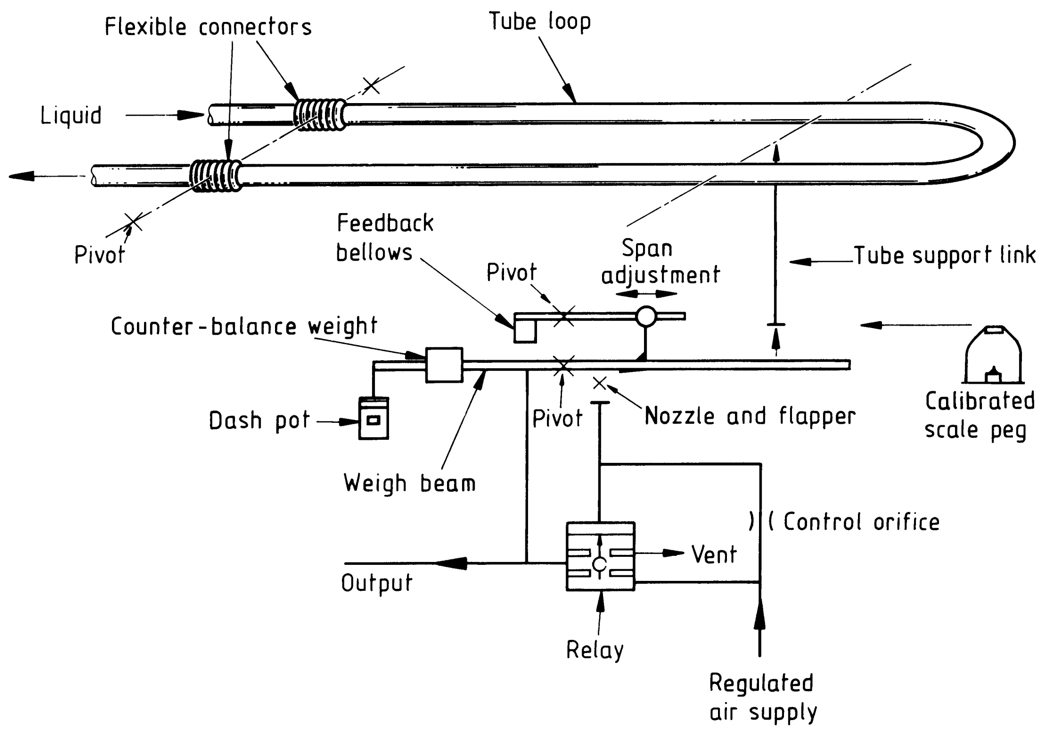


Figure 5.3.1 — Process weighing-based densitometer

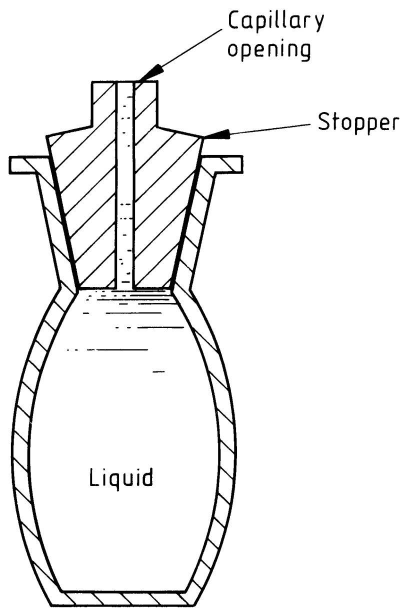


Figure 5.3.2 — Pyknometer bottle

5.3.4 Hydrostatic head methods for liquids

The use of pressure transducers to infer fluid density is growing in industrial applications due to the convenience of the method. The basic principle is illustrated in Figure 5.3.3(a). The difference in pressure between two points, A and B, below the fluid surface is equal to the fluid head pressure between these two elevations.

For an incompressible fluid, referring to Figure 5.3.3(a), if the fluid pressure at levels A and B are p_A and p_B respectively and if level A is depth X (in mm) below the liquid surface level we have the following relationships:

$$p_A = p \text{ surface} + \rho g X \qquad (5.3.1)$$

$$p_B = p \text{ surface} + \rho g (X - H) \qquad (5.3.2)$$

therefore

$$\rho g H = p_A - p_B \qquad (5.3.3)$$

therefore

$$\rho = \frac{p_A - p_B}{gH} \qquad (5.3.4)$$

Hence, if the difference in pressure between levels A and B is measured and also if the distance between A and B is measured, it is possible to calculate the density ρ of the fluid. It is common practice to suppress the zero to the minimum head to be encountered and to measure only the span of the actual density changes. This allows the entire instrument span to be devoted to the differential head caused by density changes.

There is a variety of differential pressure transmitters available to determine density from hydrostatic head measurements. A complete description of the various suitable types is found in **5.1**. All types require that the dimensions of the process tank provide sufficient change of head to satisfy the minimum span of the transmitter and deep tanks are therefore preferable. Most of the transmitters used are flange mounted types, bolting directly into specially designed recesses in the vessel.

A simpler adaption of the method is shown in Figure 5.3.3(b). Here an overflow ensures a constant level on top of the DP cell. Other adaptions include level and pressure compensation techniques and the use of pressure repeaters for low system pressure or vacuum applications. Details of these methods can be found in Higham (1985).

5.3.5 Vibrating element process densitometers

5.3.5.1 *General*

The most common form of on-line process densitometer uses resonant elements to determine density. The operating principle is the same for all fluids, but there are differences in the mechanical construction of liquid and gas vibrating elements due to the required sensitivity and the large difference between gas and liquid densities.

Figure 5.3.4 shows the basic principle of operation. When a mass M_1 filled with fluid of mass M_2 is displaced and released it will oscillate at its natural frequency until viscous damping causes it to come to rest. This viscous effect can be overcome by driving the system at resonance. The natural frequency of such a system is then given by:

$$f \propto \frac{1}{2\pi}\sqrt{\left(\frac{EI}{M_1 + M_2}\right)} \qquad (5.3.5)$$

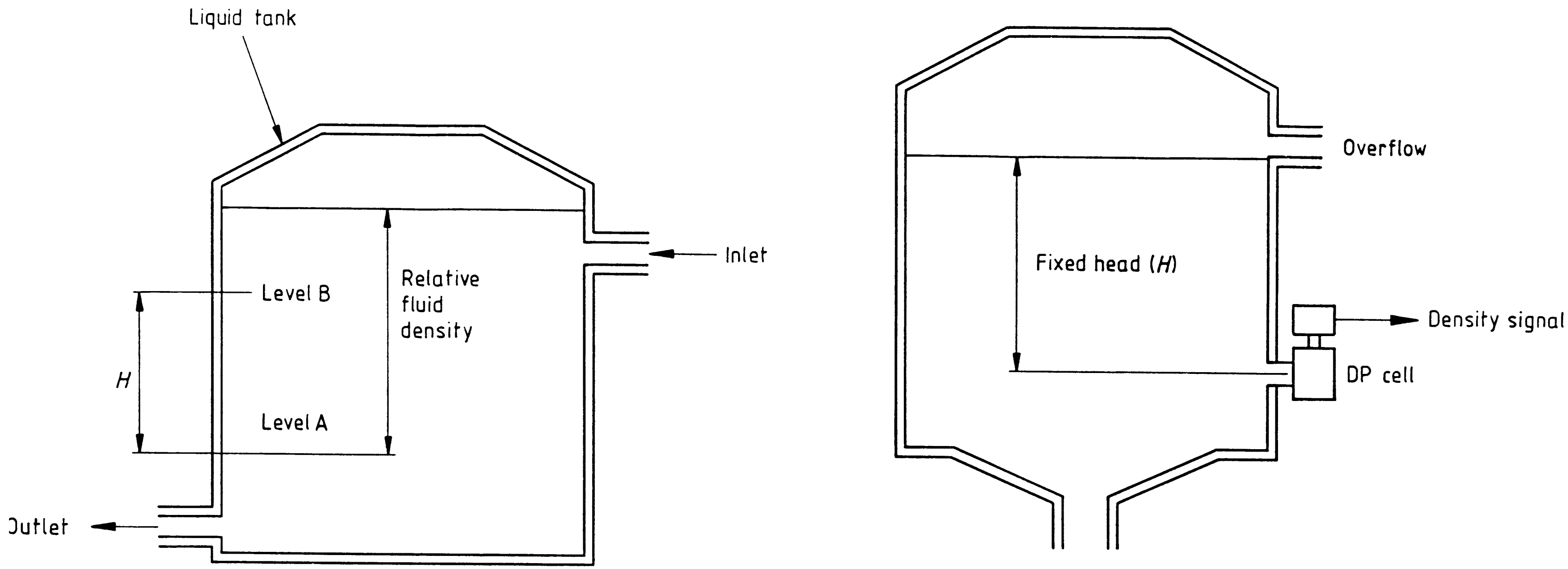
where

E is the elasticity (in N/m^2);

I is the stiffness (in kg·m^2);

M_1 is the mass of the element (in g);

M_2 the mass of the fluid (in g).



