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МЕЖДУНАРОДНАЯ ОРГАНИЗАЦИЯ ПО СТАНДАРТИЗАЦИИ

Centrifugal, mixed flow and axial pumps — Code for hydraulic performance tests — Precision class

Pompes centrifuges, hélico-centrifuges et hélices — Code d'essais de fonctionnement hydraulique — Classe de précision

Reference number
ISO 5198 : 1987 (E)

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work.

Draft International Standards adopted by the technical committees are circulated to the member bodies for approval before their acceptance as International Standards by the ISO Council. They are approved in accordance with ISO procedures requiring at least 75 % approval by the member bodies voting.

International Standard ISO 5198 was prepared by Technical Committee ISO/TC 115, *Pumps.*

Users should note that all International Standards undergo revision from time to time and that any reference made herein to any other International Standard implies its latest edition, unless otherwise stated.

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Centrifugal, mixed flow and axial pumps — Code for hydraulic performance tests — Precision class

0 Introduction

This International Standard is the first of a set of International Standards dealing with performance tests of centrifugal, mixed flow and axial pumps (in the rest of the text referred to as "pumps").

It specifies precision class tests (former class A). Engineering class I and class II tests (former classes B and C) will be the subject of a further International Standard.[1]

The aims of these classes are quite different.

The precision class is mainly used for research, development and scientific purposes in laboratories, where an extremely high accuracy of measurement is important.

The engineering classes are generally applied for acceptance tests.

In most cases, engineering class II is adequate for acceptance tests. The use of engineering class I is restricted to special cases when there is a need to have the pump performance more precisely defined. However, there may be cases of high importance, in which even an engineering class I acceptance test will be judged inadequate for the precision required for defining pump performance. In these cases the use of the precision class may exceptionally be necessary for an acceptance test.

Attention must be paid to the fact that the accuracy required for a precision class test significantly increases the test costs by comparison with the costs for an engineering class test.

Precision class tests may not always be practicable, even when great effort and expense are devoted to measurements. Performance tests to precision class specifications will be required, and are possible, only in suitable circumstances. Therefore both the purchaser and the manufacturer shall carefully examine whether the accuracy required for a precision class test might be achieved either on site, on the manufacturer's test bed or in a mutually agreed laboratory. It should be noted that it may not be possible to guarantee precision class accuracy in advance of the tests.

The purpose of this International Standard is to specify how to carry out a test with extremely high precision.

This International Standard does not recommend any constructional tolerance nor any global tolerance for acceptance purposes; it is devoted to specifying and describing procedure and methods for accurately ascertaining the performance of a pump under the conditions in which it is tested. Contractual interpretation of the test results must be the subject of a special agreement between the parties concerned (see annex B).

Pump performance may be greatly affected by the installation conditions, and this must be especially considered when drawing up the contract if a precision class test is to be carried out.

1 Scope

This International Standard specifies precision class performance tests for centrifugal, mixed flow and axial pumps.

It defines the terms and quantities that are used and specifies general requirements for tests. It specifies ways of measuring the characteristic quantities of the precision class so as to ascertain the performance of the pump and thus provide a basis for comparison with the performance specified in the contract.

The structural details of pumps and the mechanical properties of their components lie outside the scope of this International Standard.

This International Standard does not specify constructional tolerances, which are purely contractual.

2 Field of application

This International Standard gives recommendations for hydraulic performance testing of centrifugal, mixed-flow and axial pumps when these tests have to meet very special requirements for research, development or acceptance of industrial high-tech. pumps, or when very accurate knowledge of performance characteristics is of prime importance.

This International Standard also applies to models and prototypes whether the pumps are tested on a test bench or on site if installation conditions so permit.

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1) At present, they are dealt with in ISO 2548 and ISO 3555.

It applies

- either to the pump itself without fittings, which requires that the pump ends are accessible; or
- to the whole assembly of pump and of all or part of its upstream and downstream fittings, which is the case for pumps with inaccessible ends (submerged pumps, etc.).

NOTES

1 Attention is drawn to the fact that nearly all industrial needs are covered by the codes of acceptance testing of industrial classes I and II.

2 Acceptance tests for site and model storage pumps are dealt with in IEC Publications 198 and 497.

3 References

ISO 31, *Quantities, units and symbols.*

ISO 555, *Liquid flow measurement in open channels — Dilution methods for measurement of steady flow —*

Part 1: Constant-rate injection method.

Part 2: Integration (sudden injection) method.

Part 3: Constant-rate injection method and integration method using radioactive tracers.

ISO 1438, *Liquid flow measurement in open channels using thin-plate weirs and venturi flumes.*

ISO 1438/1, *Water flow measurement in open channels using weirs and venturi flumes — Part 1: Thin-plate weirs.*

ISO 2186, *Fluid flow in closed conduits — Connections for pressure signal transmissions between primary and secondary elements.*

ISO 2548, *Centrifugal, mixed flow and axial pumps — Code for acceptance tests — Class C.*

ISO 2975, *Measurement of water flow in closed conduits — Tracer methods —*

Part 1: General.

Part 2: Constant rate injection method using non-radioactive tracers.

Part 3: Constant rate injection method using radioactive tracers.

Part 6: Transit time method using non-radioactive tracers.

Part 7: Transit time method using radioactive tracers.

ISO 3354, *Measurement of clean water flow in closed conduits — Velocity-area method using current-meters.*

ISO 3534, *Statistics — Vocabulary and symbols.*

ISO 3555, *Centrifugal, mixed flow and axial pumps — Code for acceptance tests — Class B.*

ISO 3846, *Liquid flow measurement in open channels by weirs and flumes — Free overfall weirs of finite crest width (rectangular broad-crested weirs).*

ISO 3966, *Measurement of fluid flow in closed conduits — Velocity area method using Pitot static tubes.*

ISO 4185, *Measurement of liquid flow in closed conduits — Weighing method.*

ISO 4359, *Liquid flow measurement in open channels — Rectangular, trapezoidal and U-shaped flumes.*

ISO 4360, *Liquid flow measurement in open channels by weirs and flumes — Triangular profile weirs.*

ISO 4373, *Measurement of liquid flow in open channels — Water level measuring devices.*

ISO 5167, *Measurement of fluid flow by means of orifice plates, nozzles and venturi tubes inserted in circular cross-section conduits running full.*

ISO 5168, *Measurement of fluid flow — Estimation of uncertainty of a flow-rate measurement.*

ISO 7194, *Measurement of fluid flow in closed conduits — Velocity-area methods of flow measurement in swirling or asymmetric flow conditions in circular ducts by means of current-meters or Pitot static tubes.*

ISO 8316, *Measurement of liquid flow in closed conduits — Method by collection of the liquid in a volumetric tank.*[1]

IEC Publication 34-2, *Rotating electrical machines — Part 2: Methods for determining losses and efficiency of rotating electrical machinery from tests (excluding machines for traction vehicles).*

IEC Publication 41, *International code for the field acceptance tests of hydraulic turbines.*

IEC Publication 193, *International code for model acceptance tests of hydraulic turbines.*

IEC Publication 198, *International code for the field acceptance tests of storage pumps.*

IEC Publication 497, *International code for model acceptance tests of storage pumps.*

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[1] At present at the stage of draft.

Section one: General recommendations

4 Definitions and symbols

4.1 Definitions

For the purposes of this International Standard, the following definitions apply.

4.1.1 measuring system: System composed of a measuring instrument, including a transducer which picks up physical information, and one or several elements in series transmitting or transforming the resulting signal.

Such a system has a response function which can be illustrated by a gain response or a phase response curve over a frequency range. In particular, a filtering effect appears between the picked up physical quantity and the observed signal. This filtering effect is essentially characterized by a cut frequency. In most measuring systems which are used, the continuous component of the signal can pass and the cut frequency is then strongly related to the response time of the system.

4.1.2 measuring instrument: Instrument, forming part of a measuring system, which transforms any physical quantity (pressure, speed, current, etc.) into a signal which can be directly observed (a mercury level, a point on a dial scale, a digital reading, etc.).

4.1.3 first order statistical moment: mean value of a signal: Characterization of a random process $x(t)$ by a first order statistical moment which generally is the mean μ_x calculated over a period of time T given by the equation

$$\mu_x = \frac{1}{T} \int_t^{t+T} x(t)\, \mathrm{d}t$$

NOTE — To calculate the mean value of a signal or physical quantity, an integration period T much longer than the response time of the corresponding measuring system is usually chosen.

To determine simultaneously the mean value of several signals of several physical quantities corresponding to the same operating point, the integration period T is chosen by considering the longest response time among all the measuring systems which are used.

According to the value of the integration period T chosen to calculate the mean value of the signals, the operating conditions will be determined to be either steady or unsteady.

4.1.4 second order statistical moment: variance or autocorrelation function: Characterization of a random process $x(t)$ by a second order statistical moment calculated over a time period T and for which can be chosen either the variance σ_x^2 expressed as :

$$\sigma_x^2 = \frac{1}{T} \int_t^{t+T} [x(t) - \mu_x]^2\, \mathrm{d}t$$

or the autocorrelation function, R_{xx}, given by the equation

$$R_{xx}(t, T) = \frac{1}{T} \int_t^{t+T} x(t)\, [x(t+T)]\, \mathrm{d}t$$

4.1.5 steady and unsteady process: Random process $x(t)$ is said to be **slightly steady** or **steady in a general sense** when its first order statistical moment (mean μ_x) and its second order statistical moment [variance σ_x^2, or autocorrelation function $R_{xx}(t, T)$] are not dependent on time t, at which the observation begins nor on the period of time T during which the observation is made.

Inversely, when the statistical moments are dependent on t or T, the physical phenomenon is said to be **unsteady.**

When all statistical moments of the process $x(t)$ (beyond the second order), which completely describe the statistical property of $x(t)$, are not dependent on t and T, the process is then said to be **strongly or strictly steady.**

NOTE — From a practical point of view and in this International Standard, only slightly steady processes are considered (first and second order statistical moments). It should be noted that when the considered process follows a normal or Gaussian distribution law, the first and second order statistical moments are sufficient to describe the statistical properties of the process completely and both concepts of strong or slight steadiness are then equivalent.

4.1.6 steady operating conditions: The operating conditions are said to be steady when the different signals delivered by the measuring systems and the physical quantities calculated from these signals have first order (mean μ_x) and second order [variance $\sigma_x{}^2$, or autocorrelation function $R_{xx}(t, T)$] statistical moments which do not depend on the time t at which the observation begins nor on the duration T during which the observation is made.

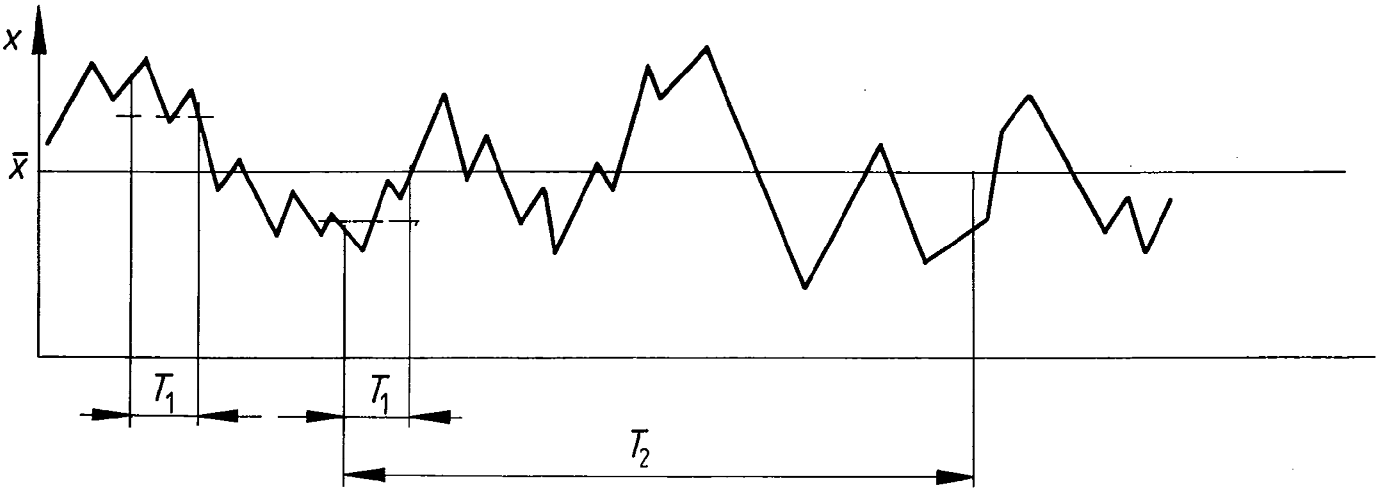
NOTE — The random signal delivered by a measuring system can be found to be steady only if the integration period T is sufficiently long. This point is difficult to check for one is never calculated for a sufficient duration; this is why, from a practical point of view, only a steadiness with a certain confidence level is defined.

4.1.7 unsteady operating conditions: The operating conditions are said to be unsteady when the different signals delivered by the measuring systems and the physical quantities calculated from these signals have a first order (mean μ_x) or second order [variance σ_x^2, or autocorrelation function $R_{xx}(t, T)$] statistical moment which depends on the time t at which the observation begins or on the period T during which the observation is made.

NOTE — The dynamic component (see figure 1) of the picked up physical quantities has different origins:

a) a random origin: turbulence, white noise of the electronic system, etc.,

b) a determinist origin: blade passing frequency, speed of rotation in connection with the electric network frequency, flow singularities, vibration modes, etc.



T_1 is an insufficiently long integration period. The mean value, $\bar{x}$, of x as estimated from T_1 will vary.

T_2 is a sufficiently long period.

Figure 1 — Graph of the evolution of a phenomenon (supposed to be known)

It is supposed that the possible unsteadiness of the operating conditions has a frequency lower than that corresponding to these phenomena (less than half the lowest encountered frequency); as a consequence, the integration period T will not be less than twice the period T corresponding to the lowest frequency mentioned above.

4.1.8 fluctuations: Periodic or random evolutions of a phenomenon $x(t)$ as a function of time, varying around a mean value and describing a physical quantity or a signal delivered by a measuring system.

All evolutions having a period or a pseudo-period less than twice the integration period chosen to calculate the mean values are considered as fluctuations. Then the fluctuations can be considered as being "rapid" compared to the variations of the mean value (see 4.1.9).

NOTE — Only fluctuations having a period or a pseudo-period higher than twice the response time of the corresponding measuring system can be detected.

4.1.9 variations of the mean value (in unsteady operating conditions): Evolution of the mean value of a physical quantity or of signal delivered by a measuring system, between one reading and the next, in unsteady operating conditions.

The variations of the mean values should show a period or a pseudo-period higher than twice the integration period T chosen to calculate the mean value.

Then the variations of the mean value can be considered as being "slow" compared to fluctuations (see 4.1.8).

4.1.10 readings: Visual observations allowing the recording of the value of the signal delivered by a measuring system.

Two types of readings should be considered:

a) the "quasi-instantaneous" reading of the signal, which is made during as short a time as possible (but not shorter than the response time of the measuring system considered);

NOTE — The group of "quasi-instantaneous" readings made during the integration period T allows the calculation of statistical moments (see 4.1.3 and 4.1.4).

b) the "averaging reading" of the signal which is made over or at the end of the integration period T depending on the measuring system, this "averaging reading" leads directly to the mean value of the signal.

4.1.11 set of readings: Group of "quasi-instantaneous" readings leading to the determination of the values of the different signal or physical quantities characterizing an operating point.

4.1.12 response time of a measuring instrument: Time interval between the instant when a stimulus is subjected to a specified abrupt change and the instant when the response reaches and remains within specified limits of its final steady value.

4.1.13 Prandtl number, Pr:

$$Pr = \frac{\mu c_p}{\lambda}$$

where

μ is the dynamic viscosity of the fluid;

λ is its thermal conductivity.

(Definition taken from ISO 31/12.)

4.2 Quantities, symbols and units

Table 1 gives concepts and some of their uses in this International Standard, together with any associated symbols which have been allocated; it is based on ISO 31.

The definitions, particularly those given for kinetic energy coefficient, specific energy and NPSH may not be appropriate for completely general use in hydrodynamics, and are for the purposes of this International Standard only.

Table 2 gives an alphabetical list of symbols used, and table 3 gives a list of subscripts.

Table 1 — List of quantities (based on ISO 31)[1]

Quantity	Definition[2]	Symbol	Dimension[3]	Unit
Mass		m	M	kg
Length		l	L	m
Time		t	T	s
Temperature		θ	Θ	°C
Area		A	L^2	m^2
Volume		V	L^3	m^3
Angular velocity		ω	T^{-1}	rad/s
Velocity		v	LT^{-1}	m/s
Acceleration due to gravity[4]		g	LT^{-2}	m/s^2
Speed of rotation	Number or rotations per unit time	n	T^{-1}	s^{-1}
Density	Mass per unit volume	ϱ	ML^{-3}	kg/m^3
Pressure	Force per unit area. Unless otherwise specified all pressures are gauge pressures, i.e. measured with respect to atmospheric pressure.	p	$ML^{-1}T^{-2}$	Pa (1 bar = 10^5 Pa)
Kinematic viscosity		ν	L^2T^{-1}	m^2/s
Specific energy	Energy per unit mass	E	L^2T^{-2}	J/kg
Power (general term)		P	ML^2T^{-3}	W
Reynolds number		Re	dimensionless	
Diameter		D	L	m
Flow rates				
Mass rate of flow	The mass rate of flow designates the external mass rate of flow of the pump, i.e. the rate of flow discharged into the pipe from the outlet branch of the pump. NOTE — Losses or abstractions inherent to the pump, i.e. : a) discharge necessary for hydraulic balancing of axial thrust; b) cooling of bearings of the pump itself; c) water seal to the packing; d) leakage from the fittings, internal leakage, etc., are not to be reckoned in the quantity delivered. On the contrary, if they are taken at a point before the flow measuring section, all derived quantities used for other purposes, such as : e) cooling of the motor bearings; f) cooling of a gear box (bearings, oil cooler), etc., should be added to the measured rate of flow.	$q_m (q)$	MT^{-1}	kg/s

Table 1 — List of quantities (based on ISO 31)[1] *(continued)*

Quantity	Definition[2]	Symbol	Dimension[3]	Unit
Volume rate of flow	The outlet volume rate of flow is given by the equation $q_V = \frac{q_m}{\varrho}$ For the purposes of this International Standard, this symbol may also designate the volume rate of flow in a given section[5] of the pump outlet; it is the quotient of the mass rate of flow in this section by the density. (The section may be designated by subscripts.)	q_V (Q)	L^3T^{-1}	m^3/s
Mean velocity	The mean velocity of flow equal to the volume rate of flow divided by the pipe cross-section[5] $U = \frac{q_V}{A}$	U	LT^{-1}	m/s
Local velocity	Velocity of flow at any point	v	LT^{-1}	m/s
Gauge pressure	Any pressure used in this International Standard except atmospheric and vapour pressure; the effective pressure, relative to the atmospheric pressure. Its value is — positive if this pressure is greater than the atmospheric pressure; — negative if this pressure is less than the atmospheric pressure.	p_e	$ML^{-1}T^{-2}$	Pa
Atmospheric pressure (absolute)		p_b	$ML^{-1}T^{-2}$	Pa
Vapour pressure (absolute)		p_v	$ML^{-1}T^{-2}$	Pa
Head	The energy per unit mass of fluid divided by gravitational acceleration.		L	m
Height	Elevation of a point above a reference plane. If the point is below the reference plane, z is negative.	z	L	m
Reference plane	Any horizontal plane to be used as a datum for height measurement. A materialized reference plane may be more practical than an imaginary one for measurement purposes.	—	—	—
Inlet impeller height (or eye height)	The height of the centre of the circle described by the external point of the entrance edges of the first impeller blades. In case of double inlet pumps, z_s is the higher impeller height. The manufacturer should indicate the position of this point with respect to precise reference points on the pump.	z_s	L	m
Velocity head	Height of fluid corresponding to the kinetic energy per unit mass of fluid divided by gravitational acceleration. Its value is given by the formula $\alpha U^2/2g$		L	m
Velocity head coefficient	A coefficient relating velocity head in the section with the mean velocity in that section. It is defined by the equation $\alpha = \frac{\int_A v^3 \mathrm{d}A}{U^3 A}$ If v is constant, $\alpha = 1$	α	dimensionless	
Available velocity head	The part of the velocity head contributing to the total head. Its value is given by the formula $\alpha_a U^2/2g$ where $1 < \alpha_a < \alpha$ See 8.1.1.3		L	m
Available velocity head coefficient	A coefficient relating available velocity head in a section to the mean velocity in that section. See 8.1.1.3	α_a	dimensionless	

Table 1 — List of quantities (based on ISO 31)[1] *(continued)*

Quantity	Definition[2]	Symbol	Dimension[3]	Unit
Total head (in section *i*)	Total head in a given section, *i*, is usually calculated as: $H_i = z_i + \frac{p_{ei}}{\varrho_i g} + \alpha_{ai} \frac{U_i^2}{2g}$ This equation assumes that pressure varies hydrostatically in the section and that compressibility of the liquid pumped may be neglected. See 8.1.1.2 concerning the correctness of this last assumption.	H_i	L	m
Inlet total head	Total head at inlet section 1	H_1	L	m
Outlet total head	Total head at outlet section 2	H_2	L	m
Pump total head	Algebraic difference between outlet total head H_2 and inlet total head H_1: $H = H_2 - H_1$ Separate evaluation of H_1 and H_2 is not always necessary. Other methods may even be recommended if compressibility is to be accounted for. See 8.1.1.2.	H	L	m
Loss of head at inlet	The difference between the total head of the liquid at the measuring point, or possibly of the liquid without velocity in the suction chamber, and the total head of the liquid in the inlet section of the pump.	H_{J1}	L	m
Loss of head at outlet	The difference between the total head of the liquid in the outlet section of the pump, and the total head of the liquid at the measuring point.	H_{J2}	L	m
Net positive suction head; NPSH	Inlet total head increased by the head (in flowing liquid) corresponding to the atmospheric pressure at the test location and decreased by the sum of the head corresponding to the vapour pressure of the pump liquid at the inlet temperature and of the inlet impeller height. $(\mathrm{NPSH}) = H_1 + \frac{p_b}{\varrho_1 g} - \frac{p_v}{\varrho_1 g} - z_1$ NOTES 1 To maintain consistency between precision class and engineering classes I and II, the arbitrary definition of (NPSH) is the same. Therefore, in calculating (NPSH) values, the value of α_{a1} is taken to be equal to unity (see velocity head coefficient). 2 Local velocity distribution may influence (NPSH) performance of the pump. Limitation of local velocity variation is given in clause 12. 3 It is necessary to make a distinction between — the (NPSH) required at given flow and speed of rotation for a given pump — this is specified by the manufacturer; — the (NPSH) available for the same flow, which is inferred from the installation; — the cavitation test (NPSH). Subscripts may be used to differentiate these quantities [for example $(\mathrm{NPSH})_r$ when the value required by the pump is concerned, $(\mathrm{NPSH})_a$ when the available value is concerned and $(\mathrm{NPSH})_c$ when cavitation test (NPSH) is concerned].	(NPSH)	L	m
Critical net positive suction head	Net positive suction head associated with [2 + (K/2)] % either of head drop in the first stage or of the efficiency drop.	$(\mathrm{NPSH})_c$	L	m

Table 1 — List of quantities (based on ISO 31)[1] (*concluded*)

Quantity	Definition[2]	Symbol	Dimension[3]	Unit
Type number	A number defined by the equation $K = \frac{2\pi n (q'_V)^{1/2}}{(gH')^{3/4}} = \frac{\omega q'_V{}^{1/2}}{E'^{3/4}}$ where q'_V is the volume rate of flow per eye and H' is the head of the first stage. This quantity shall be calculated at the best efficiency point.	K	dimensionless	
Pump power input	Mechanical power transmitted to the pump shaft.	P	ML^2T^{-3}	W
Driver power input	Power input to driving unit.	P_{gr}	ML^2T^{-3}	W
Pump power output	The power transferred to the liquid at its passage through the pump $P_u = \varrho q_V g H = \varrho q_V E$	P_u	ML^2T^{-3}	W
Pump efficiency	$\eta = \frac{P_u}{P}$	η	dimensionless	
Overall efficiency	$\eta_{gr} = \frac{P_u}{P_{gr}}$	η_{gr}	dimensionless	

1) Further symbols used in the thermodynamic method are given in table 9.

2) In order to avoid any error of interpretation, it is deemed desirable to reproduce the definitions of quantities and units as given in ISO 31 and to supplement these definitions by some specific information on their use in this International Standard.

3) M = mass, L = length, T = time, Θ = temperature.

4) For precision class tests, the local values of g should be used. Nevertheless, in most cases, a value of 9,81 m/s² would not involve significant error. The local value should be calculated by the equation

$$g = 9{,}780\,3\,(1 + 0{,}005\,3 \sin^2\varphi) - 3 \times 10^{-6} z$$

where φ and z are respectively the latitude, in degrees, and the altitude, in metres.

5) Attention is drawn to the fact that in this case q_V may vary for different reasons across the circuit.

Table 2 — Alphabetical list of symbols

Symbol	Quantity	Units
A	Area	m^2
D	Diameter	m
e	Relative value of uncertainty	—
E	Specific energy	J/kg
f	Frequency	Hz
g	Acceleration due to gravity	m/s^2
H	Pump total head	m
H_J	Losses in terms of head of liquid	m
k	Equivalent uniform roughness	m
K	Type number	dimensionless
l	Length	m
m	Mass	kg
n	Speed of rotation	s^{-1}
(NPSH)	Net positive suction head	m
p	Pressure	Pa
P	Power	W
q_m	Mass rate of flow	kg/s
q_V	Volume rate of flow	m^3/s
Re	Reynolds number	dimensionless
t	Time	s
U	Mean velocity	m/s
v	Local velocity	m/s
V	Volume	m^3
z	Height above reference plane	m
α	Velocity head coefficient	dimensionless
η	Efficiency	dimensionless
θ	Temperature	°C
λ	Universal coefficient for head loss	dimensionless
ν	Kinematic viscosity	m^2/s
ϱ	Density	kg/m^3
ω	Angular velocity	rad/s

NOTE — See also clause 11.

Table 3 — List of letters and figures used as subscripts

Subscript	Designation
1	inlet
2	outlet
a	available
ac	acoustic
b	atmospheric
c	critical
d	drop
e	effective (gauge)
f	fully developed
gr	unit (overall)
H	pump total head
int	intermediate
M	manometric
m	mass
mot	motor
P	pump power input
p	pump
r	required
s	eye
sp	specified
t	total
T	translated
u	useful
V	volume
v	vapour (pressure)
vis	visible
η	efficiency

5 Specified duty

5.1 Main specification

One or more of the following quantities may be specified under the conditions and speed or rotation stated in the contract:

a) pump total head, H_{sp}, at the agreed flow rate, q_{Vsp}, or flow rate of the pump, q_{Vsp}, at the agreed total head, H_{sp}.

b) power input or efficiency of the pump or combined pump-motor unit at the specified q_{Vsp}, H_{sp} point.

c) net positive suction head, (NPSH), required by the pump at the agreed flow rate q_{Vsp} for a specified cavitation effect as defined, for example, in 12.1.3.2 at the agreed flow rate.

d) other points of the $H(q_V)$ curve may be indicated by specifying either the total head at a reduced or increased flow rate, or the flow rate at a reduced or increased total head.

5.2 Other specifications

Unless specifically agreed otherwise in the contract, the specified values are valid in the following conditions :

a) unless the chemical and physical properties of the liquid are stated, it shall be taken that the points specified apply to clean cold water (see table 4);

Table 4 — Specification of "clean cold water"

Characteristic	Unit	max.
Temperature	°C	40
Kinematic viscosity	m^2/s	$1,5 \times 10^{-6}$
Density	kg/m^3	1050
Non-absorbent free solid content	kg/m^3	2,5
Dissolved solid content	kg/m^3	50

b) the relation between the specified values under clean cold water conditions and the likely performance under other liquid conditions shall be agreed in the contract;

c) specified values shall apply only to the pump as tested by the methods and in the test arrangements specified in this International Standard.

6 General requirements for tests

6.1 Organization of tests

6.1.1 Place of testing

Performance tests shall be carried out at the manufacturer's works, or alternatively at a place to be mutually agreed between the manufacturer and the purchaser.

Both purchaser and manufacturer shall be entitled to have representatives present at all tests and calibrations in order to verify that they are performed in accordance with this International Standard and any prior written agreements.

6.1.2 Time of testing

The time of testing shall be mutually agreed by the manufacturer and the purchaser.

6.1.3 Staff

Accurate measurements depend not only on the quality of the measuring instruments used, but also on the ability and skill of the persons operating and reading the measuring devices during the tests. The staff entrusted with effecting the measurements shall be selected just as carefully as the instruments to be used in the test.

A chief of tests possessing adequate experience in measuring operations shall be appointed. Normally, when the test is carried out at the manufacturer's works, the chief of tests is a staff member of the manufacturing firm.

All persons charged with effecting the measurements are subordinated during the tests to the chief of tests, who conducts and supervises the measurements, reports on test conditions and the results of the tests and then drafts the test report. All questions arising in connection with the measurements and their execution are subject to his decision.

The parties concerned shall provide all assistance that the chief of tests considers necessary.

6.1.4 State of pump

When tests are not carried out at the manufacturer's works, opportunity shall be allowed for preliminary adjustments by both the manufacturer and the installer.

6.1.5 Test programme

Only the specified operational data shall form the basis of the test; other data determined by measurement during the tests shall have merely an indicative (informative) function and this shall be stated if they are included in the programme.

6.1.6 Test equipment

When deciding on the measuring procedure, the measuring and recording apparatus required shall be specified at the same time.

The chief of tests shall be responsible for checking the correct installation of the apparatus and its perfect functioning.

All measuring apparatus shall be covered by reports showing, by calibration or by comparison with other International Standards, that it complies with the requirements of 6.4. These reports shall be presented if required.

The measuring devices used shall have valid calibration. Periodic calibration shall be performed by an entitled body. During the pump tests, the indications of the various instruments shall be cross-compared to check that their calibration is maintained. Generally after site testing or in case of dispute, new calibration shall be performed as soon as possible.

6.1.7 Test report

After actual scrutiny, the test results shall be summarized in a report signed either by the chief of tests alone, or by him and representatives of the manufacturer and of the purchaser.

All parties to the contract shall receive a copy of the report as an essential condition for the completion of the contract.

The test report shall contain the following information :

a) place and date of the performance test;

b) manufacturer's name, type of pump, serial number, and if possible year of construction;

c) specified characteristics, operational conditions during the performance test;

d) specification of the pump's drive;

e) description of the test procedure and the measuring apparatus used including calibration data;

f) observed readings;

g) evaluation and analysis of test results with calculation of measuring uncertainties according to 6.4, 6.5 and annex A;

h) conclusion : comparison of the test results with the specified duties (see annex B).

All test records and record charts shall be initialled by the chief of tests and by the representatives of both the purchaser and the manufacturer, each of whom shall be provided with a copy of all records and charts.

The evaluation of the test results shall be made as far as possible while the tests are in progress and, in any case, before the installation and instrumentation are dismantled, in order that measurements regarded as suspect can be repeated without delay.

6.2 Test arrangements

The performance of a pump in a given test arrangement, however accurately measured, cannot be assumed to be a correspondingly accurate indication of its performance in another arrangement.

Moreover, the conditions which permit the most accurate measurements to be taken are not necessarily those under which the pump may perform most satisfactorily nor those under which the user may ultimately require it to perform.

This International Standard therefore defines the conditions necessary to measure performance most accurately and discusses the errors which may be caused by failing to meet those conditions, in order that the interested parties may define the test arrangement most suited to the circumstances.

Recommendations and general guidance about suitable pipe arrangements upstream of a measuring device are given in clauses 7 and 8; if necessary, they can be used in conjunction with International Standards on flow measurement in closed conduits concerning the different flow measurement methods.

6.2.1 Standard test arrangements

The most accurate measurement of head is possible when the flow at the measuring section has:

a) an axially symmetrical velocity distribution;

b) a uniform static pressure distribution;

c) freedom from swirl induced by the installation.

The complete flow patterns at both inlet and outlet measuring sections may be influenced by both the pump and by the geometry of the installations.

It is recommended that for standard test circuits leading from reservoirs with a free surface, or from large stilling vessels in a closed circuit, the inlet straight length, L, be determined by the equation:

$$L \geqslant (1{,}5\,K + 5{,}5)\,D$$

where

L is the inlet straight length;

D is the pipe inside diameter;

K is the type number.

In a standard works or laboratory test rig, satisfactory conditions established by previous tests should be considered as sufficient proof for subsequent tests.

If the inlet conditions are not satisfactory, this may be remedied in one or more of the following ways:

a) increasing the straight length following the source of disturbance causing the flow maldistribution;

b) fitting an appropriate straightener or swirl remover (ISO 7194 gives a detailed description of the functional and geometrical characteristics of these devices.)

c) changing the nature of, or removing, the source of disturbance.

If none of these devices is practicable on site, precision class measurements cannot be made.

NOTE — Attention is drawn to the fact that in some particular cases where this International Standard applies to partial flow rate operation, for which pre-swirl occurs, the arrangements agreed upon for that part of the test installation at the suction side may modify the pump performance.

6.2.2 Simulated test arrangements

When pumps are tested under simulated site conditions, flow straighteners shall not be installed immediately before the pump. It is important that the characteristics of flow to the simulated circuit should be controlled, and that the flow should, as far as possible, be free from significant swirl induced by the installation and have a symmetrical velocity distribution. If necessary, the velocity distribution of the flow into the simulated circuit shall be determined by careful Pitot tube traverses, in order to establish that the required flow characteristics exist. If not, the required characteristics can be obtained by the installation of an adequate straightener (see ISO 7194); however, care shall be taken to ensure that the test conditions will not be affected by the high, irrecoverable pressure losses associated with efficient straightening devices.

6.2.3 Pumps tested with fittings

If specified in the contract, standard tests can be carried out on a combination of a pump and

a) associated fittings at the final site installation; or

b) an exact reproduction thereof; or

c) fittings introduced for testing purposes and taken as forming part of the pump itself.

Connection on the inlet and outlet sides of the whole combination shall be made in accordance with 6.2.

6.3 Test conditions

6.3.1 Performance of tests

In order to obtain consistent results having regard to the degree of accuracy to be achieved, the duration of the test shall be sufficient to take more particularly into account the response time (see 4.1.12) of measuring instruments and the relative steadiness of each operating point, within the limits defined in table 5.

The measurements shall be made under either steady operating conditions (see 4.1.6) or unsteady conditions (see 4.1.7) within the limits defined in table 5.

The decision to make measurements when such conditions cannot be obtained shall be a matter of agreement between the parties concerned.

When only one duty point is indicated for checking, at least five measurement points closely and evenly grouped around the duty point shall be recorded, for instance between 0,9 $q_{V,\,\mathrm{G}}$ and 1,1 $q_{V,\,\mathrm{G}}$.