(a) Static head method

(b) Constant head method

Figure 5.3.3 — Density determination

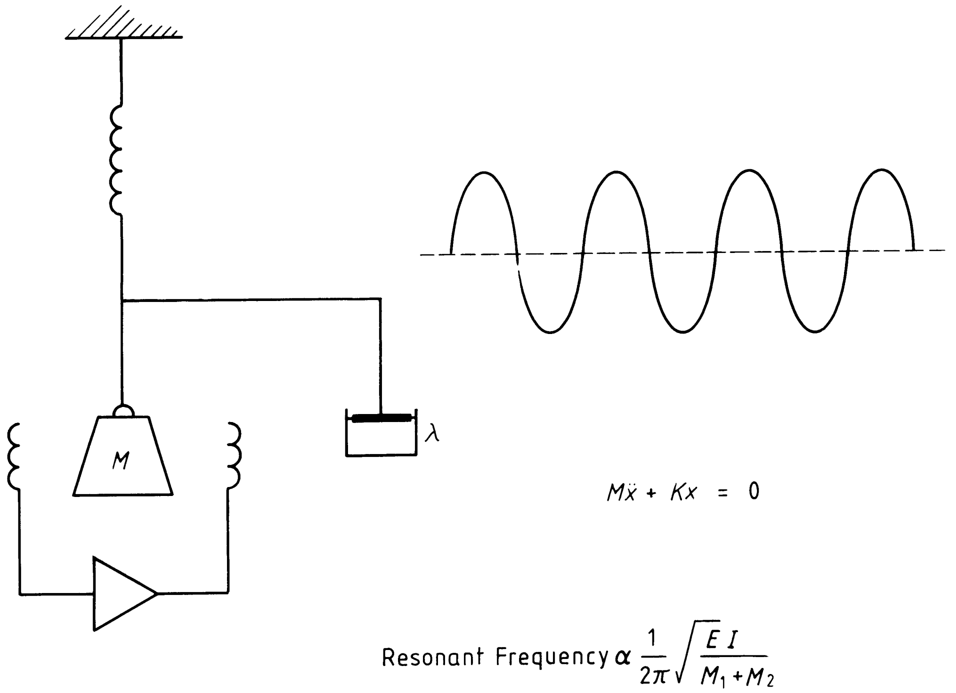


Figure 5.3.4 — Operating principle of vibrating element densitometer

If *E, I* and M_1 are all constants then the density of the fluid, ρ (in kg/M^3), can be written in the form:

$$\rho = K' + \frac{K}{f^2} \tag{5.3.6}$$

where *K* is a constant.

As period of vibration, τ, is the inverse of frequency, we have:

$$\rho = K' + K\tau^2 \tag{5.3.7}$$

In practice the equation used is of the form:

$$\rho = K_0 + K_1\tau + K_2\tau^2 \tag{5.3.8}$$

Most process densitometers are suitable for continuous measurement. Ideally the device should have no pressure, flow rate, viscosity and temperature dependence and should offer a clean flowpath for the process fluid.

5.3.5.2 *Liquid transducers*

One such variant for liquids is shown in Figure 5.3.5. The tube is vibrated lengthwise by coils mounted on the outside of the tube assembly. The single straight tube offers good flow conditions through the device, and is isolated from the instrument case by flexible couplings. These also reduce stresses from adjoining pipework and from thermal expansion. Ideally the materials of construction should have a low and stable coefficient of expansion but temperature corrections can be applied in those applications where there are large variations in process or ambient temperature. Normal construction materials include 316 stainless steel, Hastelloy or Ni-span C tube.

The claimed uncertainty under controlled calibration conditions is around 0.2 kg/m^3 with repeatabilities of 0.02 kg/m^3 over a density range of 300 kg/m^3 to 1 600 kg/m^3. Actual performance depends on the uncertainty of the calibration, with three or more fluids usually being required to establish the frequency density relationship for each transducer with sufficient confidence. In the majority of cases traceability to agreed reference standards is easy to accomplish.

These instruments can be used on fluids up to three times the density of water. Pressures of up to 50 bars can be accommodated using standard materials but special designs up to 150 bar operating pressure for liquids and 250 bar for gases are available.

5.3.5.3 ***Gas transducers***

The basic design of gas density transducers differs from the liquid density transducers described in **5.3.5.2** in the size of the vibrating element and hence in the size of the unit required.

Constants K_0, K_1 and K_2, in equation 5.3.8, are obtained from a calibration of the individual instrument in nitrogen or argon, or synthetic natural gas. Corrections have to be made if the actual measurement takes place at a different temperature from the calibration temperature. In addition, corrections have to be made if the gas composition during measurement differs from the gas in which the calibration took place. This latter correction is widely known as the velocity of sound correction. The uncertainty typically associated with these gas instruments is 0.15 % of reading on pure gases and 0.2 % of reading on natural gas mixtures.

Where there is a requirement to measure the specific gravity of a gas mixture, available commercial transducers can be used, one of which is shown in Figure 5.3.6. The vibrating element transducer is surrounded by a constant volume reference chamber, which is initially pressurized with a sample of gas. The reference gas pressure acts through the chamber control valve so that the pressures on both sides of the diaphragm are equal. As the ambient temperature changes, so the pressure of the reference gas will also change, thereby self-compensating the gas transducer for pressure and temperature changes.

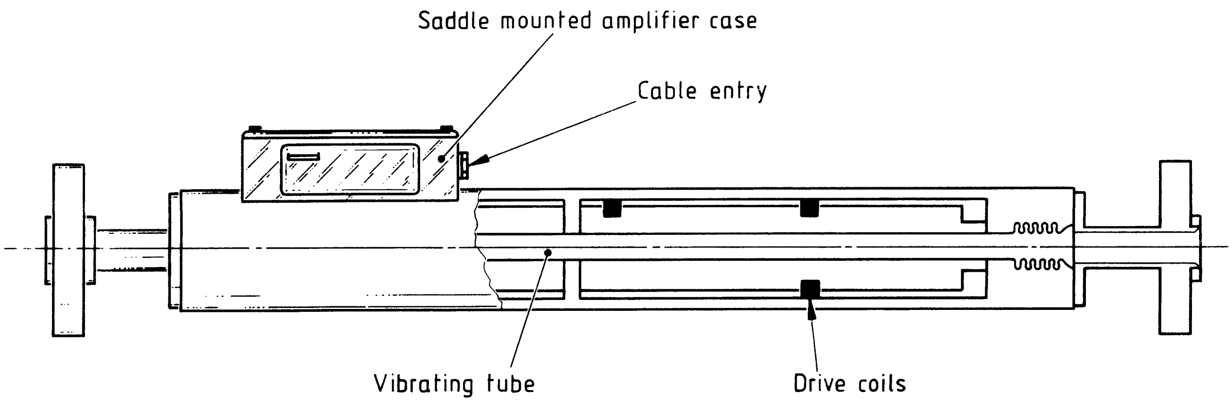


Figure 5.3.5 — Typical liquid densitometer

The output signal from the density transducer is a measure of the molecular weight (or specific gravity) of the sample.

These instruments have claimed density determination uncertainty of around 1 % of reading, with repeatabilities of around 0.02 % of reading. The design shown in Figure 5.3.6 has a cylinder vibrated in a hoop made by electromagnetic drive coils, with the maximum amplitude occurring in the centre of the cylinder. The measuring cylinder has wall thicknesses around 0.1 mm to obtain sufficient sensitivity with the low gas densities involved. The actual installation and operating guidelines for use with flowmeters are discussed in **5.3.8**. As with direct density transducers, these instruments are calibrated on pure gases whose thermodynamic properties are well documented.

For reliable performance from both density and specific gravity transducers, it is essential to use filters upstream of the density transducer to prevent dirt deposition on the sensitive measuring element. Such an occurrence would change the effective mass of the vibrating element and thereby introduce systematic errors in the output. Systematic errors can also arise from the effects of changing gas composition, although these shifts are usually small. Most manufacturers have a wealth of operating data and can advise on possible sources of error.

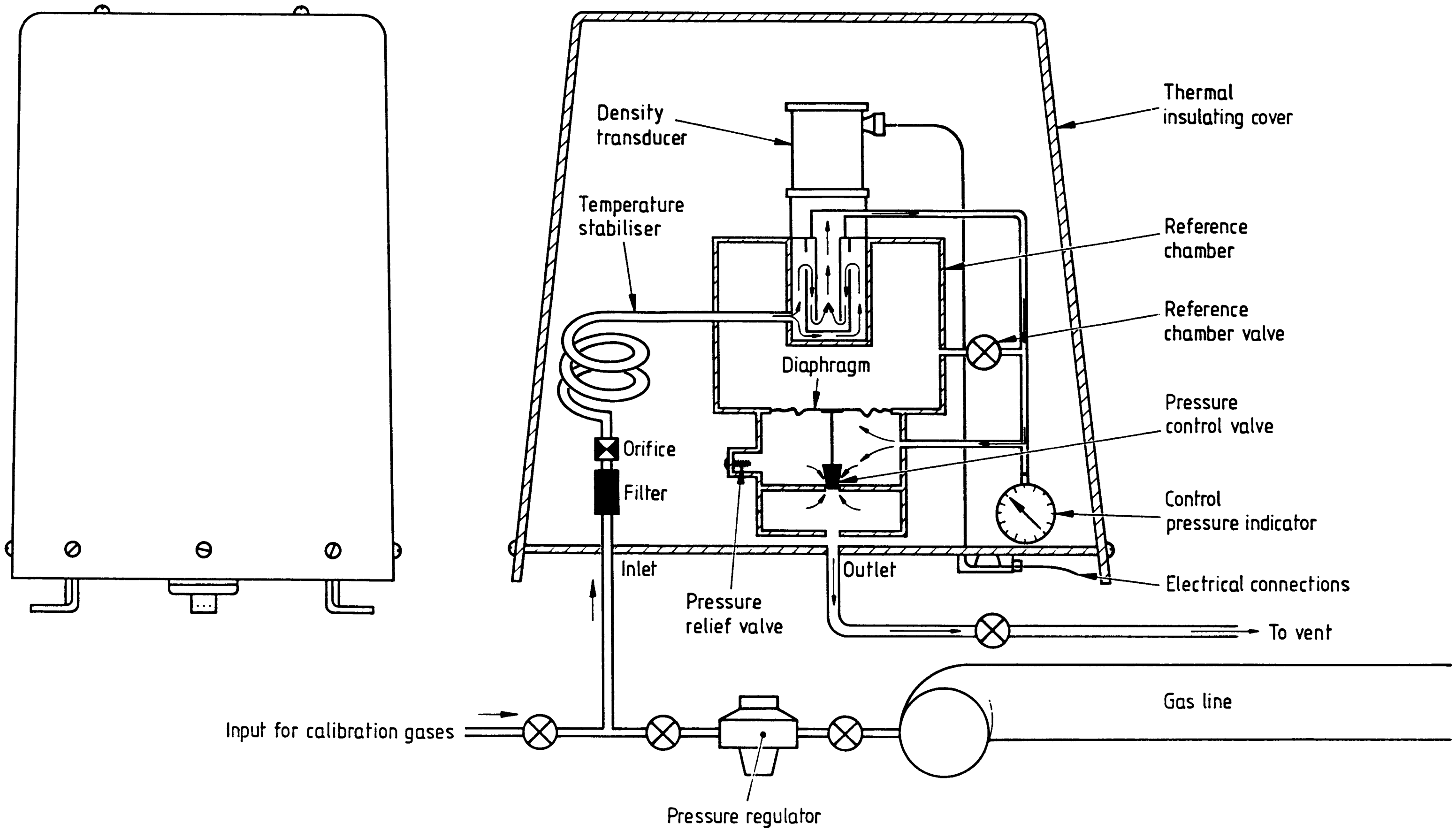


Figure 5.3.6 — Typical specific gravity transducer for gases

5.3.6 Radiation based densitometers

Density can be determined by measuring the amount of attenuation experienced by a beam of gamma or x-rays fired through the pipe walls. The higher the fluid density, the greater will be the attenuation measured by a suitable detection device positioned opposite the source of the beam. The basic equation describing the principle of operation is:

$$I = I_o \, e^{(\mu x)} \tag{5.3.9}$$

where

I is the received radiation

I_o is the source (transmitted) radiation

μ is the absorption coefficient of the fluid

x is the distance transversed by the radioactive beam

Nuclear density gauges are usually applied to measure and control fluid density in slurry type applications where performances as high as ± 0.03 % is claimed. The pipe size is not normally a problem as source strength can be increased as line size increases. Such techniques have been used on pipelines from 25 mm to 750 mm bore and on conveyor systems for the measurements of solids.