When performance over a range of operating conditions is to be determined, a sufficient number of measurement points duly distributed shall be recorded, in order to establish the performance within the uncertainty stated in 6.4.

If the test has to be carried out at a speed of rotation different from that specified, the limits stated in 6.3.3 shall be respected and the characteristics obtained at the actual speed of rotation can be translated to the specified speed of rotation; see 6.5.2.1.

6.3.2 Steadiness of operating conditions

6.3.2.1 Definitions

For the purposes of this International Standard the following concepts (see 4.1) are used :

- measuring system and instrument;
- first order statistical moment, mean value of a signal;
- second order statistical moment, variance and autocorrelation;
- steady and unsteady phenomena;
- steady operating conditions;
- unsteady operating conditions;
- fluctuations;
- variations of the mean value (in unsteady operating conditions);
- readings;
- set of readings.

6.3.2.2 Fluctuations of the signals delivered by the measuring systems and of the physical quantities determined from the signals

The physical quantities considered in a test and especially those relating to the turbulent flow in the pipes or in the pump are naturally fluctuating ones. Nevertheless, the fluctuations which appear on the signals delivered by the measuring systems are only seen through the response function of these systems which leads to a partial or total filtering effect, and more particularly to a damping effect over a given frequency range.

Therefore measuring instruments with low inertia and a very short response time may give a fluctuating signal with large fluctuations at every operating point. Conversely, measuring instruments with high inertia and a long response time may give only small fluctuations and sometimes only in the abnormal operating range of the pump.

6.3.2.2.1 Direct visual observation of the signals delivered by measuring systems

To make a satisfactory direct visual observation, the maximum permissible amplitudes of fluctuations given in table 5 shall be respected for each measured quantity.

Where the operating conditions of a pump are such that fluctuations of great amplitude occur, measurement may be carried out by providing, in the elements of the measuring system, a filtering or damping device capable of reducing the fluctuation amplitude to within the values given in table 5.

As the damping may significantly affect the accuracy of the readings, a symmetrical and linear damping device, for example a capillary tube, shall be used.

Where pressure measurements particularly are concerned the damping device shall comply with the specifications of 8.4.1.3.

Table 5 — Maximum permissible amplitude of fluctuations as a percentage of mean value of quantity to be measured, for direct visual observation

Measured quantity	Maximum permissible amplitude of fluctuations %
Rate of flow Head Torque Power	± 3
Speed of rotation	± 1

When using a differential pressure device to measure flow, the maximum permissible amplitude of the fluctuation of the observed differential head can be ± 6 %.

In the case of separate measurement of inlet total pressure head and outlet total pressure head, the maximum permissible amplitude of fluctuation should be calculated on the basis of the pump total head.

6.3.2.2.2 Automatic recording or integration of signals delivered by measuring systems

When the signals delivered by the measuring systems are automatically recorded or integrated by the measuring device, the maximum permissible fluctuation amplitude of these signals may be higher than the value given in table 5, if

a) the measuring system used includes an integrating device carrying out automatically, with the required accuracy, the integration necessary to calculate the mean value as defined in 4.1.3; or

b) the integration necessary to calculate the mean value may be carried out later on, from the continuous or sampled record of the analogue signal $x(t)$. (The sampling conditions should be specified in the test report.)

6.3.2.3 Number of sets of readings or number of averaging readings

The number of sets of readings or the number of averaging readings necessary to obtain consistent results having regard to the degree of accuracy required and within the limits of error stated in 6.4 is dependent on the steadiness of the operating conditions of the pump in the test installation.

When several sets of readings have to be made, for the same operating point, only speed and temperature may be controlled. Throttle valve, water level, gland, and balance water settings shall be left completely unaltered.

In order to determine whether the operating conditions are steady, it is necessary to check whether the different signals delivered by the measuring systems employed are steady, slightly steady or unsteady (see 4.1.6 and 4.1.7).

6.3.2.3.1 Steady operating conditions

When operating conditions are steady, the signals delivered by the measuring systems may be constant or present steady fluctuations.

When the signal is constant only one set of readings or only one averaging reading may be taken at the considered operating point.

When the signal fluctuates, the observer shall check that the operating conditions are steady before determining the quantity to be measured, which requires several sets of readings or several averaging readings.

6.3.2.3.2 Unsteady operating conditions

In cases where the unsteadiness of test conditions gives rise to doubts concerning the accuracy of the tests, several sets of readings shall be taken for each operating point considered (see 6.3.2.3). The difference between the mean values deduced from the repeated readings of the same quantities will be a measure of the unsteadiness of the test conditions, which are at least partly influenced by the pump under test as well as the installation.

A minimum of three sets of readings shall be taken at unequal intervals at the chosen point and the mean value of each quantity and of the efficiency derived from each set of readings shall be recorded. The percentage difference between the largest and smallest mean values of each quantity shall not be greater than that given in table 6. It will be noted that a wider tolerance is permitted if the number of readings is increased up to the maximum requirement of nine readings.

These tolerances are designed to ensure that the errors due to scatter, taken together with the systematic error limits given in clauses 7 to 12 will result in overall measurement errors not greater than those given in table 7.

Table 6 — Limits of variation between repeated mean values of the same quantity (based on 95 % confidence limits as defined in annex A)

Number of sets of readings	Maximum permissible difference between largest and smallest mean values of each quantity	
	Rate of flow Head Torque Power	Speed of rotation
	%	%
3	0,8	0,25
5	1,6	0,5
7	2,2	0,7
9	2,8	0,9

The arithmetic mean of the mean values from all sets of readings for each quantity shall be taken as the actual value given by the test for the operating conditions considered.

If the values given in table 6 cannot be reached, the cause shall be ascertained, the conditions rectified and a new complete set of readings made, i.e. all the readings in the original set shall be rejected. No reading or selection of readings in the set of readings may be rejected because it lies outside the limits given in table 6.

Where the excessive variation is not due to procedure or instrumentation errors, and cannot therefore be eliminated, the number of sets of readings shall be increased and the limits of error shall be calculated by statistical analysis (see annex A).

It is unlikely that variations outside the requirements of table 6 will occur for the majority of pump tests carried out under well-controlled conditions, particularly in a laboratory or at the manufacturer's works.

6.3.3 Deviation from specified speed

A difference of ± 20 % between the specified speed of rotation and the test speed of rotation measurement may be allowed for the determination of flow rate, head and pump efficiency. For $(\mathrm{NPSH})_c$ measurements, the difference allowed between the test speed and the specified rotational speed shall be within the limits of ± 20 % provided that the flow rate is between 70 % and 120 % of the value corresponding to the maximum efficiency at the same speed. For cavitation appearance tests, see annex D.

Scale effects are not sufficiently established to permit precise performance forecasts outside these limits and therefore should be a matter of agreement.

For a combined motor pump unit, the motor efficiency change between specified and test speeds shall be established at the time of agreeing the contract.

6.3.4 Control of operating conditions

The test conditions may be obtained, among other methods, by throttling at the outlet or possibly at the inlet or both at inlet and outlet. Nevertheless, control of the operating conditions by throttling at the inlet is not considered a normal test method. When throttling at the inlet, due consideration shall be given to the possibility of flow distortion, increase in turbulence, or of air coming out of the water, all phenomena which may affect the operation of the pump (see 12.2) or of the flow measuring device (see 7.1) or both.

6.3.5 Tests carried out with a different liquid

If the liquid used during the tests differs from the liquid pumped in normal operation, its kinematic viscosity and the speed of rotation of the pump shall be such that the mean friction coefficient λ estimated for the whole pump does not differ by more than 5 % from its value in the conditions of use of the pump. In the case of larger variations of the friction coefficient λ, a conversion formula may be used by agreement between the parties. The variations of the Reynolds number :

$$Re = \frac{D_1\sqrt{2gH'}}{\nu}$$

where

D_1 is the inlet diameter of the pump;

H' is the head generated by stage;

shall be estimated from figure 29 and the admissible variations of the ratio n/ν shall be deduced.

The tests for total head, flow rate and efficiency carried out under these conditions are valid as long as no cavitation appears and compressibility is negligible.

6.4 Measuring uncertainty

6.4.1 General

When the methods, instruments, and calibrations employed comply with this International Standard, the measurements obtained represent, at the time, the best estimates of the true value of the quantities being measured. Better, or more accurate, estimates can be obtained only by gathering new data.

It is essential that the parties concerned should establish, before the test, the range of uncertainty that can be tolerated. Strictly speaking, the measuring uncertainties can only be calculated when the results of the measurements are complete.

6.4.2 Level of confidence

The uncertainty on a set of measurements of a single quantity depends on the confidence level attached to this uncertainty. The higher the confidence level, the higher the absolute value of the uncertainty and the higher the probability that any measurement falls within the uncertainty bandwidth. It is then necessary to specify the confidence level with which this uncertainty is evaluated, together with the permissible uncertainty. In this International Standard, the uncertainty is associated to a 95 % confidence level, i.e. there is one possibility out of twenty that a reading lies outside the measurement uncertainty bandwidth (see ISO 3534).

6.4.3 Uncertainties of individual quantities

In any one test, enough evidence is seldom available to make exhaustive analyses of all possible sources of error and deduce percentage confidence levels as described in textbooks on statistics. Where there is such evidence, it should be used, but in its absence estimates should nevertheless be made based on the available data together with past experience of the method of measurement.

Strictly speaking, the uncertainty on each individual measured quantity (q_V, H, P, η, etc.) can only be evaluated when the results of measurements are complete.

The fact that the uncertainties used may be, at best, estimates in no way detracts from the value of defining agreed explicit terms in a contract using numerical quantities which can be processed in an unbiased way.

For guidance, some values of the uncertainties which may be expected in satisfactory measuring conditions are given in clauses 7 to 11 dealing with the measurement methods of each quantity, and maximum values which should not be exceeded for precision class tests are given in table 7.

6.4.4 Errors

The error of a measurement depends partly on the residual error in the instrument or measuring system at the start of the tests. At this time, all known errors will have been removed by calibration, careful measurement of dimensions, proper installation, etc. The uncertainty still remaining is called systematic error, and always exists, however small.

Another source of error arises from the non-repeatability of measurements, which must always exist provided the readout equipment has adequate discrimination. Such errors may arise either from the characteristics of the measuring system, or from changes in the quantity being measured, or both. They are observed directly in the form of scatter readings, unlike systematic errors, which do not affect repeatability during the test. This second type of error is called random error.

Repetition of a set of measurements using the same equipment can reduce the uncertainty introduced by random experimental errors, but has no effect on the systematic error. The latter can be reduced only if equipment of a higher standard of accuracy is used, or if the same equipment can be calibrated to a higher standard. The systematic error does not contribute in any way to the scatter of repeated observations.

6.4.5 Mean values

The mean value of a large number of repeated measurements is a better estimate of the true value than the average of a smaller one, provided there is no systematic change with time of the measuring system or the measured quantity which cannot be corrected. When analysing test results, the chief of tests shall satisfy himself that no such tendency is present.

6.4.6 Treatment of errors

It is advisable to treat systematic and random errors separately as described in annex A.

Table 7 — Maximum permissible limits of uncertainty[1]

Quantity	Maximum permissible limit %
Rate of flow	± 1,5
Pump total head Pump power input (direct method) Electrical power input by the motor-pump group	±1
Pump power input (determined from the efficiency of the motor)	± 1,3
Speed of rotation	± 0,2
Overall efficiency of motor-pump unit	± 2
Pump efficiency	± 2,25

[1] This table gives, as guidance, maximum values of the uncertainties which may be obtained with the apparatus existing at the present time. These values are for normal site conditions : laboratory and works tests may be more accurate.

6.5 Analysis of test results

6.5.1 Test data required for the analysis

The characteristics which may be specified by the manufacturer are given in clause 5.

The measurement methods of the quantities necessary for the calculation of these characteristics are given in clauses 7 to 12.

6.5.2 Conversion of the test results to the specified conditions

Such conversion serves to determine whether the performance specification would have been fulfilled if the tests had been conducted under the same conditions as those on which the performance specification is based.

6.5.2.1 Conversion of the test results into data based on the specified speed of rotation or frequency

All test data obtained at speeds of rotation other than the one specified shall be converted to the basis of the specified speed of rotation n_{sp}.

If the deviation from this speed of rotation to the specified speed of rotation n_{sp} does not exceed the permissible variations stated in 6.3.3, and if the deviation from test liquid to specified liquid is within the limits stated in 6.3.5, the measured data on the flow rate q_V, the total head H, the power input P, and the efficiency η, can be converted by means of the equations:

$$q_{V,\text{T}} = q_V \frac{n_{\text{sp}}}{n}$$

$$H_{\text{T}} = H \left(\frac{n_{\text{sp}}}{n}\right)^2$$

$$P_{\text{T}} = P \left(\frac{n_{\text{sp}}}{n}\right)^3 \times \frac{\varrho_{\text{sp}}}{\varrho}$$

$$\eta_{\text{T}} = \eta$$

and the results obtained for the (NPSH) can be converted by means of the equation:

$$(\text{NPSH})_{\text{T}} = (\text{NPSH}) \left(\frac{n_{\text{sp}}}{n}\right)^x$$

The value $x = 2$ may be used as a first approximation for the (NPSH) if the specified conditions given in 6.3.3 for the speed of rotation and the flow rate have been fulfilled and if the physical state of the liquid at the entrance of the impeller is such that no awkward gas separation can affect correct operation of the pump. If the pump operates near the cavitation limits, or if the deviation of the test speed from the specified speed exceeds the specifications given in 6.3.3, the phenomena may be influenced by factors such as thermodynamic effects, the variation of the surface tension or the differences in dissolved or occluded air content. Values of exponent x between 1,3 and 2[1] have been observed and an agreement between the parties to establish the conversion formula to be used is mandatory.

In the case of combined motor-pump units, or where the performance specifications are with respect to an agreed frequency and voltage instead of an agreed speed, the flow rate, pump total head, power input, and efficiency data are subject to these conversion laws, provided that n_{sp} is replaced by the frequency f_{sp} and n by the frequency f.

Such conversion, however, shall be restricted to the cases where the frequency during the test varies by no more than 1 % from the frequency prescribed for the characteristics specified. If the voltage used in the test is no more than 5 % above or below the voltage on which the specified characteristics are based, the other operational data require no change.

If these tolerances, i.e. 1 % for frequency and 5 % for voltage, are exceeded, it will be necessary for the purchaser and the manufacturer to reach agreement.

6.5.2.2 Tests made with (NPSH) different from that specified

After correction for speed of rotation within the permitted limits (see 6.3.3), measured pump performance at a higher (NPSH) cannot be accepted to indicate performance at a lower (NPSH).

After correction for speed of rotation within the permitted limits (see 6.3.3), measured pump performance at a low (NPSH) can be accepted to indicate performance at a higher (NPSH) provided that the absence of cavitation has been checked in accordance with clause 12.

6.5.3 Presentation of test results

The presentation of test results shall be made using the overall uncertainties computed from the test or alternatively using contractually pre-agreed values, chosen taking account of the agreed test method and conditions.

Taking into account the total uncertainty on each coordinate, each measured operating point may be represented by an ellipse. The axes of this ellipse represent the total uncertainty for a confidence level of 95 %. They are calculated in annex A.

The absolute values of the uncertainties are:

— for pump discharge	$\pm\ e_Q Q$
— for pump head	$\pm\ e_H H$
— for pump input	$\pm\ e_P P$
— for pump efficiency	$\pm\ e_\eta \eta$

where e represents the fractional total error in the quantities being considered.

After having determined the total uncertainties and drawn the ellipses for each measured point, an upper and lower envelope of the ellipses shall be drawn (see figure 2).

The test result therefore is a band of measurement limited by the two envelopes. All points within this band are equally valid.

Concerning adherence to specification, see annex B.

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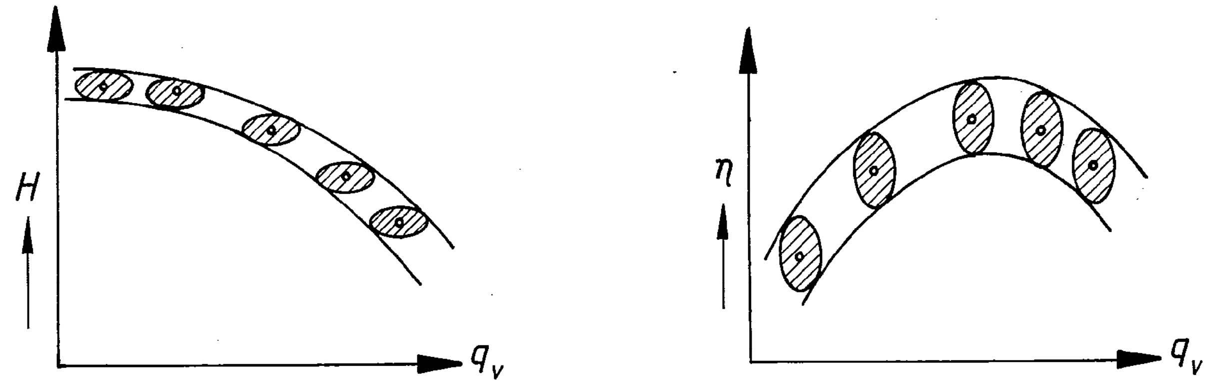
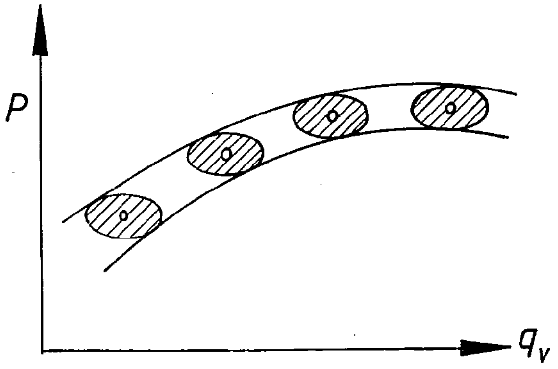
[1] See RÜTSCHI, K., *Messung und Drehzahlumrechnung des NPSH-Wertes bei Kreiselpumpen*, Schweizer Ingenieur und Architekt 39/80.



a) $H (q_V)$ curve

b) $\eta (q_V)$ curve



c) $P (q_V)$ curve

Figure 2 — Envelopes of the ellipses of total uncertainty for each measured point

Section two: Measurement methods

7 Measurement of rate of flow

7.1 General

The choice of the method for measuring the volume rate of flow q_V (see table 1) depends on a number of factors of which the following may be cited:

a) the value of the flow rate to be measured;

b) the type of test (on a model or on the full-size machine; on a test platform or on site);

c) practical conditions of installation and layout of the circuit;

d) the accuracy desired;

e) the cost of putting the method into operation and possible time out of action.