In a typical arrangement a radioisotope source, inside a lead lined shutter controlled storage vessel, is clamped on one side of the pipeline and a suitable counter is positioned opposite on the other side of the pipe. The received radiation is then proportional to the density of the fluid in the pipe. Corrections can be applied for absorption due to the pipe material by calibrating the system with the pipe empty. The detector then converts the received radiation into an electrical signal which can then be interfaced with suitable readout equipment.

As the radiation source strength decays with time, compensation has to be applied to ensure constancy of performance. Most suppliers of this type of equipment have compensating electronics which eliminate the zero drift caused by the radioisotope source decay. Zero and span can be adjusted when the pipe is first empty and then full of the process fluid. Once the system is calibrated, on-line reliability and performance is good. This technique is mainly limited to the difficult applications where fast response is not required. The major advantage is the non-contacting nature of the measurement.

5.3.7 Acoustic densitometers

The density of a fluid can be determined from the propagation of ultrasonic waves through it. As a result of the major influence of process variations such as pressure and temperature, this technique is normally only used to indicate changes in fluid density as opposed to absolute values. For liquids the velocity of sound, c (in m/s), is related to density by the equation:

$$c = \left[\frac{1}{\beta_a \rho}\right]^{½} \tag{5.3.10}$$

where

β_a is the fluid adiabatic compressibility (in $N{\cdot}m^{-2})^{-1}$.

For gases the relationship is more dependent on pressure p by the relation:

$$c = \left[\frac{\gamma p}{\rho}\right]^{½} \tag{5.3.11}$$

where

γ is the ratio of the specific heats for the gas.

One application where such techniques have been applied with success is in slurry applications. These fluids have a tendency to settle out and if ultrasonic transducers are used in a vessel where the fluid is agitated, control of concentration within ± 0.1 % of the desired value has been reported. In general the specific gravity range that can be covered is somewhat limited as the slurry particles attenuate the ultrasonic beam.

5.3.8 Use of densitometers with flowmeters

Densitometers find widespread use in flow measurement systems in calculating mass flow rate from measurements of density and volume flow rate, particularly in the custody transfer of hydrocarbons. When density signals are used to correct flowmeter outputs for use in mass balance calculations, it is important to minimize variations in physical properties between the point of flow measurement and that of density measurement. Often the flowmeter and densitometer outputs are compensated, a typical liquid metering system being shown in Figure 5.3.7. In fiscal metering systems, the instruments installed will also permit the mass/volume outputs to be corrected from the line conditions to some agreed base conditions.

Gas densitometers are normally installed downstream of the flowmeter. The distance varies with flowmeter type but it is recommended that the two instruments should be as close as possible without the presence of one interfering with the output of the other. Densitometers can either be installed in the main line to sample the stream or in a bypass loop. In bypass installations either fluid is extracted from the line or the pressure drop across the meter is used to drive fluid through the densitometer. Further details on these methods can be found in the Institute of Petroleum's "Petroleum measurement manual" (1983).

5.4 Humidity measurement

5.4.1 General

The most frequently used quantity is relative humidity (r.h.), a measure of how close the air is to saturation. The relative humidity for a given volume is:

$$\text{r.h.} = \frac{\text{mass of water vapour present}}{\text{mass required to saturate at same temperature}} \times 100\ \%$$

The relative humidity is usually referred to simply as humidity and is expressed as a percentage. Saturation corresponds to 100 % r.h.

The relative humidity can be increased either by the evaporation of more water or by a reduction in temperature. Thus air approaches saturation as it cools. Eventually the air becomes completely saturated and water then condenses into droplets. This condensation begins at the dew point, i.e. the temperature at which the water vapour present is just sufficient to saturate the air.

Situations where humidity measurements may be required are as follows:

a) when the density of moist air is needed for the application of buoyancy corrections during gravimetric measurements;

b) when using a wet gas flow measurement system;

c) laboratory environmental monitoring;

d) in-house checks or calibrations on working hygrometers.

5.4.2 Types of instrument

5.4.2.1 *General*

There are about 10 principles which are commonly used in hygrometry, but six of these account for 95 % of hygrometers in use in the UK. Table 5.4.1 summarizes the six main categories, and gives typical applications.

5.4.2.2 *Mechanical hygrometers*

The dimensions of many natural and synthetic materials change as they adsorb or desorb moisture to maintain their equilibrium with the surrounding gas. Traditionally the most common materials were human hair and animal membranes, but in recent years various plastics materials and textiles have come into use.

Usually a simple mechanical linkage moves a pointer or a pen. Often contacts are provided to operate an alarm, and there are some instruments which have electrical or pneumatic outputs.

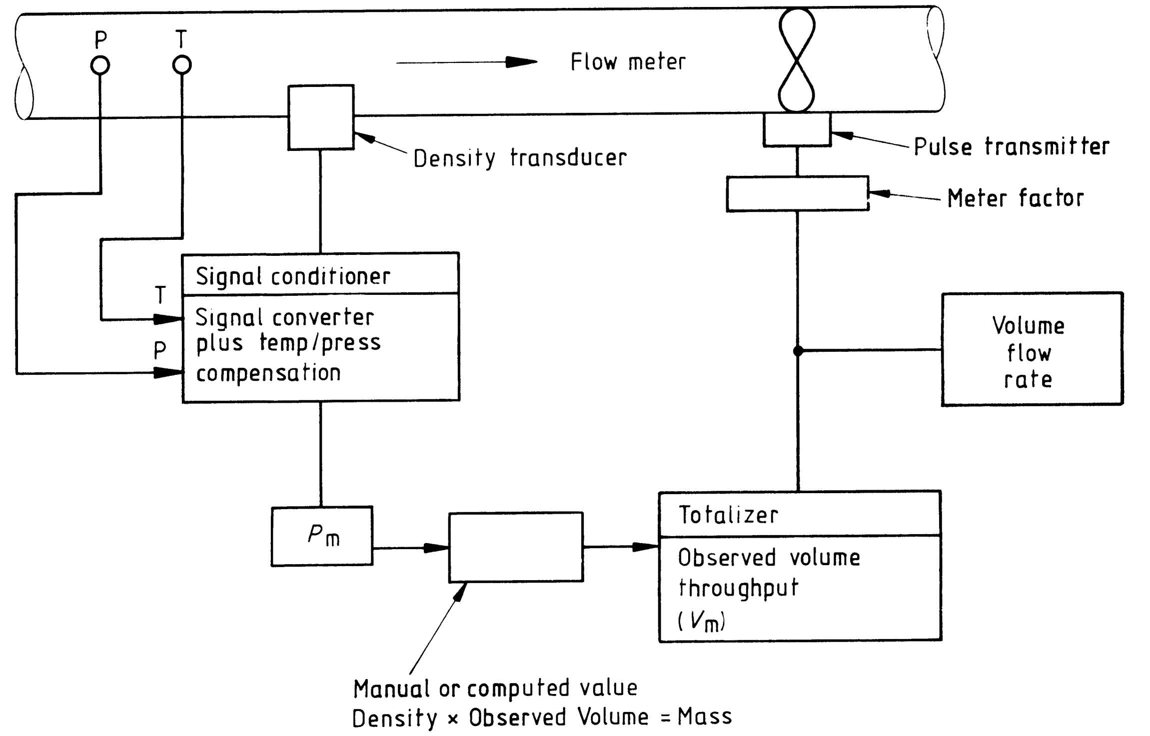


Figure 5.3.7 — Schematic pressure, temperature and density compensated metering system

Mechanical hygrometers are generally used at ambient humidities. The typical range is 25 % r.h. to 80 % r.h. Because the sensor element is usually thick, response is slow. Hysteresis is usually several per cent of relative humidity, and performance is unlikely to be better than ± 8 % r.h. Even this is normally only possible over the mid-range because many of the materials used respond in a non-linear manner at high and low humidities. Often there is little change at the humidity extremes. Mechanical hygrometers may be affected by vibration, and some materials show ageing effects.

5.4.2.3 ***Psychrometer (wet and dry hygrometer)***

When water evaporates, energy is required to effect a change of state. This fact is exploited by psychrometers which measure the humidity by determining the ambient (dry-bulb) temperature, and the temperature of an evaporating water source (wet-bulb) temperature.

In practice the source of moisture is usually a moistened wick surrounding a thermometer. Data are available to determine the humidity from the initial (ambient) temperature of the gas and the wet-bulb temperature. One limitation is that most of the available data are for air at ambient pressures, and give the humidity in terms of relative humidity. Various types of temperature sensor are used, but the most common is the simple liquid-in-glass thermometer. The method is simple and cheap, but is sensitive to small temperature errors, which may occur for several reasons, including thermometer inaccuracy and contamination of the wick.

An adequate flow rate is essential for good performance, and for this reason the "whirling" psychrometer should not be used. Except for the large meteorological types of whirling psychrometer, it is almost impossible to maintain the required flow velocity of 3 m/s to 5 m/s for the time necessary to achieve thermal equilibrium (several minutes), without severely affecting local humidity with body moisture.