Table 8 sets out the methods which may be envisaged for each case, and the accuracy or systematic uncertainty that may be expected when they are used in good measurement conditions by experienced personnel and in accordance with existing International Standards. In particular, the values of the uncertainty given in this table imply that the flow is steady and free from disturbance produced by the pump. **It must be emphasized that the overall value of uncertainty for each case can only be determined after the tests.** The methods mentioned vary considerably in accuracy, but they all have an estimated uncertainty of less than 2 % (at a confidence level of 95 %). By virtue of this and depending on test conditions, any one of them may be envisaged for precision class tests.

Other methods which are not indicated in table 8 may also be used subject to the following two conditions :

— their systematic measurement uncertainty shall be determined and checked by periodic calibration using a primary method;

— the resulting uncertainty shall be compatible with table 7.

Table 8 — Methods for flow rate measurement

Values as percentages

Measurement methods and standards	Systematic measuring uncertainty (at a confidence level of 95 %)		
	Laboratory model tests	Tests on full-size pumps	
		on test platform	on site
Primary methods: by weight (ISO 4185)	± 0,1 to ± 0,3	± 0,1 to ± 0,3	—
Primary methods: volumetric (ISO 8316)	± 0,1 to ± 0,3	± 0,1 to ± 0,3	± 0,5 to ± 1,5
Primary methods: travelling screen (IEC Publication 193)	± 0,1 to ± 0,3	± 0,1 to ± 0,3	—
Differential pressure devices[1] (ISO 5167 and ISO 2186) Turbine flowmeter[1]	± 0,3 to ± 0,5	± 0,3 to ± 0,5	± 0,5 to ± 1
Electromagnetic flowmeter[1]	± 0,5 to ± 1	± 0,5 to ± 1	± 1 to ± 1,5
Calibrated weir (ISO 1438/1, ISO 3846, ISO 4359, ISO 4360): by a primary method	± 0,5 to ± 1,5	± 0,5 to ± 1,5	—
Calibrated weir (ISO 1438/1, ISO 3846, ISO 4359, ISO 4360): by a secondary method	—	—	± 1 to ± 2
Standardized orifice plate (ISO 5167 and ISO 2186)	± 1 to ± 1,5	± 1 to ± 1,5	± 1 to ± 1,5
Standardized venturi tube (ISO 2186)	± 1 to ± 2	± 1 to ± 2	± 1 to ± 2
Velocity area methods: by current meters (ISO 3354)	—	—	± 1 to ± 2
Velocity area methods: by Pitot tube (ISO 3966)	± 1 to ± 2	± 1 to ± 2	± 1 to ± 2
Tracer methods (ISO 2975 and ISO 555/1 to 3): dilution	—	—	± 1 to ± 2
Tracer methods (ISO 2975 and ISO 555/1 to 3): transit time	—	—	± 1 to ± 2

1) Calibrated by a primary method.

7.2 Measurement by weighing

ISO 4185 specifies two alternative methods:

a) the "static weighing method" which consists of diverting the flow alternately inside and outside the weighing tank;

b) the "dynamic weighing method", where the weighing is made "in flight", the flow being directed permanently into the tank.

The weighing method, which gives only the value of the average flow rate during the time taken to fill the weighing tank, may be considered the most accurate method of flow rate measurement.

It is affected by errors relating to weighing, to measuring the filling time, and to the determination of the density taking into account the temperature of the fluid. There may also be errors in connection either with diverting the flow (static method) or with dynamic phenomena at the time of weighing (dynamic method). Furthermore, a buoyancy correction has to be made to the readings of the weighing machine to take account of the difference between the up-thrust exerted by the atmosphere on the liquid being weighed and on the reference mass used during the calibration of the weighing machine.

With high quality apparatus, the systematic uncertainty on the measurement of the flow rate (at a confidence level of 95 %) may be in the region of 0,1 to 0,2 %.

It should be noted that the weighing method requires large fixed installations which are only really practicable in a laboratory and for relatively low flow rates (less than 1,5 m^3/s for instance).

7.3 Volumetric method

For the description of this method, see ISO 8316.

The volumetric method approaches the accuracy of the weighing method and similarly only supplies the value of the average flow rate during the time it takes to fill the gauged capacity.

The volumetric method is affected by errors relating to the calibration of the reservoir, the measurement of levels, the measurement of filling time, and also by errors in connection either with diverting the flow (static method) or with dynamic phenomena at the time of gauging (dynamic method). Moreover, the watertightness of the reservoir shall be checked and a leakage correction made if necessary.

The calibration of the reservoir may be obtained by measuring the water level after successive volumes of water determined either by weighing or by means of a gauged pipette are poured into the reservoir tank.

With high quality apparatus, the estimated uncertainty (at a confidence level of 95 %) may be in the region of 0,1 to 0,3 %. However, in its normal form as described above, the volumetric method is subject to the same limitations as the weighing method.

On the other hand, there exists a variant to the volumetric method which can be used on site and for larger flow rates, where a natural reservoir the volume of which has been determined by geometrical or topographical procedures can be used as the gauged capacity (see IEC Publication 41). It must, however, be emphasized that the accuracy of this method is much less than that of the volumetric method used in the laboratory, notably on account of the inaccuracy in measuring the reservoir, uncertainty about possible leaks or inflows, and the difficulty of determining the levels and disturbances due to atmospheric conditions. Depending on the particular circumstances (whether the reservoir is natural or artificial, the capacity of the reservoir compared to the flow rate to be measured, the stability of conditions over a relatively long period of time, etc.) the systematic uncertainty of a flow rate measured by this method may be estimated at 1 to 2 %.

7.4 Travelling screen

A description of this method and the conditions for its use are given in IEC Publication 193.

Its principle, which is close to that of the volumetric method, makes this a very accurate one, for it only requires the measurement of the dimensions of the channel, the level of the water and the moving time of the screen.

However, as in 7.2 and 7.3, measurement by travelling screen requires large and very carefully maintained apparatus, so that it can only be used for laboratory tests or tests in the works on a full-size pump platform. It is particularly well adapted to the latter type of test, as it enables relatively high flow rates to be obtained (around 3 m^3/s, for example) with a systematic uncertainty (at a confidence level of 95 %) of about 0,2 to 0,3 %.

7.5 Differential pressure devices

For the construction, installation and use of orifice plates, nozzles and venturi tubes, see ISO 5167; for specifications on connecting piping for the manometer, see ISO 2186. Different types of standardized differential pressure devices are shown in figure 3.

In particular, attention should be drawn to the minimum straight lengths to be adhered to upstream of the differential pressure device; these are specified in ISO 5167 for various configurations of piping. If it is necessary to place the differential pressure device downstream of the pump (a case not covered in ISO 5167), the pump may be considered to create a disturbance in the flow equivalent to two elbows not in the same plane. However, when working away from the operating conditions corresponding to the best efficiency of the pump, the swirl of the flow produced by the pump can involve more severe conditions. To overcome these it will be necessary to install, downstream of the pump, a swirl remover or flow straightener of one of the types given in ISO 5167, provided the straight lengths specified in this International Standard upstream and downstream of the straightener are complied with.

It should also be noted that the diameter of the pipe and the Reynolds number must fall within the ranges specified in the International Standard for each type of device.

In these conditions, if there is no special calibration, using the discharge coefficient indicated in the relevant International Standards may be considered to give a systematic uncertainty on the flow rate (at a confidence level of 95 %) of 1 to 1,5 %, for an orifice plate or an ISA 32 nozzle, and from 1 to 2 % for a long-radius nozzle or a venturi tube.

If a departure is made from the standardized conditions, or if greater accuracy is required, the differential pressure device shall be calibrated in its particular conditions of use by means of one of the primary methods described in 7.2 to 7.4. In good measuring conditions, a systematic uncertainty (at a confidence level of 95 %) of approximately 0,3 to 0,5 % can then be obtained.

When choosing between the various types of differential pressure devices, the following factors should be considered:

a) the greatest accuracy for uncalibrated devices conforming to the relevant International Standards is achieved with orifice plates, the least with venturi tubes;

b) head loss is much lower for venturi tubes than for orifice plates and nozzles (about five times as low, given an equal differential pressure);

c) the straight lengths required are much smaller for classical venturi tubes than for orifice plates, nozzles and venturi nozzles;

d) building and positioning is much simpler for an orifice plate than for a nozzle or a venturi tube — the latter requires a large distance between flanges;

e) in the case of orifice plates, a significant error can arise if buckling of the plate occurs due to the existence of a large differential pressure across the plate.

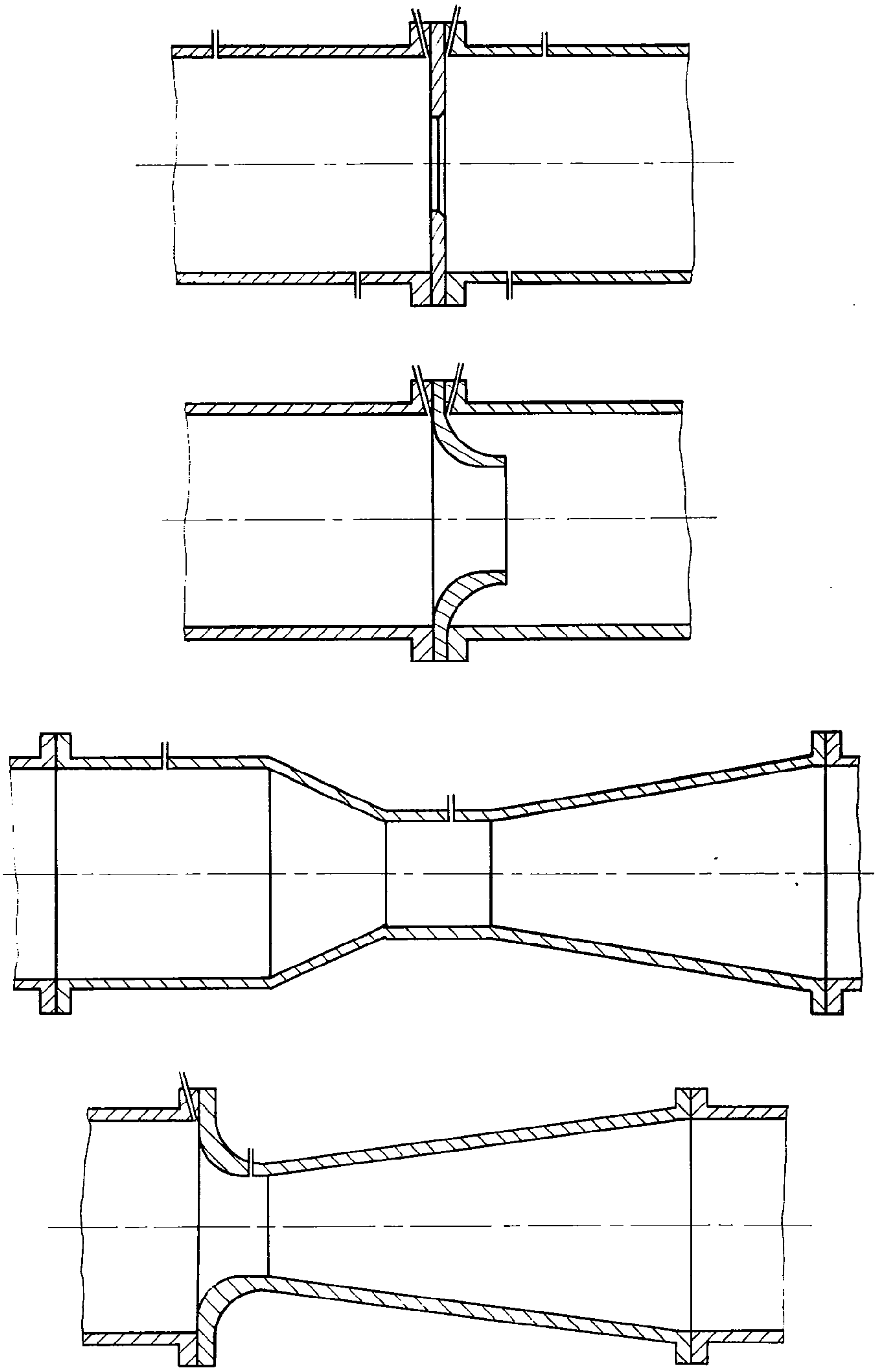
7.6 Weirs

The specifications for thin-plate weirs and measuring flumes are given in ISO 1438/1 and ISO 4359 and those for various types of broad-crested weirs in ISO 3846 and ISO 4360. Figure 4 shows the different types of standardized structures schematically.

However, even for rectangular thin-plate weirs, which are the best known and the most stable, the uncertainty which surrounds the normalized discharge coefficient is not compatible with the accuracy being sought in this International Standard.

On the other hand, if it is possible to calibrate the weir in its position in the exact conditions of use since great sensitivity to velocity distribution in the approach channel exists and periodically to check this calibration by means of one of the primary methods described in 7.2 to 7.4, for laboratory or platform tests a flow rate measurement with an estimated uncertainty (at confidence level of 95 %) of about 0,5 to 1,5 % may be attained. For on-site tests, calibrating the weir by means of one of the methods described in 7.8 or 7.9 can lead to a systematic uncertainty of 1 to 2 %.

To achieve this, however, great care must be taken to maintain the weir in perfect condition; it may be noted that it is easier to conserve and check the sharpness of the edge of a thin-plate weir than the roughness of the sill and walls of a broad-crested weir or a measuring flume.



Orifice plate
(with corner taps, *D* and *D*/2 taps, or flange taps)

Nozzle
(long radius or "ISA 32")

Classical
Venturi tube

Venturi nozzle

Figure 3 — Different types of standardized differential pressure devices (see ISO 5167)

7.7 Turbine meters and electromagnetic flowmeters[1]

Though quite different in conception, these two types of flowmeter have many points in common with regard to practical conditions of use.

In no circumstances should they be used unless calibrated beforehand by means of one of the primary methods described in 7.2 to 7.4. Although these devices do not require very long upstream straight pipe lengths, in general it is desirable that the conditions of calibration should reproduce the circuit configuration in which they will be used. If they are installed permanently on a test platform, the possibility of a periodic check on their calibration must be taken into account. In these conditions, a flow rate may be obtained with a systematic uncertainty (at a confidence level of 95 %) of about 0,3 to 0,5 % for turbine flowmeters and 0,5 to 1 % for electromagnetic flowmeters.

NOTE — The fact that these flowmeters send an electric signal direct makes their integration into an automatic measuring system particularly easy.

7.8 Velocity area methods

ISO 3354 and ISO 3966 specify methods for discharge measurements in closed conduits by means of current meters and Pitot tubes respectively. They give all the specifications considered necessary concerning conditions for application, choice and operation of the apparatus, the measurement of point velocities and the calculation of the flow rate by graphical or numerical integration of the velocity distribution.

In the most favourable measuring conditions, the systematic uncertainty in the measurement of the flow rate (at confidence level of 95 %) is 1 to 2 %.

The main disadvantages of these methods are that

a) they require fairly long straight lengths to ensure a regular velocity distribution;

b) with current meters, they can only be used in large diameter pipes;

c) it is rather difficult to put them into operation; as a result the installation may not be available for several days.

On the other hand, the velocity integration method is often the only one that can be applied when testing pumps with large flow rates.

Among precautions to be taken, it should be particularly ensured that the support of the current meters or Pitot tubes does not create excessive obstruction in the pipe.

Furthermore, except in very long pipe installations, it is preferable that the measuring section should be placed upstream of the pump in order to avoid too much turbulence or swirling flow.

Where the plant comprises a sufficiently long artificial open channel, the discharge may be measured by the velocity area method using current meters in this channel (see IEC Publication 198).

7.9 Tracer methods

The various parts of ISO 2975 apply to the measurement of the flow rate in pipes, by both the dilution method (constant rate injection) and the transit time method (also called the salt velocity method); each method uses either radioactive or non-radioactive tracers. Furthermore, ISO 555/1 to 3 specifies dilution methods for discharge measurements in open channels.

These methods have the advantage of being usable for a very wide range of flow rates, and some of them only require minimal interference with the pipe. The length required in some cases to ensure adequate mixing of the solution injected can in practice be reduced on the one hand by injecting into the suction pipe of the pump which is then used as a mixer or on the other hand by increasing in each section the number of injection positions and sampling or measuring positions.

These methods should only be used by trained staff and it may be noted that the use of radioactive tracers is subject to certain constraints.

It may be considered that the systematic uncertainty in the determination of the flow rate (at a confidence level 95 %) with these methods is from 1 to 2 %.

8 Measurement of head

8.1 General

8.1.1 Principles of measurement

8.1.1.1 Total head and specific hydraulic energy

Although expressed as a height of pumped liquid column, the pump total head, H, calculated in accordance with its definition given in table 1, represents in actual fact the energy transmitted by the pump per unit weight of liquid.

This concept of specific energy may replace the one of head and its use is to be recommended, since for instance the column of liquid representing the total head is not exactly the difference in height that may be read at a liquid column (supposing no difference in elevation or available kinetic energy between inlet and outlet). This discrepancy is due to liquid compressibility and atmospheric pressure related to elevation.

8.1.1.2 Effect of liquid compressibility on total head evaluation

Total head is in fact the maximum amount of mechanical energy per unit weight that may be released in bringing the liquid from its actual conditions to reference conditions.

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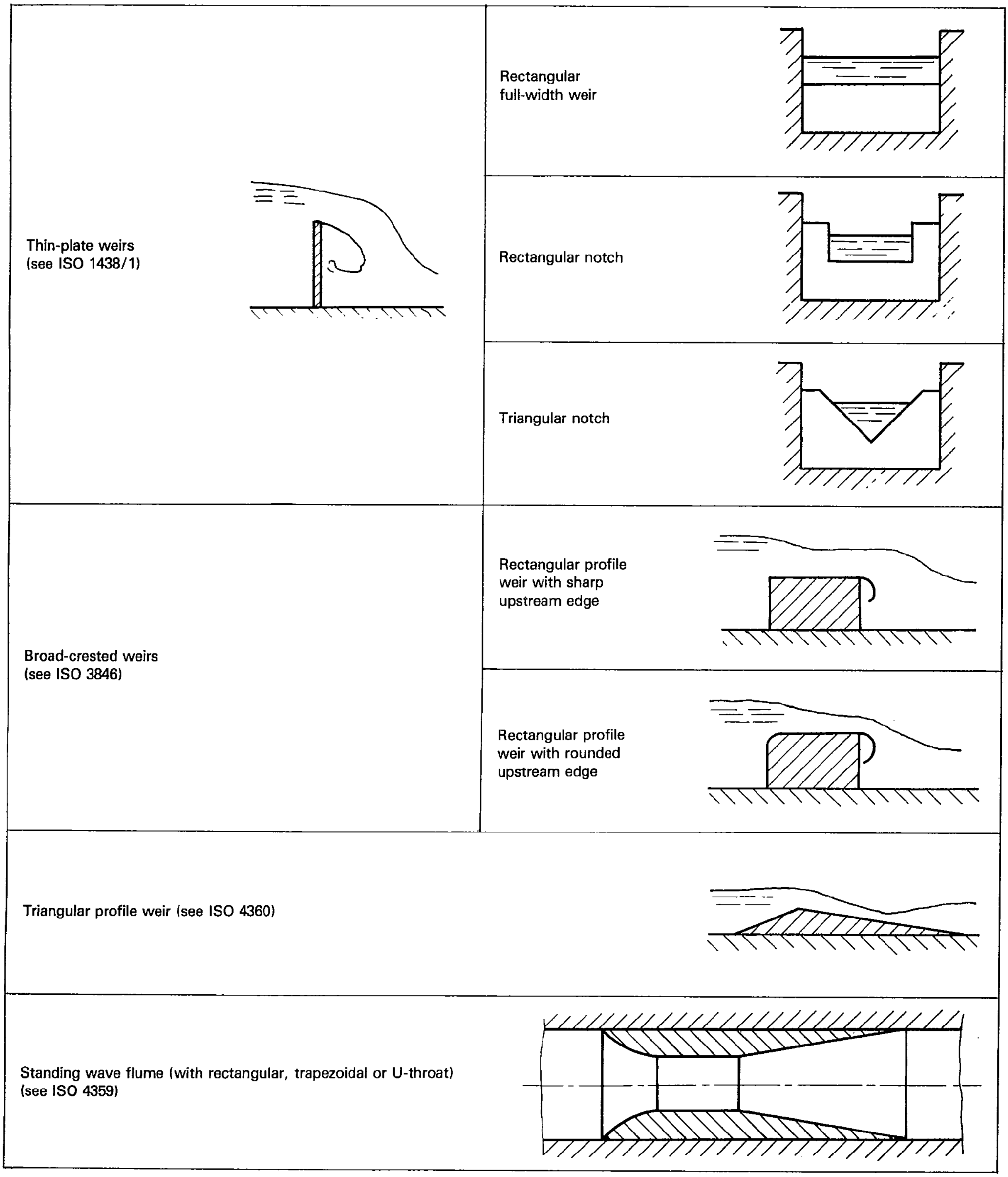
[1] These will form the subject of a future International Standard.



NOTE — The accuracy required in this International Standard can only be achieved if the discharge coefficient of such devices is determined by individual on-site calibration; thus it is not permitted to use the values of coefficients as they are given in the relevant International Standards.

Figure 4 — Different types of standardized weirs and flumes

Reference conditions are generally sea level and standard atmospheric pressure, but within the frame of a test where only differences in energy level are of concern, other reference conditions may be chosen, for example floor elevation and atmospheric pressure at the time of test.

For liquid at elevation z_i at the pressure p_{ei}, with velocity U_i and g being constant, the correct evaluation of total head is given by the equation:

$$H_i = z_i + \frac{1}{g}\int_{p_o}^{p_{ei}} \frac{dp}{\varrho} + \alpha_{ai}\frac{U_i^2}{2g}$$

This integration is to be evaluated for an isentropic process. Tables and formulae may be found giving the value of this integral for water.

Generally speaking, ϱ varies with pressure and temperature, therefore evaluation is not straightforward. However, pressure dependence is low and nearly linear and one may write

$$H_i = z_i + \frac{2\,p_{ei}}{(\varrho_i + \varrho_o)g} + \alpha_{ai}\frac{U_i^2}{2g}$$

This approximation holds for water up to 40 °C and up to 15 MPa[1]. The definition of total head given table 1 is a complementary simplification based on the assumption that

$$\varrho_i = \varrho_o$$

It is the responsibility of the chief of tests to decide whether compressibility may be fully neglected in relation to the acceptable uncertainty allowed by each specific tests.

Direct evaluation of pump total head is recommended where compressibility cannot be disregarded, due to the following

$$\frac{1}{g}\int_{p_o}^{p_{e2}} \frac{dp}{\varrho} - \frac{1}{g}\int_{p_o}^{p_{e1}} \frac{dp}{\varrho} = \frac{1}{g}\int_{p_{e1}}^{p_{e2}} \frac{dp}{\varrho}$$

This calculation requires analytic expression of the state function $v = f(p)$. However, if linearization is possible, the following will be valid :

$$\frac{1}{g}\int_{p_{e1}}^{p_{e2}} \frac{dp}{\varrho} = \frac{2\,(p_{e2} - p_{e1})}{(\varrho_2 + \varrho_1)g}$$

where

ϱ_1 is unit mass of fluid at p_{e1} and θ_1;

ϱ_2 is unit mass of fluid at p_{e2} and θ_1.

NOTE — The temperature at the end of the reversible process is slightly different from θ_1. The error due to neglecting this difference does not exceed 0,1 % on efficiency when the pressure is less than 150 bar and the temperature is less than 250 °C (see 11.2).

8.1.1.3 Available velocity head

The velocity head prevailing in a measuring section cannot be fully converted into total head. This is especially the case at the pump outlet [see section (2) of figure 5].

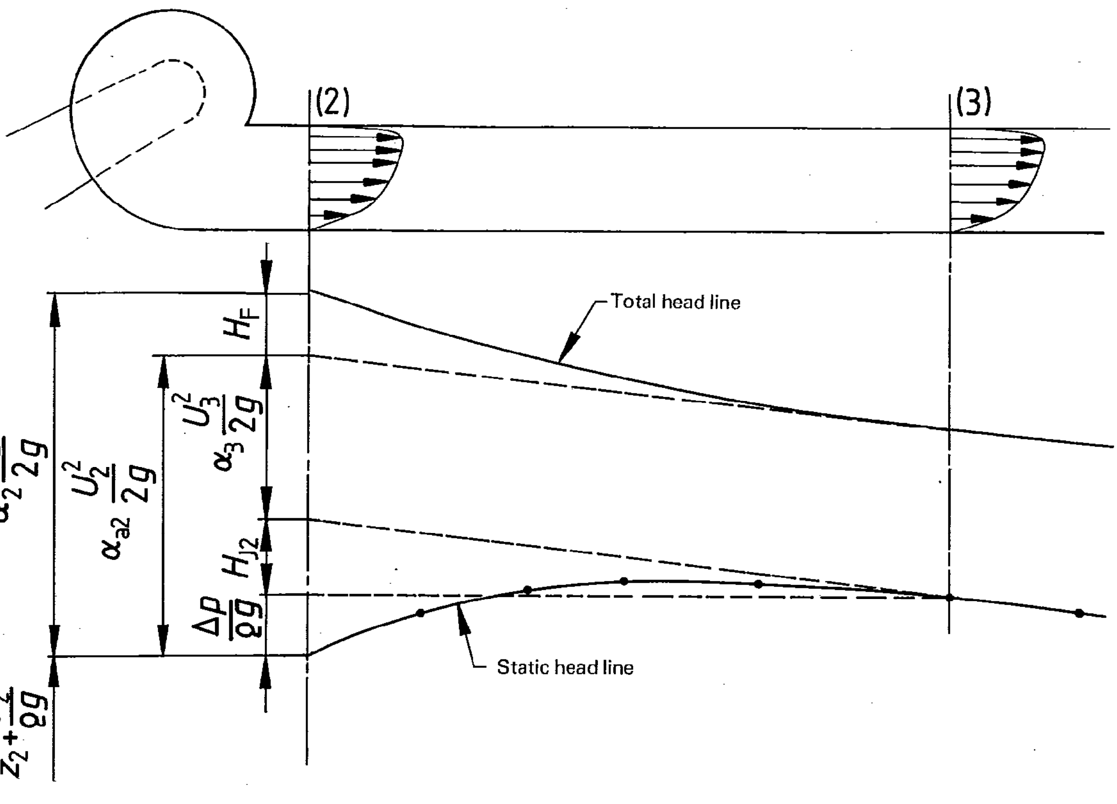


Figure 5 — Determination of available velocity head

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[1] 1 MPa = 10 bar

In section (3) of figure 5, further downstream, part of the velocity head remains as such, part is converted into a pressure increase Δp and the remainder is dissipated as friction within the flow.

This friction is due to velocity rearrangement and is definitely unavailable to the user. Available velocity head is then given by the equation

$$\alpha_{a2}\frac{U_2^2}{2g} = \frac{\Delta p}{\varrho g} + \alpha_3\frac{U_3^2}{2g} + H_{J2} = \alpha_2\frac{U_2^2}{2g} - H_F$$

where H_F is the friction loss caused by velocity rearrangement.

Where practicable, α_{a2} shall be evaluated from the static head line plotted from measurements in successive sections, as shown in figure 5. Where this is not possible it may be assumed that $\alpha_{a2} = \alpha_2$ and its value may be evaluated from the determination of the velocity distribution in section (2) (see 8.2.4.2).

8.1.1.4 Loss of head between inlet or outlet sections and measuring sections

The various quantities specified in the definition of head (see table 1) should as a rule be determined in the inlet section S_1 and the outlet section S_2 of the pump (or of the pump set and fittings which are the subject of the tests); practically, for reasons of convenience and of measurement accuracy, the measurements are generally carried out in cross-sections S'_1 and S'_2 some way upstream from S_1 and downstream from S_2 (see figure 6). Thus, account shall be taken of the friction losses in the pipe, i.e. H_{J1} between S'_1 and S_1 and H_{J2} between S_2 and S'_2 (and possibly for the local head losses), and the pump total head is given by the equation

$$H = H'_2 - H'_1 + H_{J1} + H_{J2}$$

where H'_1 and H'_2 are the total head at S'_1 and S'_2.

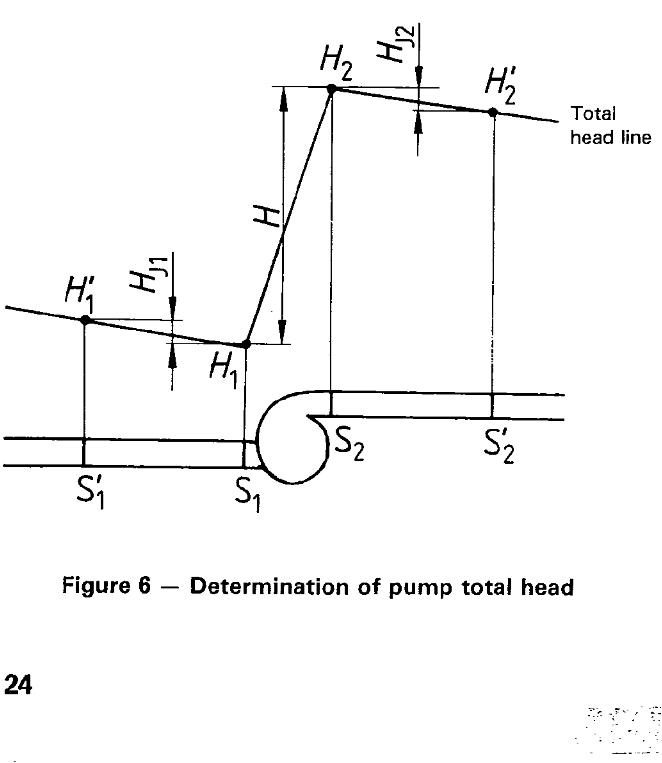


Figure 6 — Determination of pump total head

Some requirements concerning the definition of the measuring sections in various types of installations and a method of estimating the head losses are given in 8.2.

8.1.2 Various methods of measurement

Depending on the installation conditions of the pump and on the layout of the circuit, the pump total head may be determined either by measuring the inlet and outlet total heads separately, or by measuring the differential pressure between inlet and outlet and adding the differences in velocity head, if applicable, taking into account potential head and density variations due to the measuring system.

Total heads may also be deduced either from pressure measurements in conduits or from water level measurements in basins.

The selection of the measuring section, the various measuring devices which can be used and the determination of the velocity head for each of these cases are dealt with in 8.3 and 8.4.

8.1.3 Uncertainty of measurement

The uncertainty of the pump total head measurement shall be obtained by combining the estimated uncertainties of each term of which it is composed; thus the manner of conducting this calculation depends on the methods of measurement used: separate measurements of the inlet and outlet total head or differential measurement between the pump ends, pressure or water level measurement and type of apparatus. It is therefore possible to give only general information on the various errors involved.

8.1.3.1 Errors in potential energy values

The elevations, referred to an arbitrary reference plane, of the central point of the measuring sections as well as those of the zero or the reference point of the various sets of measuring apparatus are given by surveying processes which are generally very accurate. The uncertainty of these components may be regarded as negligible compared to other sources of error.

8.1.3.2 Errors in kinetic energy values

These are dependant on the one hand on the uncertainty in the mean velocity in the measuring sections, and thus of the determination of the cross-sectional areas and principally on the method of flow rate measurement used; and on the other hand on the uncertainty in the evaluation of the velocity head coefficient α_a, which is a function of the flow conditions (see 8.2.4). These errors may become more significant in pumps generating a low total head.

8.1.3.3 Errors in water level measurements

Apart from the errors which can be due to the unsteadiness and to slope of the water level, errors in water level measurements are dependent principally on the measuring apparatus used.

For guidance only, a rough estimate of the uncertainties due to the apparatus (see 8.3.2) may be taken as follows :

— staff gauges, plate gauges:	± 10 to 20 mm;
— float gauges, bubbler apparatus:	± 5 to 10 mm;
— liquid manometers, point or hook gauges:	± 1 to 3 mm.

8.1.3.4 Errors in pressure measurements

If every precaution related to pressure tappings and connecting pipes has been taken, and if the measurements are not falsified by undue pressure fluctuations, the following estimates of systematic uncertainties due to the apparatus (see 8.4.2) may be used for guidance :

— liquid manometers:	± 0,2 to 1 %;
— dead-weight manometers, pressure weighbeams:	± 0,05 to 0,5 %;
— spring pressure gauges:	± 0,5 to 1 %;
— pressure transducers:	± 0,2 to 1 %.

8.2 Definition of the measuring sections

8.2.1 General case of a pump tested alone

In most cases, the purpose of the tests is to check the hydraulic performance of the pump, without any upstream or downstream fittings; thus it is desirable, as far as possible (see 8.2.3), to measure the pump total head as close as possible to the inlet and outlet flanges of the pump as described in 8.2.1.1 and 8.2.1.2.

8.2.1.1 Inlet measuring section

If the pipe connecting the pump to the source of supply is not considered as part of the pump, the inlet measuring section shall be established, if practical conditions allow, in this pipework at a distance preferably equal to at least two diameters from the pump inlet flange, in a straight parallel section in which the flow conditions are as nearly as possible those specified in 6.2.1. Errors may arise if such is not the case, for example if a pre-swirl of the flow occurs at partial loads or if the layout of the circuit induces an asymmetrical or swirling flow pattern. In such circumstances, an investigation of the flow conditions may be necessary according to 8.2.4.2.

However, in some cases, it may be advisable to measure the inlet total head either in the suction pipe at some distance from the inlet flange or even in the free level reservoir from which the pump is supplied. In both cases, it is necessary to take into account the head losses H_{J1} between the measuring section and the inlet flange, calculating them according to 8.2.5.

When the head is obtained by water level measurement, errors may arise if the free surface is unsteady (for example if surging or waves exist), or if there are locally high velocities, or if vortices occur near the pump intake; the location of measurement shall be selected and appropriate arrangements shall be used (see 8.3.1) so as to minimize these influences. Due allowance shall be made for the velocity head at the measuring location (if it is not negligible compared to the pump total head) and for the pressure acting on the surface (generally the atmospheric pressure).