A performance of better than ± 3 % r.h. can be achieved when the appropriate air flow rate, and calibration thermometers are used if it is ensured that the wick on the wet thermometer is clean. With certain thermometers (e.g. platinum resistance) performance can be ± 2 % r.h. in mid-range. Despite this, few manufacturers specify thermometer accuracy and hardly any specify air flow rate or ease of wick replacement. Usually the thermometer range is the only specification.

Table 5.4.1 — Operating principles of the most common hygrometers

Type and proportion in use	Principle	Typical application	Typical performance[a]
Mechanical (45 %)	Physical change in hair or other material	Environmental monitoring. Trend indication. Set point control for ambient humidities	± 10 %
Psychrometer (15 %)	Temperature change resulting from evaporation	More accurate measurement of ambient humidities. Set point control. Checking mechanical types. Checking relative humidity	± 3 % r.h.
Dew point sensor (capacitance) (12 %)	Change in impedance of a hygroscopic material. Often aluminium oxide. Change proportional to vapour pressure	Normally for fairly low humidities. Trends indication. Checking for leaks of water or wet gas. Checking for dryness where the upper limit is well above usual level	± 3 °C d.p.
Electrolytic (11 %)	Electrolysis of water absorbed by phosphorous pentoxide	Usually for very dry gases, or a maximum of 1 000 p.p.m. when higher accuracy required. Checking dewpoint sensors	± 10 % (p.p.m.)
Relative humidity sensor (10 %)	Change in impedance of a hygroscopic material. Often lithium chloride. Change proportional to relative humidity	More accurate measurement of humidities. Checking mechanical types. Set point control. Environmental monitoring. Instruments in this group cover a range from 1 % r.h. to 100 % r.h. and from – 40 °C to 80 °C	± 3 % r.h. (at 50 % r.h.)
Condensation (3 %)	Measurement of condensation temperature	Calibration of all other types. Can be used across the whole range covered above and with higher accuracy but expensive, more difficult to use and less suitable for contaminated or transient conditions	± 3 °C d.p.

[a] Instrument output may be in other units.

The method works below 0 °C, but it is difficult to develop and maintain an ice layer on the wet thermometer. At high temperatures some psychrometers are unable to maintain an adequate water supply to the wick.

5.4.2.4 ***Dew point sensor***

Most dew point sensors are based on the electrical impedance change of an aluminium oxide capacitor as moisture penetrates the pore structure. However, other oxides can be used, and there are other types of sensor in which the measured electrical property changes in relation to the dew point of vapour pressure, rather than the relative humidity.

The performance of instruments with dew point sensors is unlikely to be better than 2 °C d.p. (degrees Celsius dew point), and can be worse than 3 °C d.p. for humidities above about – 30 °C d.p. At lower humidities it may be much worse.

Sensors have temperature coefficients which cannot be ignored, and they should therefore be calibrated at the operating temperature. Hysteresis is also usually significant. Dew point sensors can be slow to respond at low, falling humidities, and may take several days to settle at or below – 60 °C d.p. For rising humidities they respond more quickly (within seconds), when the humidity is above about – 50 °C d.p.

Ageing is a problem with the dew point sensor hygrometer. Ageing occurs more rapidly at high temperatures, and so use above 60 °C is not recommended. Manufacturers use temperature and humidity cycling to pre-age the sensors, but despite this, frequent calibration is necessary if the stated performances are to be achieved.

5.4.2.5 ***Electrolytic hygrometer***

The electrolytic hygrometer relies on phosphorus pentoxide (P_2O_5), which is a very powerful desiccant, to absorb the moisture from the gas sample. The phosphorus pentoxide is supported on a non-conducting substrate between electrodes (usually platinum), and the water is electrolysed to form hydrogen and oxygen.

Theoretically (according to Faraday's law) the electrolysis current is related to the rate of water uptake. However, in practice, incomplete absorption and recombination of the hydrogen and oxygen can lead to errors. It is also necessary to measure the flow rate precisely. Uncertainty is normally about 10 % of reading. In high precision gas flow rate measurement, by taking proper precautions when recoating the cell electrodes, an uncertainty of approximately 5 % of reading can be achieved. This would be the middle of the range which is usually approximately 2 p.p.m. to 1 000 p.p.m. at ambient pressure.

Use of the electrolytic hygrometer may not be possible if any of the gaseous components react with phosphorus pentoxide. If only small amounts of impurity are present, it may be possible to use the method by recoating the cell more frequently. In normal clean conditions at a flow rate of 100 mL/min, the cell life between recoating may be 250 000 p.p.m. of hydrogen (product). However, wet conditions shorten the life, and ambient humidity over-ranges the sensor. Unfortunately this instrument can appear to give sensible readings when the cell coating has deteriorated severely.

The most important application is in the range below 500 p.p.m. Response is fairly fast, and measurement is possible down to approximately 1 p.p.m. (lower if the cell can be operated at high pressure). At humidities of a few p.p.m. or lower the cell life is shortened as the dry phosphorus pentoxide can be blown off the cell.

5.4.2.6 ***Relative humidity sensor***

The sensor usually consists of a hygroscopic material whose electrical impedance varies with relative humidity. This is lithium chloride or another salt, which may be held in a gel or some other matrix. Many modern sensors, constructed using thin film technology, may be resistive, capacitive or some combination of the two.

Frequent calibration is essential, but often can be performed quickly using saturated capsules which manufacturers supply. Sensors generally have a significant temperature coefficient and so calibration at the operating temperature is desirable. Temperature coefficients are rarely specified.

Sensors can have limitations at the extreme end of the range, i.e. 0 % r.h. or 100 % r.h. This may be due to severe non-linearity, but in some cases sensor damage may occur. Saturation guarding (heating the sensor slightly) is used to overcome the high humidity problem.

An uncertainty of approximately 4 % of reading is generally achieved but 3 % is possible with regular calibration.

Response to humidity changes is usually quite fast, of the order of a few seconds, but the slower response to temperature changes can greatly influence the measurement. The type, in which a gel supports lithium chloride, exhibits a significant hysteresis, which may be more than 5 % r.h.

5.4.2.7 ***Condensation hygrometer***

The condensation hygrometer is, in some respects, the best type of hygrometer available. It can have excellent calibration stability and operates over a very wide humidity range. Its use is limited by cost and in many industrial applications the uncertainty can be increased to 1 °C d.p. or 2 °C d.p. or more by contamination. In some situations it is completely unsuitable, but for ideal conditions, such as those in a calibration laboratory, it is the most accurate type of instrument available commercially.

In the usual measurement configuration of a condensation dew point hygrometer, a Peltier cooler is used to cool a mirror. Formation of dew or frost is detected by means of an optical sensor and the rate of cooling is controlled to maintain a constant thickness of dew-layer. A temperature sensor, normally a platinum resistance thermometer, in intimate contact with the mirror surface, is used to measure a condensation temperature.

The long-term performance of the instrument is determined by the performance of the temperature sensor, and the thermal bonding between this and the mirror surface. Although other components may be repaired or replaced, they do not in themselves affect the overall performance as their individual performance can be tested without an actual humidity measurement. Performance is maintained whenever a stable, controlled dew-layer is formed on the mirror.

Although it is sometimes claimed that the condensation dew point method is fundamental, calibration is required to quantify error due to thermal gradients, which can be large. Additional uncertainties are contributed by errors in the temperature measurement system, uncertainties due to the droplet, or ice crystal, size (Kelvin effect) and due to soluble contamination in the condensate (Raoult effect).

As a result of these errors, an uncertainty approaching 0.3 °C d.p. is about the best performance for condensation dew point hygrometers. For general laboratory or industrial use the uncertainty is usually greater. However this is still better than that of many other types of hygrometer.

5.4.3 Performance aspects

It is important to realize just what is possible in humidity measurement. There is a general tendency for both manufacturers and users of hygrometers to overestimate the performance of the equipment. For hygrometers in industry and normal laboratories, except under very special circumstances, the lowest attainable uncertainty is equivalent to approximately 0.3 °C d.p. or approximately 3 % of the reading in relative humidity. Often the performance achieved will be much worse that this.

To emphasize the point, the lowest uncertainty claimed by the National Bureau of Standards (NBS) Primary Humidity Standard in the USA, is 0.4 %. This is equivalent to approximately 0.04 °C d.p., and is the best uncertainty offered by any of the five National Standard Laboratories which currently provide a humidity calibration facility.

5.4.4 Installation considerations

5.4.4.1 ***Flow rate***

Mechanical hygrometers, and most psychrometers are not configured either for sampling or for duct mounting and hence are used in the chamber or room, and are reliant on natural gas movement to bring a representative sample to them. Psychrometers require a very large sample flow rate, and also contribute a lot of water to their environment and hence work best where there is considerable gas movement. Mechanical hygrometers can be affected by vibration so high gas velocities are to be avoided.

The relative humidity sensors, dew point sensors, and saturated lithium chloride sensors are very versatile. Most manufacturers provide shields if necessary so that sensors may be mounted as remote probes in high gas velocity ducts. Equally good results can usually be obtained in relatively static situations. In addition, probe housings and instruments with integral sensors are available for situations where sampling is appropriate. There are also probes for high pressure applications.

Optical dew point instruments are also available as probes, and can be installed in the same ways as other probe-type instruments. However the flow rate at the sensor is more restricted and should normally be limited to the equivalent of about 1 L/min at the mirror.

The electrolytic hygrometer is normally restricted to sampling at a low flow rate but can operate at high pressure.

5.4.4.2 ***Safety***

Instruments of all types except the optical dew point hygrometer are available in forms suitable for use in potentially explosive atmospheres.

5.4.5 Operating limits and environment

There is no general rule which can be applied to hygrometer operating limits. Manufacturers' specifications have to be followed. Unfortunately there is a wide range of variations within each of the categories described in the previous sections; manufacturers' specifications are often inadequate, and in many cases, optimistic. Temperature, pressure, and humidity operating limits are not always given.

The following points should be considered in the proposed application of the hygrometer.

a) Condensation will destroy some of the relative humidity and dew point sensors, but it has to be avoided anyway for meaningful measurement.

b) Conditions close to saturation will damage some relative humidity sensors and will accelerate ageing on many dew point sensors.

c) Some relative humidity sensors are damaged by very dry conditions.

d) No hygrometer will function correctly in the presence of dust, oil-mist, or fluid drops, etc. These should normally be removed by filtration, or some other method. If accidentally contaminated, relative humidity sensors, dew point sensors, and mechanical hygrometers will be permanently damaged. Other types of hygrometer may be cleaned, but this may be tedious because contamination should also be removed from associated pipework, housings, etc.

e) Corrosive or unusual gases may affect the measurement, even if present in low concentrations. For relative humidity and dew point sensors the manufacturer should be consulted. Condensable components will cause errors on optical dew point hygrometers; soluble particles or gases may affect the measurement from optical dew point hygrometers, or psychrometers; anything which reacts with phosphorus pentoxide or lithium chloride will cause a problem with the electrolytic or saturated lithium chloride hygrometers respectively.

f) Temperature fluctuations cause increased uncertainty with any hygrometer and should be avoided. Stable temperature conditions are particularly important for relative humidity measurement, and are essential near saturation. The same is true of pressure fluctuations.

5.4.6 Instrument selection

There is no simple set of rules for selecting a hygrometer since so many variations exist in both instruments and applications. However, Table 5.4.1 gives some guidance on suitable applications. Mechanical hygrometers and psychrometers are the least expensive, but, except for humidity measurement at normal ambient conditions, selection will usually depend on the requirements of the application rather than on cost or convenience of use. Most manufacturers offer some applications assistance and so it is usually possible to test and assess an instrument before purchase.

5.5 Ancillary electrical equipment

5.5.1 General

This section looks at some of the electronic equipment now available for use with flowmeters. Electronic developments have resulted in alarm indication, batch control and other functions being readily performed in conjunction with flow measurement.

Modern instruments have enabled on-site, instantaneous monitoring and computation, thereby removing most of the human error and allowing on-line compensation and control to be performed effectively and economically. Figure 5.5.1 shows some of the range of instruments which can be used with a turbine meter.

5.5.2 Flow rate and flow totalization equipment

Most flowmeters are used to indicate total flow, some indicate flow rate and sometimes the meter can indicate both rate and total. This enables control, accounting and other functions to be carried out simultaneously. Flowmeters such as group 3 (displacement types) indicate total flow directly whereas others are more suited to flow rate indication. Digital flowmeters produce pulses, each of which represents a fixed amount of fluid. Counting the pulses indicates the total flow volume passed, to within ± 1 count which is insignificant if the totalization is carried out on a daily basis. In this instance the performance of the totalization system depends largely on the performance of the primary element and not on the signal processing. If analogue flow rate devices are used then there is the uncertainty of the analogue readout device together with the digital to analogue conversion to be considered. If a simple indication of flow rate is required, then analogue output meters with analogue readout devices will be sufficient.

Totalizing counters can give a record of a number of events, usually on an integral display. Manual changes to stored data of a secret nature can be provided with key protection or software password security. Mechanical counters can also provide these features with the advantage that electrical power loss does not affect system integrity. However, the disadvantages of the mechanical operating devices are:

a) they are low speed;

b) require mechanical initiation;

c) scaling has to be done externally with thumbwheel switches.

Electronic instruments are generally faster, more flexible and scaling can be performed more easily by programming links, switches or more recently by software manipulation. Typically, totalizing counters are used for the monitoring and control of production. Batch counters are also extensively used, being programmable to perform a variety of duties. They can be used to count up to or down from a preset value. In addition, output commands can be provided which initiate another series of actions to take place in sequence. This cascade linking is now an important element in certain batch processes. Displays of set batch counts and either "current actual count", "over-run quantity" or "remainder to each batch" are commonly displayed. The devices can now have operator key pad entry to show a number of variables, preset in the instrument.

There are many different types of simple rate and totalization equipment available. Solid state circuitry is universally used throughout and often modular plug-in boards can be used to configure the system to specific requirements. Non-resettable mechanical counters are also standard and reset buttons can be provided as an optional extra in many designs. These instruments can form part of a complete system and can be interlinked and driven from a common power supply. In such cases, the instruments may also be simultaneously reset or triggered from a common signal. The instruments vary widely in size and price and the user should check the range of inputs and outputs required and the compatibility of the instruments with the flowmeter chosen.

5.5.3 Timers

Timers may be required to measure the duration of a particular event or to ensure that an event takes place for a certain period of time. For example, a positive displacement meter output totalizer may need to be read periodically (either manually or automatically) and the time elapsed since the previous reading may need to be known. Displays on these devices range from the clock types to the modern LED's (light-emitting diode) and LCD's (liquid crystal display). The display will usually be in fixed units of time, but more sophisticated devices may have the option of programming to display whatever units are desired. These instruments may have start and stop output signals to switch on/off power supplies, open/close flow valves or perform similar process functions.

5.5.4 Amplifiers and converters

Preamplifiers and converters are frequently used with pulse generating devices to convert the analogue signals to digital form. Such devices are recommended where transmission over long distances is needed or where flowmeters are used in areas of high electrical noise (generated by large power sources or electrical switchgear). Transmission up to 1 mile from the meter can be achieved with some amplifiers. The housing can be made explosion proof and can be designed to connect with other external circuitry through cable glands and appropriate cable. Amplifiers are generally designed to fit onto the flowmeter and are contained within either flameproof or weatherproof housings.

Most amplifiers are also signal conditioners, taking sinusoidal input signals and converting them to square wave current or voltage pulse trains prior to transmission. The frequency range can vary from d.c. to 10 kHz but is usually between 5 Hz and 5 kHz. Power supply requirements vary between manufacturers but are generally in the range 4 V d.c. to 40 V d.c. Two-wire systems are now the most common, with the power and signal being sent along the same wires, but the older three- and four-wire systems are still available. Some manufacturers also offer intrinsically safe versions for use with zener barriers in hazardous areas.

Range extending amplifiers are also in use with some types of flowmeter. These eliminate magnetic drag effects on turbine rotors (see **3.4.9.2**) and thereby increase the range and linearity of the meter. A modulated carrier, an RF type pick-off, is used as the input signal, the frequency of which varies with the cable capacitance, the rotor mass and the distance between the rotor and pick-off. A voltage or current pulse output, compatible with totalizers, rate indicators or other auxiliary instruments is given, the frequency of which is proportional to the rotor speed.

Manufacturers also offer a range of converters designed to fit inside standard housings. Examples are frequency-to-voltage and frequency-to-current converters, the output levels of which are proportional to flow rate. The converters may also provide simultaneous pulse outputs for direct linking into digital systems.

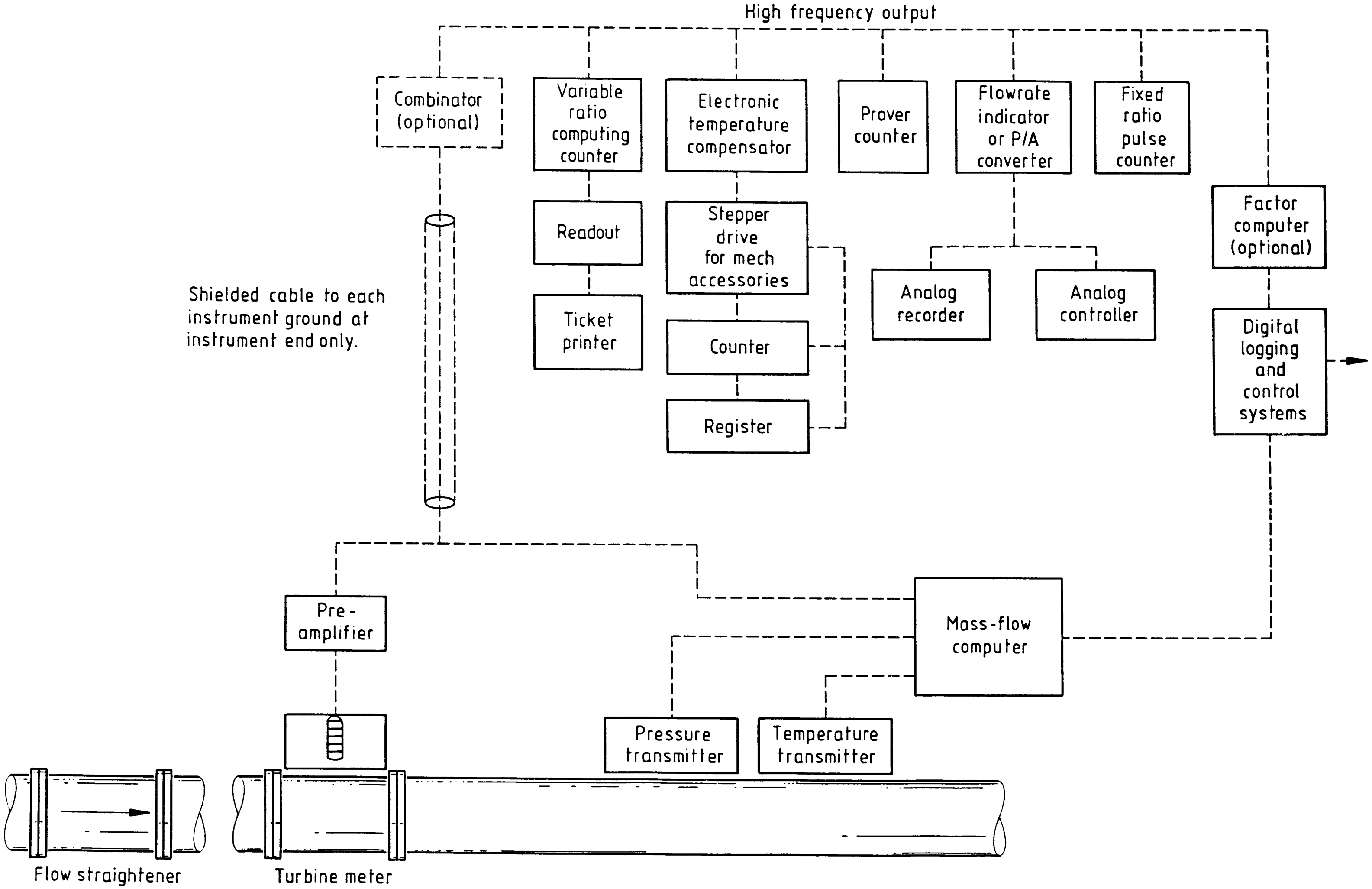


Figure 5.5.1 — Range of instruments for use with flowmeters

Similar products include scalers or *K* factor dividers which accept inputs from magnetic, RF or other pulse sources and provide pulse outputs, either scaled or unscaled, which are proportional to pulse input rate. These devices enable easy interfacing of a meter to measurement, control or other readout equipment from a different manufacturer. The devices allow the user to set the calibration factor of the meter if scaling of the pulse train is required.