8.2.1.2 Outlet measuring section

If the pipe into which the pump discharges is not considered as part of the pump, the outlet measuring section shall be established, if the practical conditions allow, in this pipework at a distance of at least 2 diameters from the pump outlet flange, in a straight parallel section.

Errors may arise in the case of asymmetric or swirling flow conditions in the measuring section; such a flow maldistribution is a reflection of the inadequacy of the pump to straighten the flow after it passes out of the impeller into the casing. This is often inevitable at flow rates other than that for which the pump was designed, especially for pumps of high type number. It may be possible to extend the flow range over which head measurement is possible within the accuracy required for precision class tests by establishing the measuring section further downstream and making allowance for the head losses H_{J2} between the outlet flange and the measuring section calculated according to 8.2.5. In order to ensure that the velocity distribution is satisfactory or to assess the kinetic energy coefficient to be applied, an investigation of the flow conditions at various loads may be necessary according to 8.2.4.

For pumps which discharge directly into a free surface reservoir through pipework which may be considered as part of the pump, the outlet total head is obtained from water level measurement in the reservoir; the same remarks as in 8.2.1.1 shall then apply.

8.2.2 Pump tested with fittings

If the tests are on the combination of the pump and the whole or part of its upstream and downstream connecting fittings, these being considered an integral part of the pump, the provisions of 8.2.1 apply to the inlet and outlet flanges of the fittings instead of the inlet and outlet flanges of the pump. This procedure debits against the pump all head losses caused by the fittings.

8.2.3 Pump with inaccessible ends

If it is impossible to gain access either to the inlet or outlet of the pump, or to both sides (this case occurs particularly where the tests are carried out on site), the measuring sections shall be located under the best local conditions; it shall be arranged by mutual agreement

— whether the tests will apply to the combination of the pump and of the part of the circuit included between the measuring cross-sections, in which case the requirements of 7.2.2 apply;

— or whether the pump total head shall be deduced from the total heads as evaluated at the measuring cross-sections by adding the head losses H_{J1} and H_{J2} on both sides of the pump, these losses being calculated in accordance with 8.2.5.

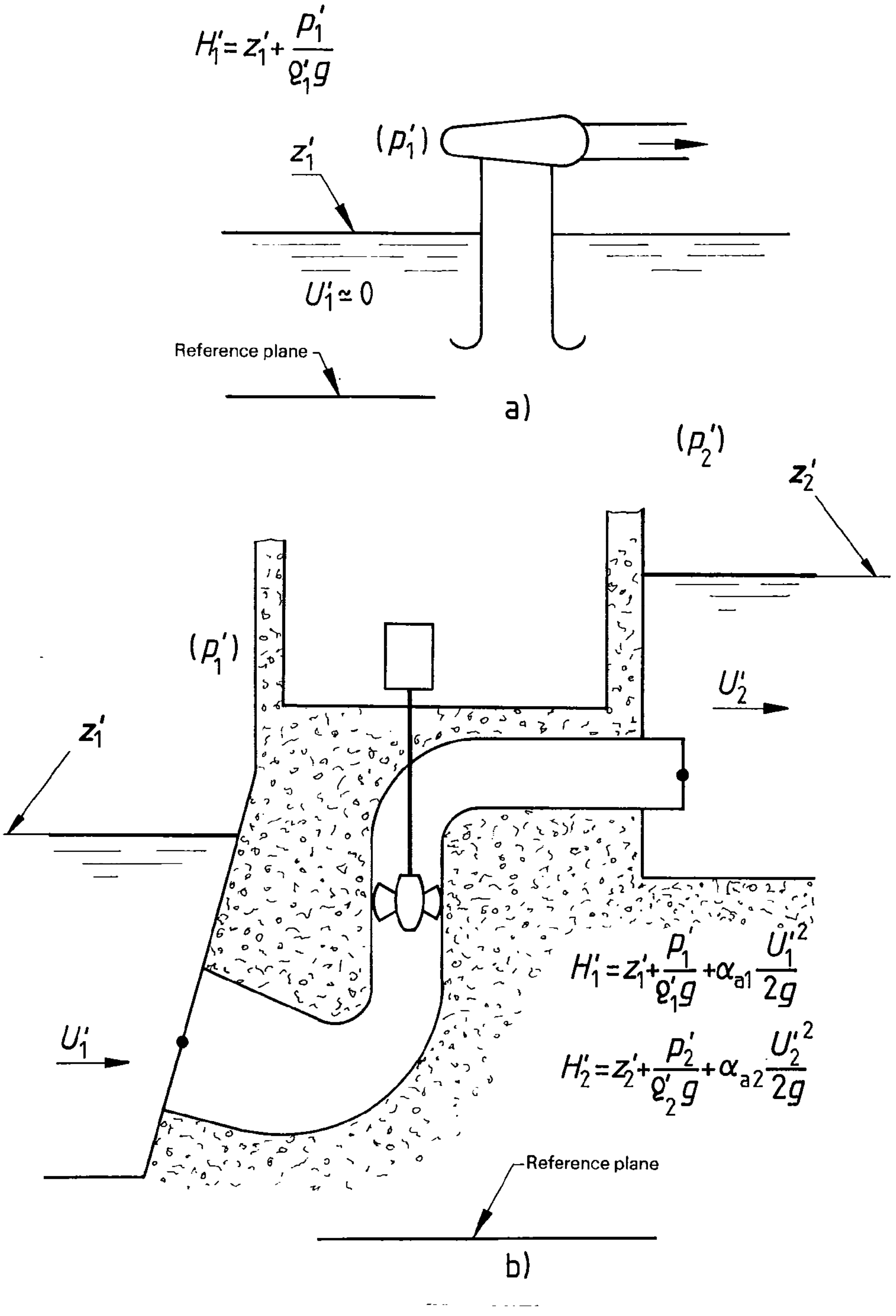
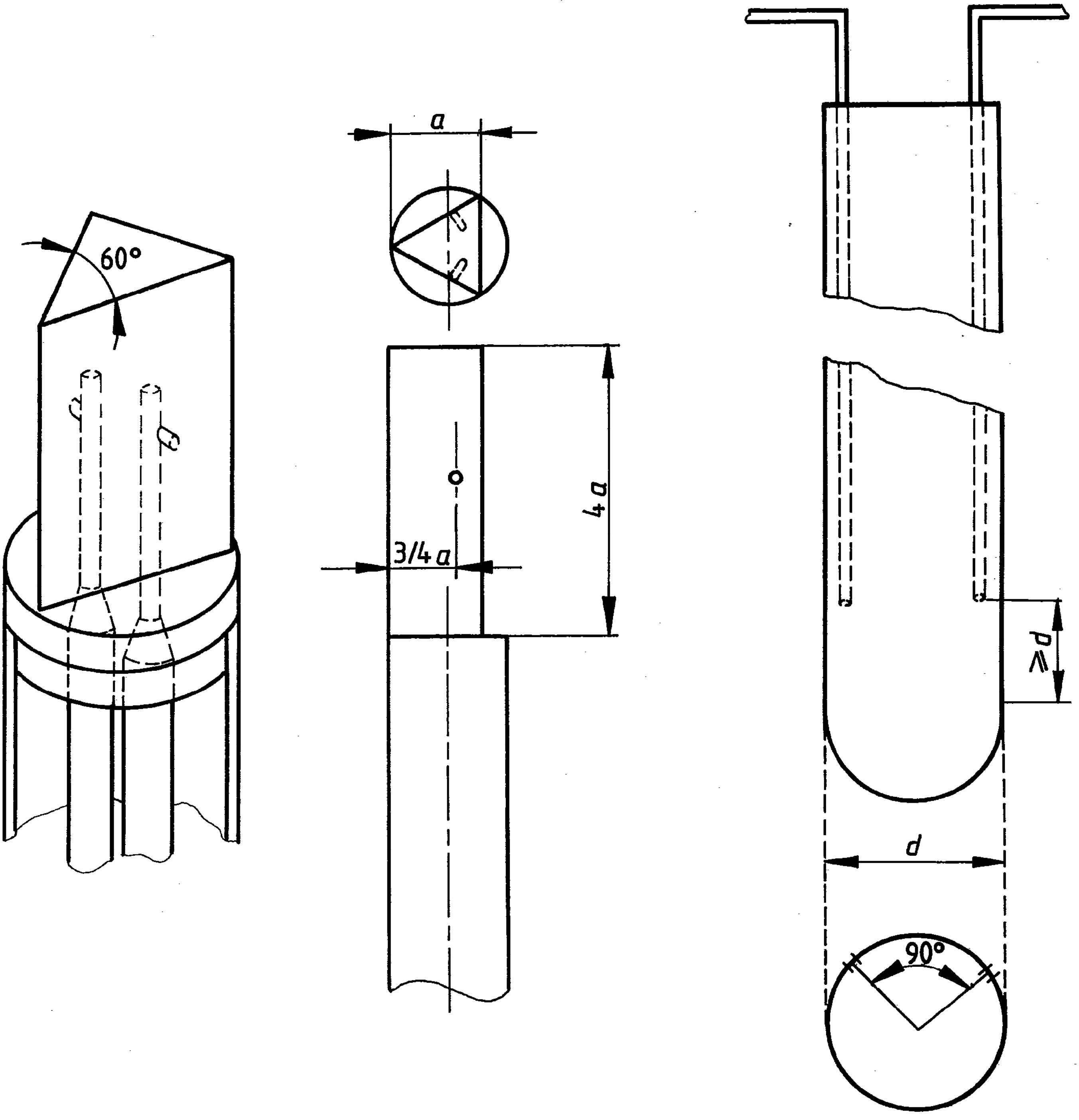


Figure 7 — Examples of total head determination by water level measurements



a) Wedge-shaped probe

b) Cylindrical probe

Figure 8 — Examples of yaw probes

8.2.4 Choice of the measuring sections and effect of flow conditions

8.2.4.1 Choice of the measuring sections

Special attention shall be given to the location of water level or pressure-measuring sections. In pump installations, where the pressure distribution and the velocity distribution at the inlet and outlet of the pump are such that the calculation of the pressure head and the velocity head from the mean values measured in these sections would result in a significant error in the determination of the pump total head, other measuring sections further upstream or downstream shall be used (see 8.1.1).

For pressure measurements in a pipe, the measuring section should be arranged in a straight pipe section of constant cross-section extending five diameters upstream and two diameters downstream from the inlet measuring section and two diameters upstream and one diameter downstream from the outlet measuring section. If the available straight length is not sufficient (for example in the case of a rather short inlet bellmouth), this length should be divided between upstream and downstream parts of the measuring section so as to take the best possible advantage of the actual conditions (for example in the ratio of 2 to 1 approximately). Sections where the velocity pattern is seriously distorted by an elbow, valve, any other flow disturbance or by the vicinity of the pump itself should be avoided.

For water level measurements, the measuring location should be selected so that

- either the velocities in the measurement area of the reservoir are very small, and thus the velocity head is negligible [see figure 7 a)];
- or the cross-sectional area used to calculate the velocity head is sufficiently well defined and readily measurable [see figure 7 b)].

8.2.4.2 Investigation of the velocity distribution

When the inlet or outlet total head is obtained by pressure measurements in conduits, it is generally unnecessary to determine the velocity distribution across the measuring section. This is particularly the case where evidence of satisfactory conditions may be considered as established, either by previous tests carried out in the same test rig or if a straight length of conduit is used, sufficient to create a fully developed velocity distribution, provided the pump itself does not induce a pre-swirl in the suction pipe.

Nevertheless, if such evidence does not exist and if the ratio of the velocity head to the pump total head is more than 0,02, an investigation of the velocity distribution in the manner here described shall then be necessary in order to ensure that the selected measuring section is suitable to accommodate measurements and also in order to allow an evaluation of the available velocity head coefficient, α_a.

In case of doubt, for example where the outlet measuring section is not very far from the outlet flange of the pump, checking the pressure distribution over the measuring section by using four pressure tappings (see 8.4.1.1 and 8.4.1.4) may be useful for deciding if an investigation of the velocity distribution shall be carried out.

The investigation of the velocity distribution should comprise the determination of the direction and magnitude of the local velocity at a number of points along at least two diameters at right angles in the plane of the measuring cross-section. This may be accomplished in a number of ways using probes. Figure 8 shows an example of such a probe. For more details, see ISO 7194.

Large and varying indicated yaw angles measured across the pipe diameter show the presence of three-dimensional flow and the probability of non-uniform pressure as well as velocity distribution; in these conditions, the measuring section is unsuitable for accurate head measurement.

A measuring section where probing has been carried out will be considered as satisfactory if :

- at no measurement point the velocity direction deviates by more than 10° from the axis of the pipe,
- at no measurement point the value of the velocity is higher than twice the value of the mean velocity,
- the pressures measured at the various pressure tappings in the measuring section are satisfactorily balanced (see 8.4.1.4).

8.2.4.3 Effect of pre-swirl induced by the pump

Errors in the determination of the inlet total head can occur if at part load the pump induces a pre-swirl of the flow in the suction pipe; figure 9 illustrates such a case. These errors can be detected and corrected on the following basis.

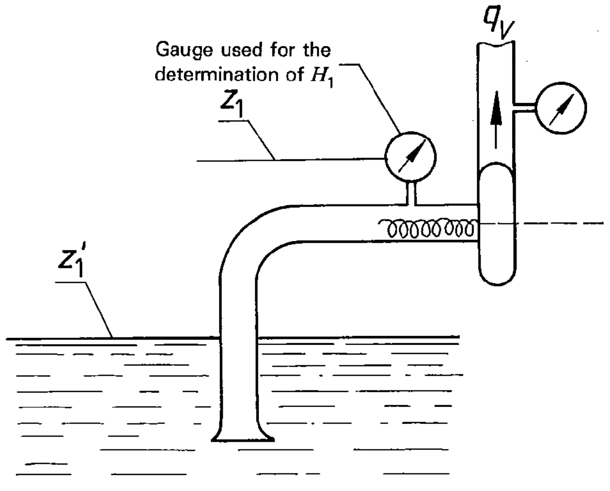


Figure 9 — Example of installation with pre-swirl

If the pump draws from a free surface reservoir where the water level and the pressure acting on it are constant, the head losses between this reservoir and the inlet measuring section follow, in the absence of pre-swirl, a quadratic law with rate of flow and therefore the same holds true in respect of the inlet total head, $H_1 = H'_1 - H_{J1}$ (see figure 10). With higher rates of flow, measuring points ranged along a straight line, $H_1 = A - Bq_V^2$, will be obtained; however, with lower rates of

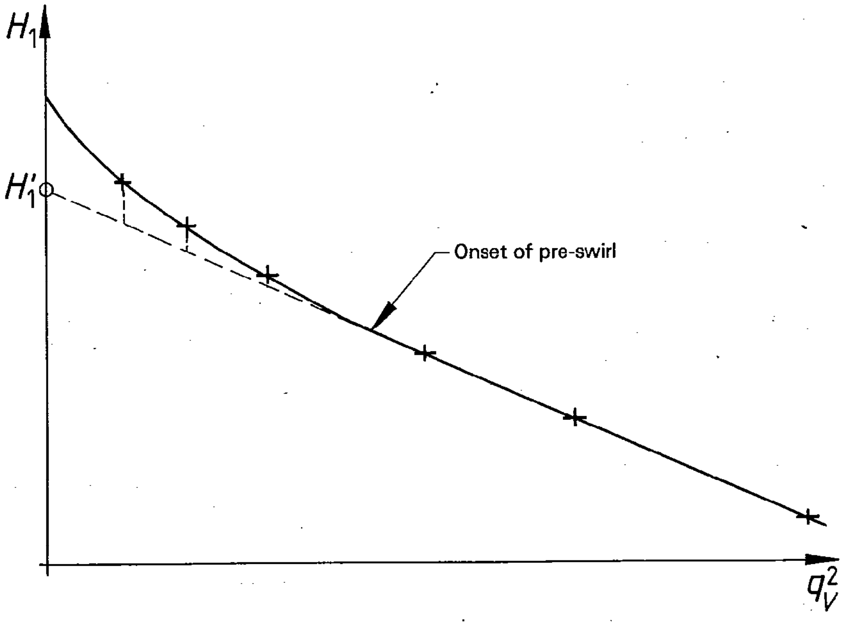


Figure 10 — Correction of measured inlet total head

flow the appearance of pre-swirl will result in errors both in pressure measurement and in velocity head evaluation, resulting in measurements deviating from this straight line.

It is then agreed to adopt as the value of the inlet total head the value read on the interpolation of the straight line obtained at higher flow rates. This value is not the true value, free from errors of measurement of the total head existing in the presence of pre-swirl, but it is the value which would exist if pre-swirl were not to occur. This procedure may be justified by the fact that the energy in the form of pre-swirl is indeed provided by the pump to which it is thus logical to attribute it.

If the pump does not draw from a constant head reservoir, another measuring section shall be selected sufficiently far upstream where the pre-swirl is known to be absent and it is then possible to use the same reasoning for the head losses between the two sections (but not directly about the inlet total head).