5.5.5 Recorders, indicators and data loggers

The recording and logging of process data is vital to the operation of most process plant. Digital or analogue recording or indicating equipment can be used depending on whether a historical or instantaneous recording is required. A common example of a digital recorder is the computer floppy disc, whilst an analogue recorder may well be a chart recorder or UV recorder as in Figure 5.5.2.

In some applications it is not possible to record the information directly, in which case it may be useful to employ a data logger. This is basically a device which accepts and stores the process inputs in low power electronic memory or on tape. Such an application may involve many and varied inputs, e.g. flowmeter pulse inputs, analogue thermocouples, strain gauge pressures, etc. Signal conditioning is performed with common techniques and a high quality analogue to digital converter. Linearization is frequently performed prior to storage with on-board software. Loggers scan the inputs at a fixed rate but some more advanced designs allow the various channels to be scanned under programmable (user) control. If remote readout is required, a serial port can be provided for this purpose. This in turn could be connected to a modem to transmit the data by the telephone wires, enabling remote outstations to be continually monitored.

5.5.6 Process and flow computers

Process and flow computers are installed on many custody transfer installations and in plants where material balances need to be continuously made as in Figure 5.5.3 and Figure 5.5.4. They are usually programmed with specific algorithms to perform the required computations. The accumulated data, flow rates, flow totals, line pressure, etc. are stored in RAM (random access memory) and can be displayed on the computer readout by the operator at any time. The incoming signals from digital devices such as turbine meters and process densitometers are conditioned before being stored. The computer receives operator instructions via a keyboard. The speed of modern electronics allows reading of all the inputs, scaling and conditioning of incoming data, calculations of varying types and data presentation on a continuous basis at intervals as short as once each second. Thus the process operator can examine short-term variations and take action accordingly.

Examples of specific applications of a flow computer are:

a) calculation and compensation of the flow rate from differential pressure devices such as an orifice plate;

b) calculation and correction of the flow rate from digital devices such as a turbine meter or vortex meter;

c) compensation for the effects of temperature or pressure on fluid properties;

d) correcting actual flow rates to reference conditions.

Digital computers have higher reliability and performance than mechanical and pneumatic systems. Their use for material accounting and accurate measurement is recommended.

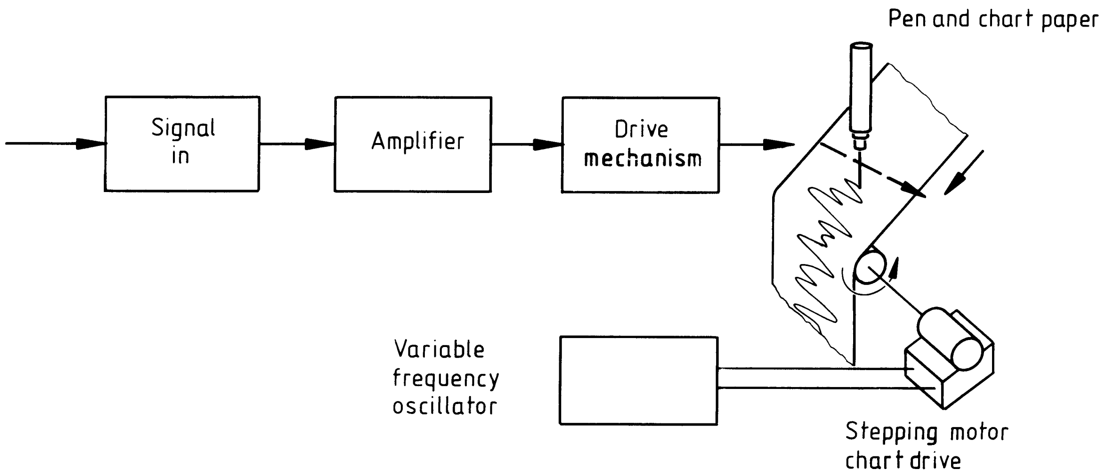


Figure 5.5.2 — Process chart recorder

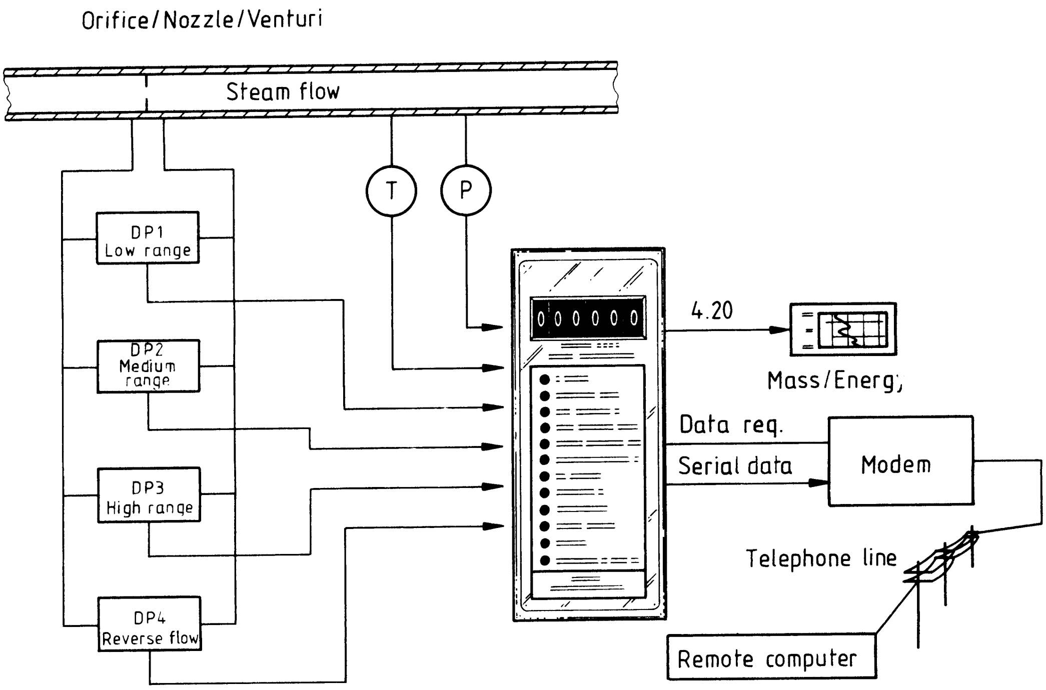


Figure 5.5.3 — Orifice metering system

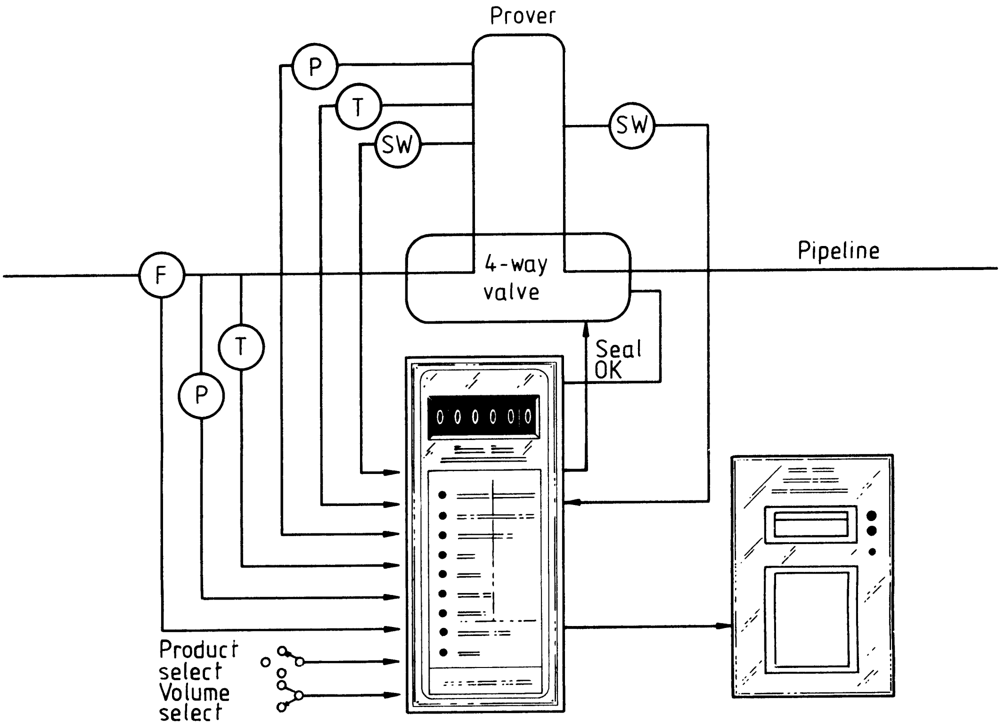


Figure 5.5.4 — Computer based proving system

The following would be a typical specification when purchasing a flow computer for general application:

Inputs:

Up to three DP transmitters 4 mA to 20 mA.

One pressure input (minimum) 4 mA to 2 mA.

One temperature input (minimum) 4 mA to 20 mA.

Three frequency inputs, range 5 Hz to 5 kHz.

Two logic inputs, d.c. to 1 kHz.

Outputs:

Contact closures for gross and net throughput.

Flow rate output (e.g. 0 V to 10 V, 4 mA to 20 mA).

Serial output for printer [RS 232 or general purpose interface bus (GPIB IEE 488 or IEC 625)] and connection to management computers.

Four contact outputs for control (two high/low alarms).

24 V d.c. at 300 mA to power pre-amplifiers, etc.

The instrument would have high performance analogue to digital conversions and would tolerate wide variations of mains frequency and voltage without degradation of performance.

5.5.7 Intrinsic safety equipment

Intrinsically safe equipment is designed to have insufficient electrical and thermal energy under normal or abnormal conditions to ignite a specific gas mixture. In practice the power is limited to about 2 W which is ideal for industrial instrumentation. The power is also suitable for the control of equipment such as electric motors but not for driving the machines. All other techniques, such as the American explosion-proof approach, rely on the maintenance of a physical barrier between the energy source and the explosive atmosphere. As a consequence, housings for intrinsic safety equipment are cheaper, lighter and have a better reliability than their explosion-proof counterparts and allow maintenance of equipment whilst live.

Table 5.5.1 to Table 5.5.3 give details of a gas classification, temperature classification and an area classification comparison of the two approaches.

Table 5.5.1 — The two main systems of gas classification

Representative (test) gas	Industry	Gas classification		Ignitability
		IEC countries (includes Europe)	USA and Canada	
Acetylene	Surface	Group IIC	Class I, Group A	↑ More easily ignited
Hydrogen		Group IIC	Class I, Group B	
Ethylene		Group IB	Class I, Group C	
Propane		Group IIA	Class I, Group D	
Metal dust		(Classification under consideration)	Class II, Group E	↑ More easily ignited
Carbon dust			Class II, Group F	
Flour, starch grain			Class II, Group G	
Fibres and flyings			Class III	
Methane	Mining	Group I	Unclassified	

Table 5.5.2 — Temperature classification system universally used

Temperature classification	Maximum surface temperature	Relative performance
	°C	
T1	450	Better equipment ↓
T2	300	
T3	200	
T4	135	
T5	100	
T6	85	

Explosions are caused by sparks or hot surfaces. The ignition characteristics of representative gases are listed in Table 5.5.1. Guidelines are available for use in the design of instrument systems for resistive, inductive and capacitive circuits for each gas. All certified intrinsically safe equipment carries a statement of the gas group it has been approved for. Minimum ignition surface temperatures have also been established with a code assigned to each gas. BS 5345 gives details of equipment for use in hazardous areas. BS 5501 should also be addressed.

An intrinsically safe circuit comprises one or more energy limiting devices connected between the equipment in the hazardous area and that in the safe area. The simplified circuit shown in Figure 5.5.5 consists of two zener diodes, which limit the voltage that can be applied to the hazardous area, and two resistors which similarly limit the current. One side of the diodes is grounded and, since this carries the fault current, the ground conductor in intrinsically safe systems is of special consideration. A fuse is normally incorporated in the circuit as shown in Figure 5.5.5. In addition, there will be limitations on the wiring and other equipment which can be connected to the terminals of the unit.

5.5.8 Printers

Printers fall essentially into two categories, impact and non-impact types. The two most common designs of the impact type are the daisy wheel and the dot matrix. The daisy wheel is capable of very high output quality but it is relatively slow at around 60 characters per second (cps). It cannot produce graphics and requires periodic ribbon changing. The dot matrix types can operate at higher speeds (in draft form up to 500 cps) and can produce special symbols or graphics.

Non-impact printers offer much higher speed and better definition. They are much quieter but are more expensive. Three common types are the laser, thermal and ink jet varieties. This last design is particularly attractive in process control rooms with the capability for colour reproduction. The laser printer can be very fast indeed with up to 200 A4 pages per minute being possible. Costs vary between suppliers but are dependent on the complexity required.

Printer interfaces can be serial (RS 232 with variable band rates) or parallel, usually with the Centronics standard (limited transmission distance) or other standards such as IEEE 488.

Table 5.5.3 — The two main systems of area classification

IEC Countries	USA and Canada
Zone 0: explosive gas-air mixture continuously present, or present for long periods Zone 1: explosive gas-air mixture is likely to occur in normal operation Zone 2: explosive gas-air mixture not likely to occur and, if it occurs, it will exist only for a short time	Division 1: hazardous concentration of flammable gases or vapours continuously, intermittently or periodically present under normal operating conditions Division 2: volatile flammable liquids or flammable gases present, but normally confined within closed containers or systems, from which they can escape only under abnormal operating or fault conditions

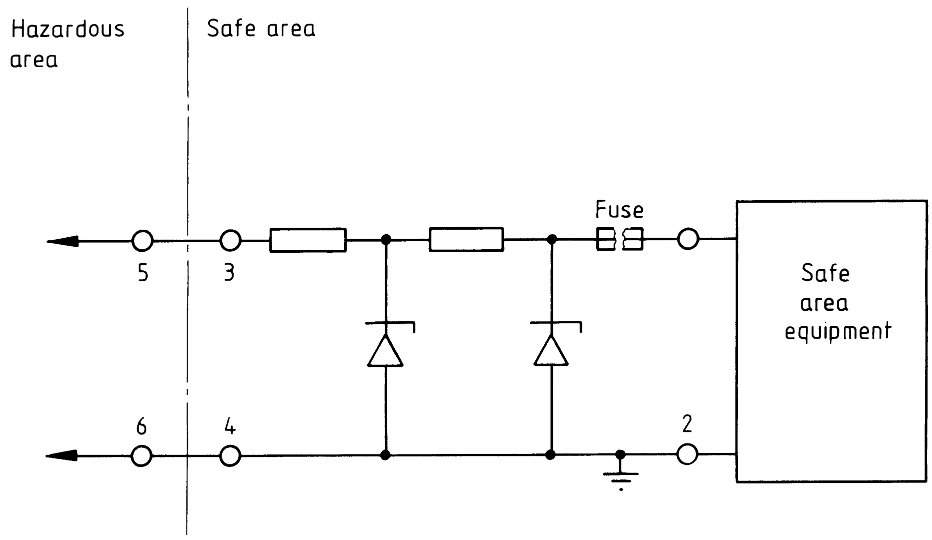


Figure 5.5.5 — Zener barrier

Section 6. Flowmeter calibration

6.0 Introduction

Most types of flowmeters have to be calibrated by passing fluid through them and comparing the reading of the meter under test with the reading of a reference meter of lower uncertainty. The aim is to establish the relationship between the output of the meter and the actual flow rate or quantity of fluid passing through the meter. The interaction of the fluid and other effects usually combine to give a flow rate uncertainty of at best 0.1 % in the reference system.

6.1 Calibration conditions

Flow stability during operation is one of the prime factors in accurate calibration. Constant head tanks, flow stabilizers and flow conditioners should all be considered to ensure the dynamic characteristics of the test stand itself are not significant. Failure to examine these effects may influence the calibration of good quality flowmeters very considerably and the data would reflect the performance of the rig and not that of the meter.

The pressure and temperature at which a flowmeter operates are important factors which have to be taken into account. Pressure and temperature not only affect key dimensions such as the bore of a nozzle or the clearances in a positive displacement meter, but can also have a significant effect on the density and viscosity of the flow, especially in gas streams. Unless the gas density is measured directly the composition of the gas has also to be considered. The gas humidity can also cause significant errors if ignored.

Most flowmeters are sensitive to the velocity profile of the approaching flow and in good calibration facilities the profile should therefore be fully developed and symmetrical. It is normal to ensure that the pipe fittings do not disturb the flow immediately downstream of the meter although this is not so important as the upstream pipe. Many calibration systems provide the facility for reproducing the actual installation conditions under which they have to operate. For example, the meter may be installed in practice close to a bend which will almost certainly affect its performance. The error due to the proximity can, however, be reduced greatly if the calibration is carried out with the bend in the same position as in the normal operation. Calibration with long lengths of upstream pipe would in this case have little resemblance to the actual operating conditions.

The error curve of the meter applies to that meter only, operating under the conditions under which it was calibrated. If conditions in service are different, the calibration may not apply. There are two important factors which should be borne in mind. Firstly, the meter cannot be calibrated at an uncertainty better than its repeatability. Secondly, that the systematic and random uncertainties of the flowmeter standard have to be combined in some agreed fashion to give an overall uncertainty level. The random uncertainties of a calibration can be estimated only from a knowledge of the calibration system and its of traceability. The systematic errors can often be checked by an intercomparison of facilities using a transfer standard.

6.2 Factors to be considered in calibration

The selection of a particular calibration method depends upon the particular circumstances involved. The following general principles are offered for guidance when a decision has to be made. It is essential to decide at the outset the required calibration uncertainty since it is uneconomic to calibrate flowmeters to a lower uncertainty.

It is sometimes not necessary or even possible to calibrate a flowmeter in a laboratory and in such cases various methods of calibration on site are available, some of which are as accurate as laboratory calibrations.

Account should be taken of the complete range of flow rates that have to be handled by the meters. Extrapolation outside the range of a calibration is not recommended.

Normally the calibration fluid should be the same as that with which the meter is to be used, but this is not always essential, e.g. depending on the type of flowmeters, air can be used instead of many other gases, or water instead of some light oils.

Similarly it is usually advisable, particularly for gases, to calibrate at the same temperatures and pressures as those at which the meter is normally used.

Detailed advice on calibration procedures may be found in BS 5857, BS 6199, Hayward (1977), Mattingly (1982) and Pursley (1986).

6.3 Calibration techniques for flowmeters

There is a number of special calibration techniques, some of which are particularly appropriate for calibration on site.

Tracer techniques are described in **3.10.3** and BS 5857.

Velocity area integration methods are described in BS 3680-8 and BS 1042-2.

For certain flowmeters it is sometimes acceptable to carry out a dry calibration, although the uncertainty may be higher than when the meter is calibrated by passing fluid through it. Such a calibration assumes that the primary element is described by empirical correlations developed from geometrically and/or hydraulically similar meters via conventional calibrations. The dry calibration is then basically a check of the secondary part of the system.

6.4 Traceability

To make any statement of performance meaningful, the calibration should be referred back to a standard, preferably the appropriate national standard. For flow measurement in UK, the custodian is the National Engineering Laboratory (NEL).

A nationwide service for the calibration of all types of measuring equipment was established in 1966. The National Measurement Accreditation Service (NAMAS) accredits laboratories to carry out calibration of instruments such as flowmeters, which ensures a high degree of confidence in calibration data.

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Appendix B Estimation of flow measurement uncertainty

B.1 General

Whenever a flow measurement is made, the value obtained is an estimate of the true value, with reference to some agreed standard. The true value may be greater than or less than the measured value depending on the system errors. Error and uncertainty should not be confused or used synonymously. The error in the estimate of a quantity is the difference between the measured and true value and is a known quantity if the standard is assumed correct. (This is not true since the standard itself will have very small errors). The uncertainty is an interval within which the true and measured values lie with a suitably high probability. It is only possible to calculate this interval and the confidence level associated with the measurements when the distribution of the measured values around the true value is known. The uncertainty and the confidence level with which it can be used are closely related. The wider the uncertainty interval, the greater is the confidence that the true value of the flow rate will be included in this interval. The confidence level must therefore be included in the uncertainty statement to make the statement meaningful. (See BS 5844 for the calculations required in order to estimate the uncertainty).