8.2.5 Head losses at inlet and outlet

As stated in 8.1.1, it may be necessary to add to the measured pump total head the friction head losses and possibly the local head losses between the measuring sections and the pump flanges. Nevertheless, such a correction may be neglected if

$$H_{J1} + H_{J2} < 0{,}001\,5\,H$$

If the pipe between the measuring sections and the pump flanges is free from any fitting and of uniform circular cross-section, the friction head losses in a piece of pipe having a length l and a diameter D are given by the equation

$$H_J = \lambda \frac{l}{D} \frac{U^2}{2g}$$

where λ is given in turbulent flow by one of the following equations

if $Re < 23 \dfrac{D}{k}$ (smooth pipe) :

$$\lambda^{-1/2} = -2 \log_{10} \frac{2{,}51}{Re\sqrt{\lambda}}$$

if $23 \dfrac{D}{k} < Re < 560 \dfrac{D}{k}$ (transition zone) :

$$\lambda^{-1/2} = -2 \log_{10} \left(\frac{2{,}51}{Re\sqrt{\lambda}} + \frac{k}{3{,}7D} \right)$$

if $Re > 560 \dfrac{D}{k}$ (rough pipe) :

$$\lambda^{-1/2} = -2 \log_{10} \frac{k}{3{,}7D}$$

where

$$Re = \frac{UD}{\nu} ;$$

k is the equivalent uniform roughness.

Annex E gives guidance on how to check whether a correction needs to be made and on how to calculate this correction if necessary.

For the friction head losses in pipes other than those of uniform circular cross-section and for the local head losses due to any irregularity in the pipe (bend, branch, valve, etc.), the correction to be applied shall be the subject of mutual agreement before the tests. Nevertheless, by reason of the poor accuracy with which such head losses are known, it is desirable that no irregularity exists in the measuring range.

8.3 Water level measurement

8.3.1 Arrangement of the measuring section

At the measuring site, the flow shall be steady and there shall be no local disturbances. If the free water surface is disturbed by small waves or swell it may be necessary, depending on the type of measuring device used, to provide a stilling well or a stilling box. This may be, for example, a well in the wall of the conduit in communication with the flow through a connecting pipe leading to the conduit through a perforated plate flush to the wall, or else a vertical pipe immersed in the flow, the bottom of which is formed by a perforated plate; the holes of the plate shall be small enough (about 3 to 5 mm in diameter) to damp the pressure fluctuations.

It is advisable to use at least two measuring points in each cross-section.

8.3.2 Measuring apparatus

Various types of water level measuring apparatus may be used, according to the circumstances (free surface accessible or not, steady or disturbed, etc.) and to the required accuracy in regard of the pump total head. The most commonly used devices are:

a) vertical or inclined gauges, fixed along a wall;

b) point or hook gauges, for which a stilling well and a supporting frame set close above the free surface are essential;

c) plate gauges, consisting of a horizontal metal disc suspended from a graduated steel-ribbon tape;

d) float gauges, which must be used in a stilling well;

e) liquid manometers in absolute or differential form, as described in 8.4.2.1;

f) bubbler apparatus, using a purge of compressed air;

g) immersed pressure transducers.

The three last types are particularly suitable where the free surface is inaccessible.

See ISO 4373 for a description of these types of apparatus.

8.4 Pressure measurements

8.4.1 Arrangement of the measuring section

8.4.1.1 Number and location of pressure tappings

As a rule four static pressure tappings at the wall shall be provided at each measuring section. In circular pipes, they shall be located on two diameters at right angles to each other; the tappings should not be located at or near the highest nor the lowest point of the cross-section in order to avoid air pockets or dirt accumulation in the pressure connections. In rectangular pipes, the tappings shall be located at the quarter and three-quarter points of the vertical walls.

However, if it has been established that the flow conditions are favourable (see 8.2.4.2), or if the velocity head does not exceed 1 % of the pump total head, only two tappings located diametrically opposite may be used by mutual agreement.

8.4.1.2 Shape and size of pressure tappings

The cylindrical bore of the pressure tapping opening in the conduit boundary should have a diameter between 3 and 6 mm or equal to 0,08 D, whichever is the smaller, and should have a minimum length of 2,5 times its diameter (figure 11). The bore shall be free from burrs and irregularities, and normal to the inner wall of the pipe; it shall be rounded off by a radius $r \leqslant d/4$ or at least a small chamfer.

The surface of the pipe shall be smooth in the vicinity of the tappings for a length at least equal to the smaller of these two values :

- 400 mm or $2D$ upstream
- 150 mm or $1D$ downstream

The tappings shall be located as far as possible from any irregularity of the pipe, such as welded joint.

The material of the pipe shall be resistant to abrasion, corrosion or chemical reaction with the liquid being pumped; failing this, a metal plate which is unaffected by the liquid shall be fastened in the wall, flush with it, through which the tapping shall be drilled (figure 12).

8.4.1.3 Connecting pipes and damping devices

Connecting pipes leading from each pressure tapping shall be at least equal in bore to the bore of the tapping.

The pressure tappings of each measuring section shall be connected through individual shut-off valves to a ring manifold of cross-sectional area not less than the sum of the cross-sectional areas of the tappings, so that the pressure from any tapping may be measured if required (figure 13).

Any high point in the line of the connecting pipes shall be fitted with a purging valve to avoid trapping of air bubbles during measurements. Piping shall be carefully checked to avoid any leak, no matter how small. Whenever possible, it is recommended that transparent tubing in plastic material be used. ISO 2186 gives detailed indications as to the connecting pipes.

Where it is necessary to reduce the amplitude of oscillations, damping devices may be inserted into measuring instruments or their connecting lines. In order not to falsify the time mean of the fluctuating pressure, it is necessary that the damping be symmetrical and linear; this can be achieved by means of a capillary tube located in the manometer liquid. Bending or pinching the flexible connecting pipes or inserting any asymmetrical nozzle, needle valve, gate valve, etc., shall be absolutely forbidden. Moreover, in the case of a differential manometer, it may be necessary to balance the damping of the two circuits. Additional information on how to deploy and check damping devices is given in ISO 3966.

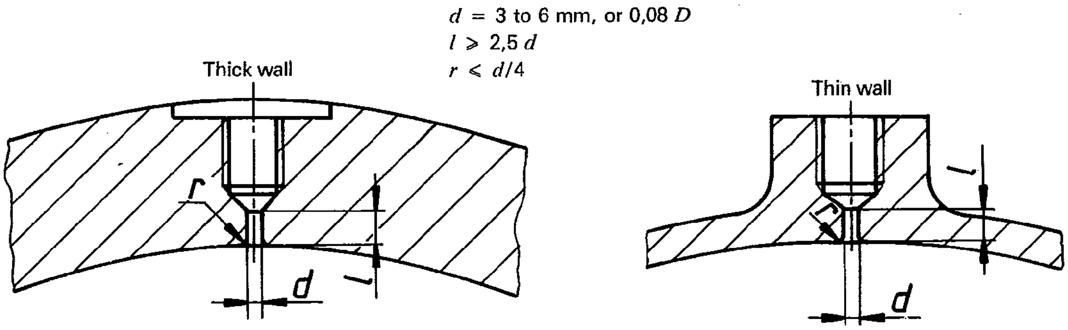


Figure 11 — Examples of pressure tappings in metallic wall

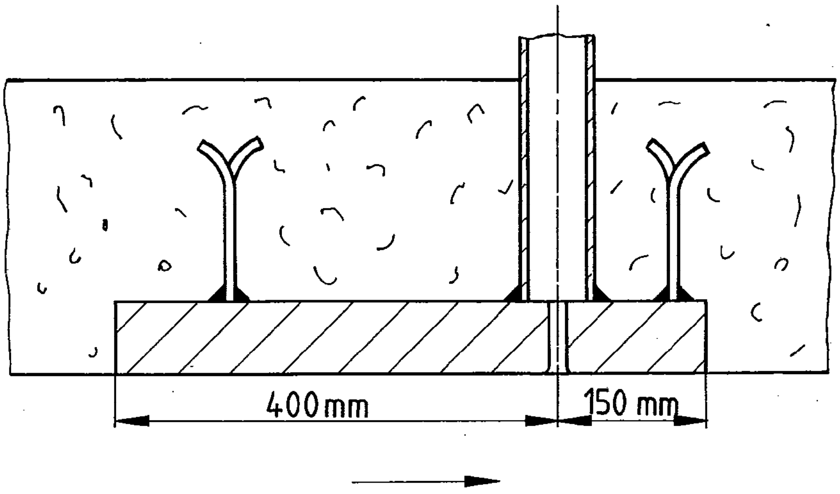


Figure 12 — Example of pressure tapping in concrete wall

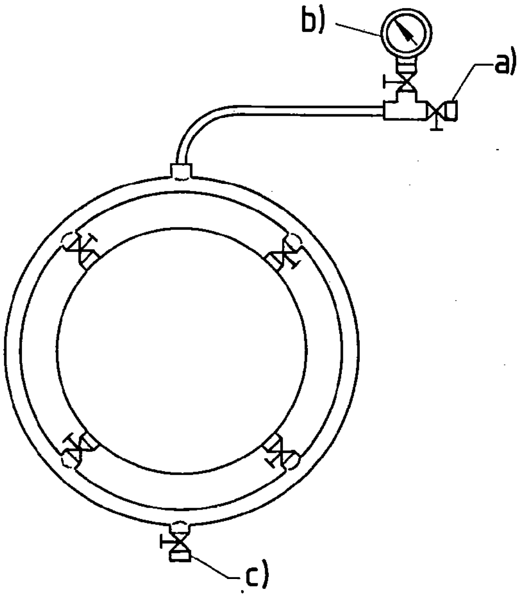


Figure 13 — Pressure tappings connected through ring main to pressure gauge:
a) purging; b) pressure gauge; c) drainage.

8.4.1.4 Checking of pressure measurements

Whenever possible, pressure readings shall be checked before and after the tests by comparison with headwater elevation under static conditions in the conduit.

In normal operation, the difference between the pressure measured at any one tapping and the average of the pressures measured at all tappings of the measuring section shall not exceed 0,5 % of the pump total head nor half the velocity head in the section. When the pressure tappings are used for NPSH measurements, this difference shall not exceed 1 % of the NPSH value nor half the velocity head.

If any pressure tapping appears to be in error, and if this cannot be attributed to the flow pattern (see 8.2.4.2), the source of the discrepancy shall be determined and removed; if this is not possible, the tapping concerned shall be eliminated.

8.4.2 Measuring apparatus

8.4.2.1 Liquid column manometers

Liquid column manometers are used to measure comparatively low pressures. Under these conditions, compressibility effects on the manometer liquids are small and can be ignored. The length of the liquid column may be modified by providing an inclined manometer or by using one manometric liquid with suitable density in place of another; the most commonly used liquids are water and mercury, but others may also be used such as ethyl tetrabromide ($C_2H_2Br_4$), carbon tetrachloride (CCl_4), diiodomethane (CH_2I_2), some metallic bromides or iodides, etc. If possible, the use of liquid columns less than 100 mm high shall be avoided; if this is impossible, attention shall be specially drawn to the errors of measurement.

In order to minimize capillarity effects, the bore of the manometer tubes shall be at least 8 mm for mercury gauges and 12 mm for water and other liquid gauges. The cleanliness of the liquid in the manometer and of the internal surface of the tubes shall be maintained to avoid errors due to variation of surface tension.

The design of the manometer shall be such that parallax errors are minimized.

Liquid column manometers may be either open-ended, or closed with the air in the circuit connecting both limbs compressed to the amount required to permit the differential head to be read on the scales, or formed by a U-tube filled with the manometric liquid. In the first case, pressures are measured from a fixed reference plane and above the surrounding atmospheric pressure which is taken as constant. The two last types allow the pump total head to be obtained from a single differential measurement.

The use of some typical liquid column manometers is shown diagrammatically in figures 14 and 15, to which reference should be made for the calculation equations.

8.4.2.2 Dead-weight manometers

For pressures exceeding the possibilities of the liquid column manometer, a dead-weight or piston manometer is of practical use whether in its simple or in its differential form. However, it can only be used beyond a minimum pressure corresponding to the weight of the rotating assembly.

The effective diameter d_e of the simple type manometer can be taken as equal to the arithmetic mean of the piston diameter d_p, measured directly, and of the cylinder diameter d_c; it can then be used for calculating pressures without further calibration if the following condition is satisfied before testing :

$$\frac{d_c - d_p}{d_c + d_p} \leqslant 0,1\ \%$$

Friction between the piston and cylinder may be practically eliminated by rotating the piston at a speed not less than 30 r/min.

It is desirable to check the dead-weight manometer by comparison with a liquid column manometer to determine the effective piston diameter in a pressure range to be as wide as possible.

Similar principles apply to the differential type weight manometer. For the measurement of variable pressures it may be advantageous to use a weight manometer mounted in series with a liquid column manometer (see figure 16) or a special weight manometer incorporating a liquid column manometer.

8.4.2.3 Pressure weighbeam

An extension of the dead-weight manometer is the pressure weighbeam, which comprises a weighbeam mounted on frictionless pivots and bearing on a weight manometer. The force exerted on the piston of the weight manometer is balanced by a jockey weight moving along the weighbeam (see figure 17). The operation of the weighbeam and jockey weight may be manual or automatic by means of a servo-motor and a screw. The sensitivity, repeatability and accuracy of such a device shall be checked against a manometer without a servo-balancing system wherever possible.

8.4.2.4 Spring pressure gauges

This type of gauge uses the mechanical deflection of a loop of tube, plain or spiral (Bourdon dial gauge) or a membrane to indicate pressure.

For precision class tests, it may be used, by mutual agreement, provided:

a) the gauge is of the highest precision;

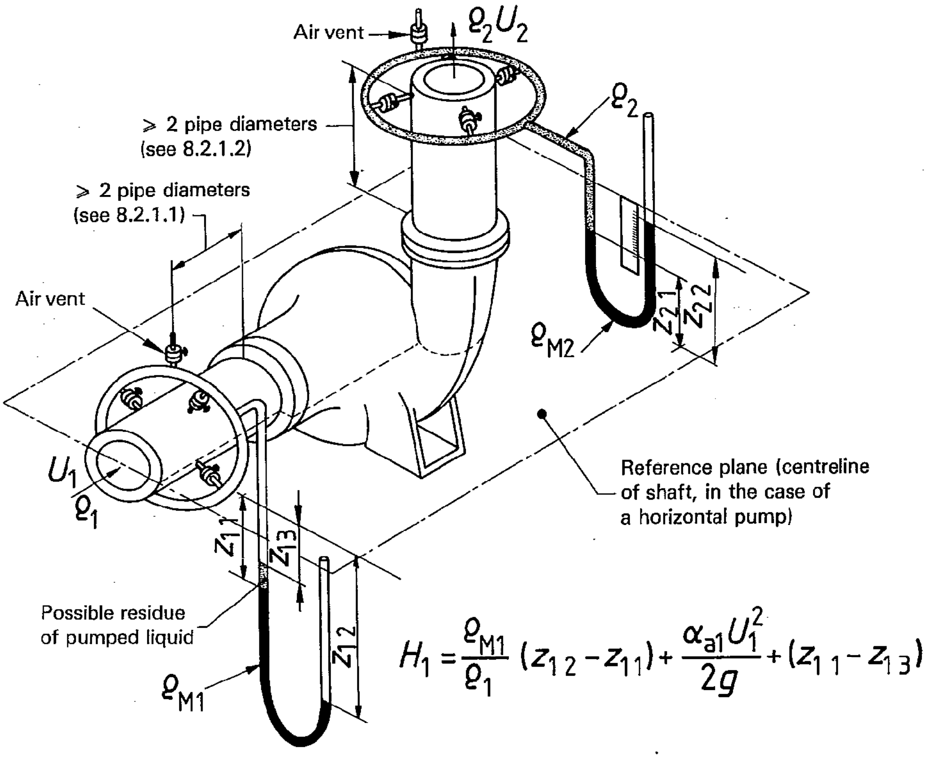
b) it is used within its optimum measuring range (usually from 60 to 100 % of its full scale);

c) the interval between two consecutive scale graduations corresponds to not more than 2 % of the pump total head.

The gauge shall be calibrated against standards before and after the tests.