B.2 Components of error

Uncertainty is made up of two major components, random and systematic error. Random error is seen in repeat measurements. Measurements do not and are not expected to agree exactly. With flow measurements, small variations for example, in turbulence and fluid pressure will give rise to random flow fluctuations. The variation between repeat readings is called the random error (or sometimes the precision). The standard deviation σ is used as a measure of the random component of error. A large standard deviation means poor repeatability. The variable s_y is calculated as an estimate of the standard deviation of the variable y and is called the precision index. It is defined as:

$$s_y^2 = \frac{\sum_{i=1}^{N} (y_i - \bar{y})^2}{N - 1} \qquad \text{(B.1)}$$

where

N is the number of measurements of variable;

$\bar{y}$ is the arithmetic mean of the N measurements;

y_i is the value of the i th value of y.

As $N \rightarrow \infty$, then $S_y \rightarrow \sigma_y$.

Unlike random errors, which can be reduced if large numbers of readings are taken, systematic errors cannot be reduced by repeat readings since each reading will have the same bias provided flow conditions remain unaltered. Constant systematic errors vary with the value obtained for the measurement but are fixed during the test. Variable systematic errors arise from inadequate flow control such as temperature effects on pressure gauges or the test fluid, or from changes in meter characteristics by component wear. The systematic (sometimes called bias) error cannot be determined unless the measurements are compared with the true value of the quantity being assessed. Thus to some extent random errors are known and systematic errors are unknown some form of traceability check is performed. This form of dynamic check is rarely performed on the flowmeter suppliers facilities. The use of repeat reference calibrations to national standards will help reduce the systematic errors on test rigs to acceptably low limits.

Items (a) to (d) of Figure B.1 summarize, in graphical form, the definitions and relationships of the terms discussed. Item (a) shows an accurate measurement which is one that has small error, both systematic and random. Item (b) shows good repeatability but poor accuracy; an example would be a turbine meter showing good repeatability but having worn bearings so that the output is shifted a fixed amount. Item (c) shows poor repeatability but the average of a large number of readings is almost the same as the true value; a single measurement here may or may not have a large error. Item (d) shows a situation to be avoided, here the flowmeter is inaccurate and does not show repeatability.

B.3 Concept of uncertainty

The uncertainty interval of a flow measurement system is calculated by combining the random and systematic errors of all the individual components and variables that can affect flow measurement accuracy. The single number that represents uncertainty has to have one interpretation, namely the largest error to be expected. It is impossible to have an absolute uncertainty because the bias component is based on judgement not fact. Thus the uncertainty is a hybrid combination of unknown quantity (systematic error) and a statistic (random error).

Total uncertainty is the sum (99 % confidence) or the root sum square (95 % confidence) of the total systematic components plus a multiple of the total random component. Mathematically this is expressed as:

$$e = (e_s + t_{95} \cdot e_R) \text{ (at 99 \% confidence)} \qquad \text{(B.2)}$$

$$e = (e_s^2 + t_{95}^2 \cdot e_R^2)^{1/2} \text{ (at 95 \% confidence)} \qquad \text{(B.3)}$$

where

e_s is the total systematic uncertainty;

e_R is the total random uncertainty for a number of repeat measurements;

t_{95} is the 95 th percentile point for the two-tailed students t distribution.

NOTE The t value reflects the number of degrees of freedom used in calculating e_R and its value reduces as the number of repeat measurements used in the sample increases.

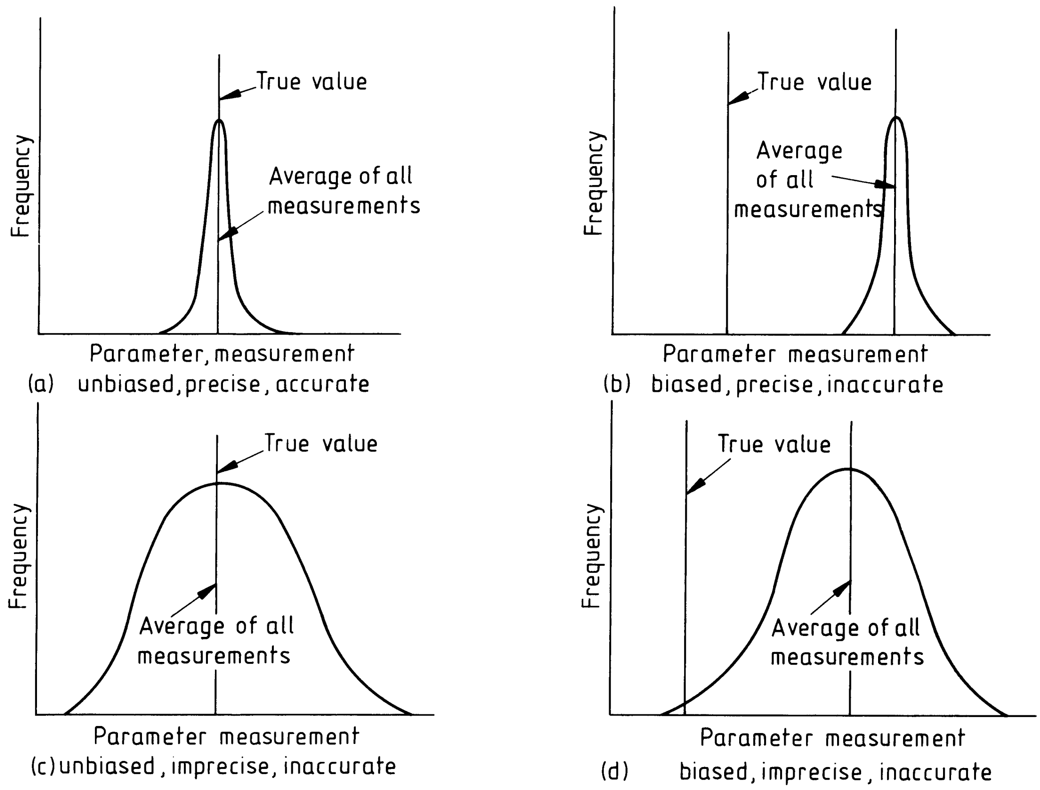

Figure B.1 — Terminology for measurement uncertainty

Index

Publication(s) referred to

BS 848, *Fans for general purposes.*
BS 848-1, *Methods of testing performance.*
BS 1041, *Temperature measurement.*
BS 1041-2, *Expansion thermometers.*
BS 1041-2.1, *Guide to selection and use of liquid-in-glass thermometers.*
BS 1041-3, *Guide to selection and use of industrial resistance thermometers.*
BS 1041-4, *Thermocouples.*
BS 1041-5, *Guide to selection and use of radiation pyrometers.*
BS 1041-7, *Guide to selection and use of temperature/time indicators.*
BS 1042, *Measurement of fluid flow in closed conduits.*
BS 1042-1, *Pressure differential devices.*
BS 1042-1.1, *Specification for square-edged orifice plates, nozzles and venturi tubes inserted in circular cross section conduits running full.*
BS 1042-1.2, *Specification for square-edged orifice plates and nozzles (with drain holes, in pipes below 50 mm diameter, as inlet and outlet devices) and other orifice plates.*
BS 1042-1.4, *Guide to the use of devices specified in Sections 1.1 and 1.2.*
BS 1042-2, *Velocity area methods.*
BS 1042-2.1, *Method using Pitot static tubes.*
BS 1904, *Specification for industrial platinum resistance thermometer sensors.*
BS 2765, *Specification for dimensions of temperature detecting elements and corresponding pockets.*
BS 3680, *Measurement of liquid flow in open channels.*
BS 3680-8, *Measuring instruments and equipment.*
BS 3812, *Recommendations for estimating the dryness of saturated steam.*
BS 4161, *Gas meters.*
BS 4937, *International thermocouple reference tables.*
BS 4937-1, *Platinum- 10 % rhodium/platinum thermocouples. Type S.*
BS 4937-2, *Platinum- 13 % rhodium/platinum thermocouples. Type R.*
BS 4937-3, *Iron/copper-nickel thermocouples. Type J.*
BS 4937-4, *Nickel-chromium/nickel-aluminium thermocouples. Type K.*
BS 4937-5, *Copper/copper-nickel thermocouples. Type T.*
BS 4937-6, *Nickel-chromium/copper-nickel thermocouples. Type E.*
BS 4937-7, *Platinum- 30 % rhodium/platinum- 6 % rhodium thermocouples. Type B.*
BS 4937-8, *Nickel-chromium-silicon/nickel-silicon thermocouples including composition Type N.*
BS 4937-20, *Specification for thermocouple tolerances.*
BS 5345, *Code of practice for the selection, installation and maintenance of electrical apparatus for use in potentially explosive atmospheres (other than mining applications or explosive processing and manufacture).*
BS 5490, *Specification for classification of degrees of protection provided by enclosures.*
BS 5501, *Electrical apparatus for potentially explosive atmospheres.*
BS 5728, *Measurement of flow of cold potable water in closed conduits.*
BS 5728-1, *Specification for single meters.*
BS 5728-2, *Specification for installation conditions for single meters.*
BS 5844, *Methods of measurement of fluid flow: estimation of uncertainty of a flow-rate measurement.*
BS 5857, *Methods for measurement of fluid flow in closed conduits using tracers.*
BS 5863, *Analogue signals for process control systems.*
BS 5875, *Glossary of terms and symbols for measurement of fluid flow in closed conduits.*
BS 6199, *Measurement of liquid flow in closed conduits using weighing and volumetric methods.*

BS 6400, *Specification for installation of domestic gas meters (2nd family gases).*

ISO 2186, *Fluid flow in closed conduits — connections for pressure signal transmission between primary and secondary element.*

ISO 3354, *Measurement of clean water flow in closed conduits — Velocity-area method using current-meters in full conduits and under regular flow conditions.*

ISO 3966, *Measurement of fluid flow in closed conduits — velocity area methods using Pitot static tubes.*

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