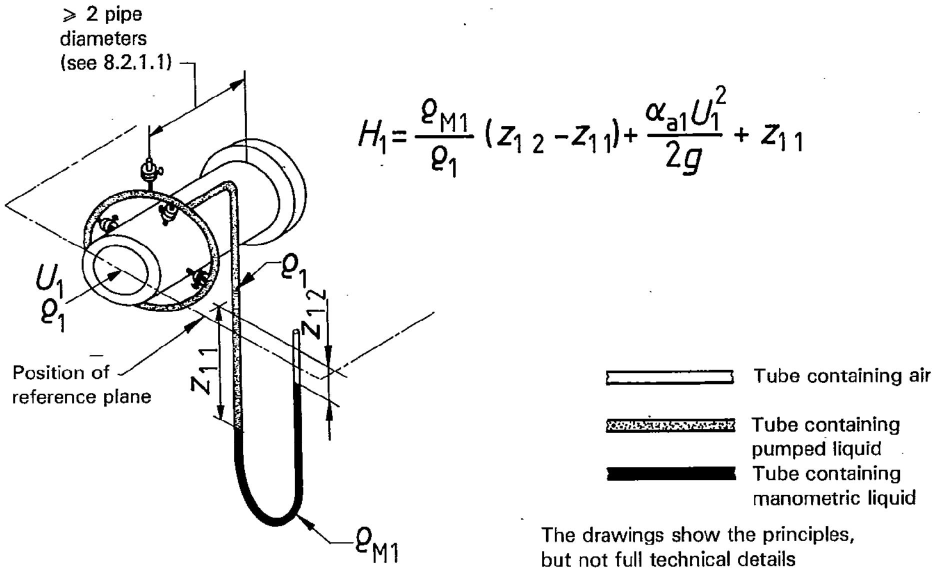
Figure 18 shows diagrammatically the use of such gauges and the corresponding calculation formulae.

$$H_2 = z_{2\,1} + \frac{\varrho_{M2}}{\varrho_2}(z_{2\,2} - z_{2\,1}) + \frac{\alpha_{a2} U_2^2}{2g}$$



$$H_1 = \frac{\varrho_{M1}}{\varrho_1}(z_{1\,2} - z_{1\,1}) + \frac{\alpha_{a1} U_1^2}{2g} + (z_{1\,1} - z_{1\,3})$$

a) Pump inlet under vacuum

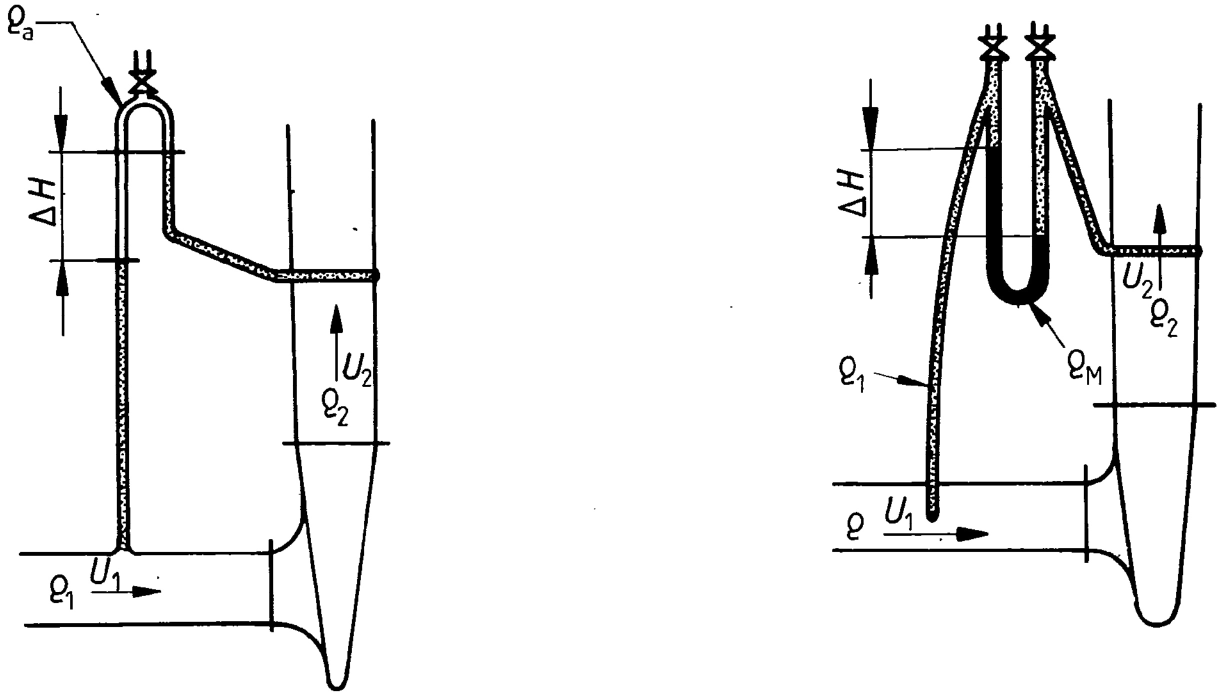


$$H_1 = \frac{\varrho_{M1}}{\varrho_1}(z_{1\,2} - z_{1\,1}) + \frac{\alpha_{a1} U_1^2}{2g} + z_{1\,1}$$

The drawings show the principles, but not full technical details

b) Pump inlet under pressure

Figure 14 — Test of a centrifugal pump by means of liquid column gauges



$$H = \frac{\varrho_1 - \varrho_a}{\varrho_1} \Delta H + \frac{\alpha_{a2} U_2^2 - \alpha_{a1} U_1^2}{2g}$$

$$H = \frac{\varrho_M - \varrho_1}{\varrho_1} \Delta H + \frac{\alpha_{a2} U_2^2 - \alpha_{a1} U_1^2}{2g}$$

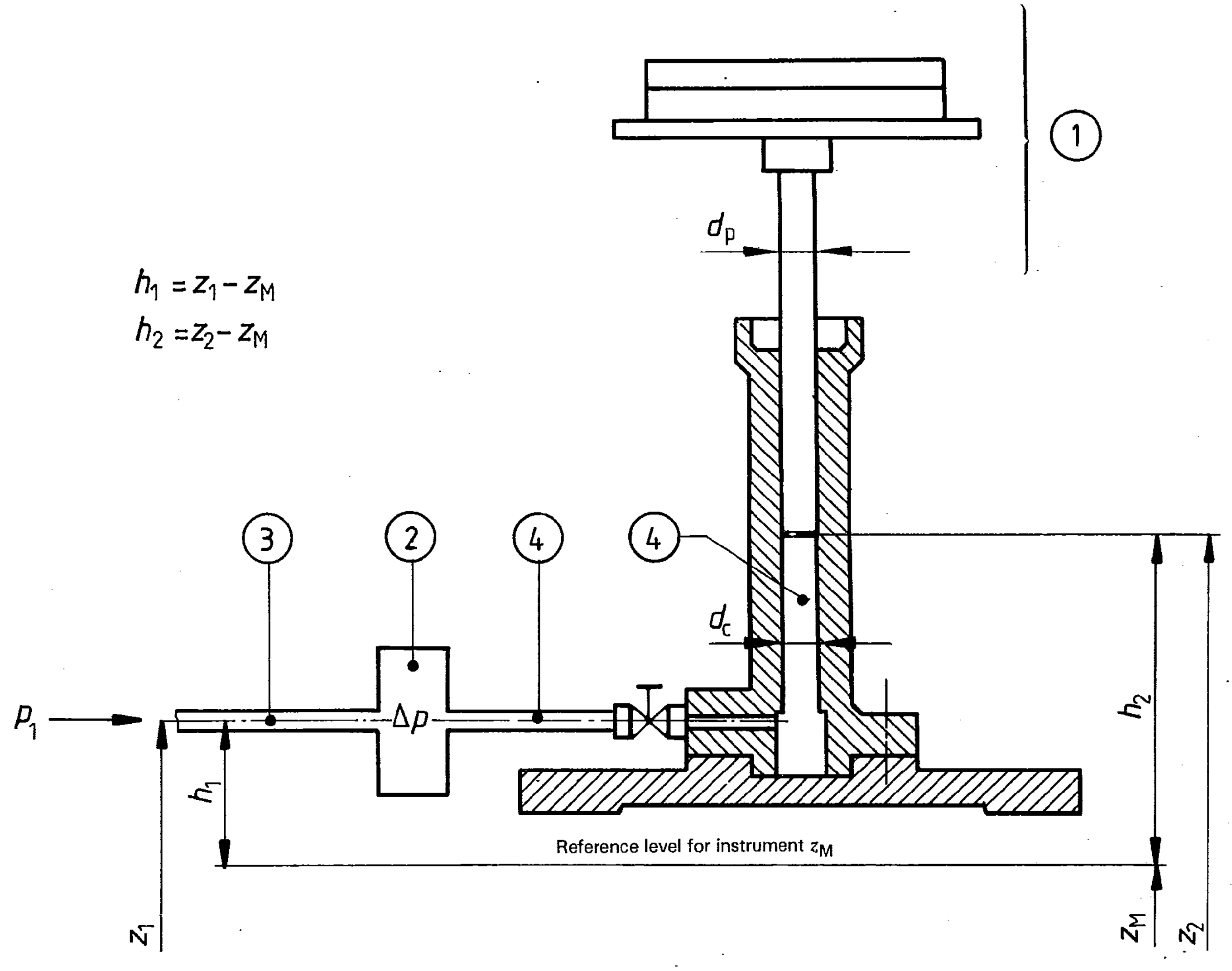
a) Air-water differential manometer

b) Mercury differential manometer

The drawings show the principles but not full technical details.

These equations are valid only if $\varrho_1 = \varrho_2$ which can never be assumed for precision class tests.

Figure 15 — Direct measurement of pump total head



Δp Differential pressure

① Acting masses, m

② Differential-pressure measuring device

③ Water

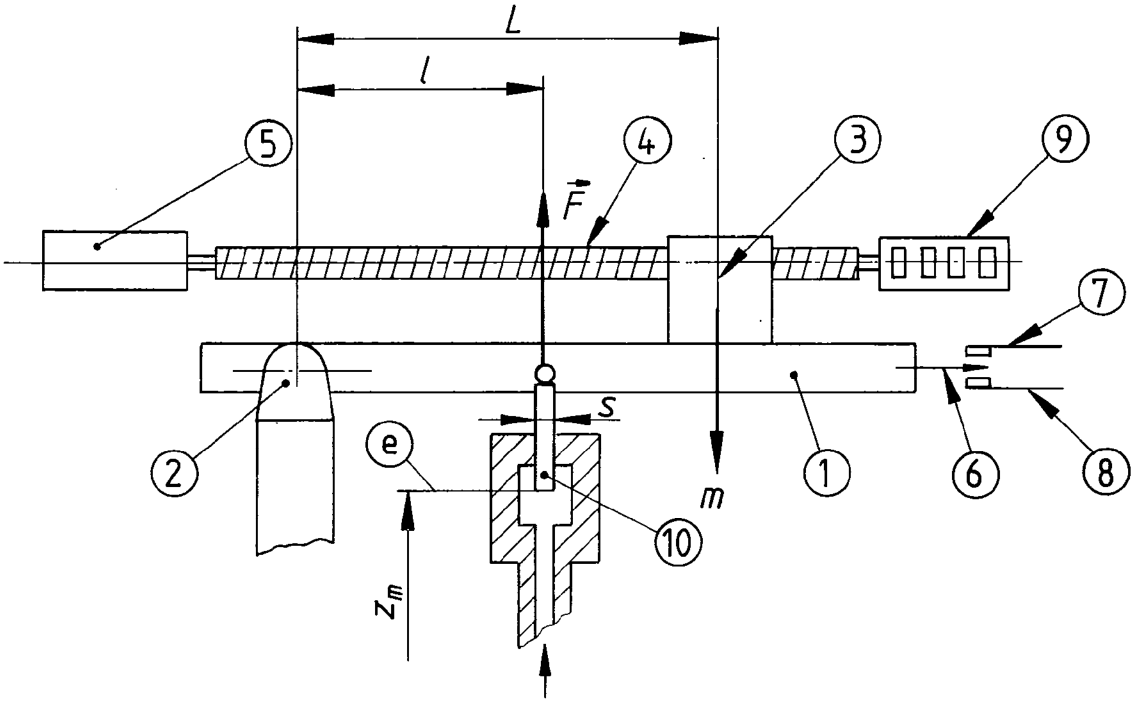
④ Oil

$$p_M = p_1 + \varrho g h_1 = p + \varrho_{oil} g (h_2 - h_1) + \varrho g h_1 + \Delta p$$

where $p = \dfrac{4\,mg}{\pi\, d_e^2}$

with $d_e = \dfrac{d_c + d_p}{2}$

Figure 16 — Dead-weight manometer with stabilization by differential pressure measurement (transducer or liquid manometer)



$$p = \varrho g(z_m - z) + \frac{L}{l}\,\frac{mg}{s}$$

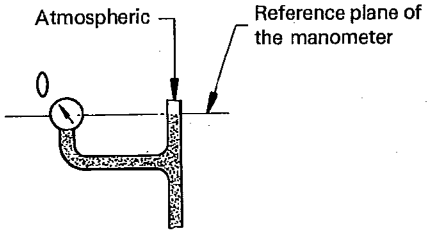
① Weighbeam
② Frictionless pivot
③ Jockey weight, mass m
④ Measuring screw
⑤ Servo-motor

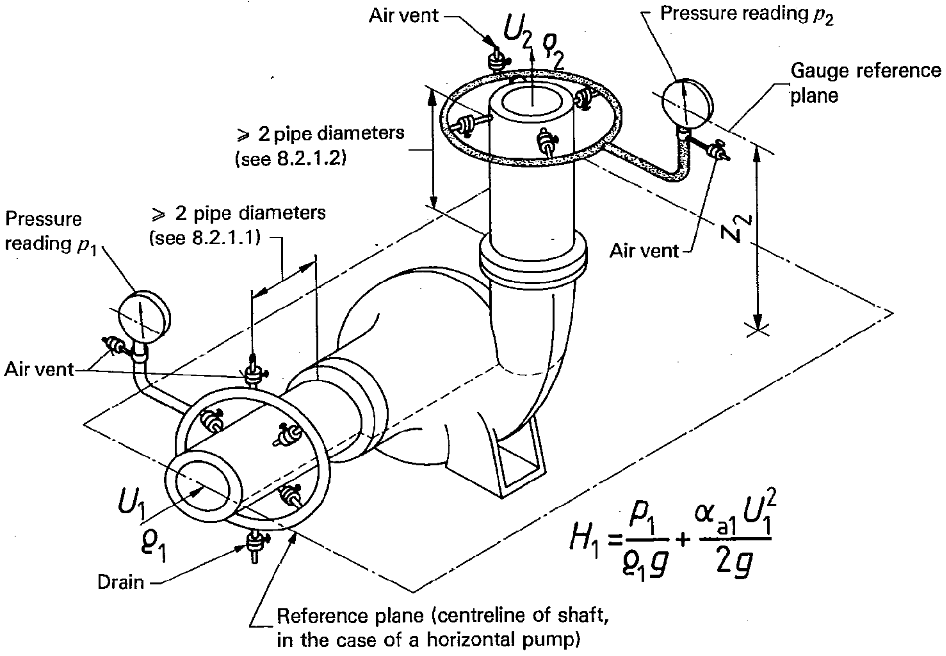
⑥ ⑦ ⑧ Electric contacts
⑨ Counter
⑩ Piston, cross-section s
ⓔ Zero point
ⓩ Altitude of the point pressure of which is to be found

Figure 17 — Pressure weighbeam

a) Arrangement for determining reference plane of Bourdon type gauge

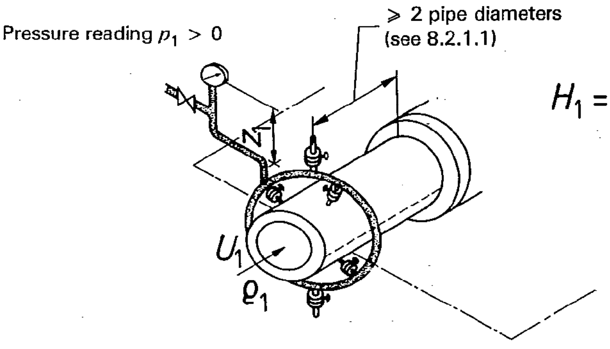
$$H_2 = \frac{p_2}{\varrho_2 g} + z_2 + \frac{\alpha_{a2} U_2^2}{2g}$$





$$H_1 = \frac{p_1}{\varrho_1 g} + \frac{\alpha_{a1} U_1^2}{2g}$$

b) Pump inlet under vacuum



$$H_1 = \frac{p_1}{\varrho_1 g} + z_1 + \frac{\alpha_{a1} U_1^2}{2g}$$

▭ Tube containing air

▨ Tube containing pumped liquid

c) Pump inlet under pressure

The drawings show the principles but not full technical details.

Figure 18 — Test of a centrifugal pump by means of a Bourdon gauge

8.4.2.5 Other types of manometers

There is a wide diversity of pressure transducers, absolute or differential, based upon the variation of various mechanical and/or electrical properties. They may be used by mutual agreement provided the required accuracy, repeatability and reliability are achieved, the transducer is used within its optimum measuring range and the transducer together with its electronic equipment are calibrated before and after the test against pressure standards of adequate accuracy.

Other methods which are not listed may also be used subject to the following two conditions :

- their systematic uncertainty shall be determined and checked by periodic calibration using a primary method;
- the maximum resulting uncertainty shall be compatible with table 7.

9 Measurement of speed of rotation

As far as possible the speed of rotation shall be measured directly by counting the number of revolutions during a known time interval with a tachometric dynamo or alternator, or an optical or magnetic counter linked to a frequency meter. In the case of an a.c. motor-driven pump, if the speed cannot be measured directly, it can be determined by measuring the mains frequency and the slip of the motor, for example with a stroboscope or an induction coil.

The uncertainty of measurement of the speed obtained with an electronic counter or any other device with an equivalent precision class is generally about ± 0,05 % to ± 0,2 %.

10 Measurement of power input

10.1 General

The pump power input, P (see table 1), shall be measured by one of the following methods:

a) indirectly, by subtracting the various electrical and mechanical losses from the measured electrical power input to the driving motor;

b) directly by determination of the speed and torque at the pump shaft. This method can be applied to any form of driver.

The accuracy required for precision class testing is such that the tests shall be carried out according to laboratory methods by suitably qualified personnel who fully understand the test requirements.

The measuring apparatus and test procedure shall be such that the accuracies required for precision class tests are achieved. It must be realized, however, that normal facilities on a manufacturer's test bed are unlikely to be satisfactory for this class of test.

Where the power input to an electric motor coupled to an intermediate gear, or the speed of rotation and torque measured by a dynamometer between gear and motor are used as a means for determining the pump power input, the losses due to the gear are determined by the calorimetric method applied to the cooling liquids of the gear unless otherwise agreed.

10.2 Indirect method

Since the motor coupled to the pump acts not only as a driving machine but as a device for measuring power, the losses should be determined accurately under the conditions of load, voltage, power factor, speed, temperature, etc., of the pump test. These losses may then be different from those obtained under standardized conditions for the measurement of the losses of the electric motors.

The losses of an electric motor shall only be determined by a specific test if the uncertainty of the assessment of these losses under test conditions by means of the available data cause an uncertainty of measurement of the pump power which is higher than the values specified by this International Standard. Clause 10.2.1 gives necessary details for this measurement.

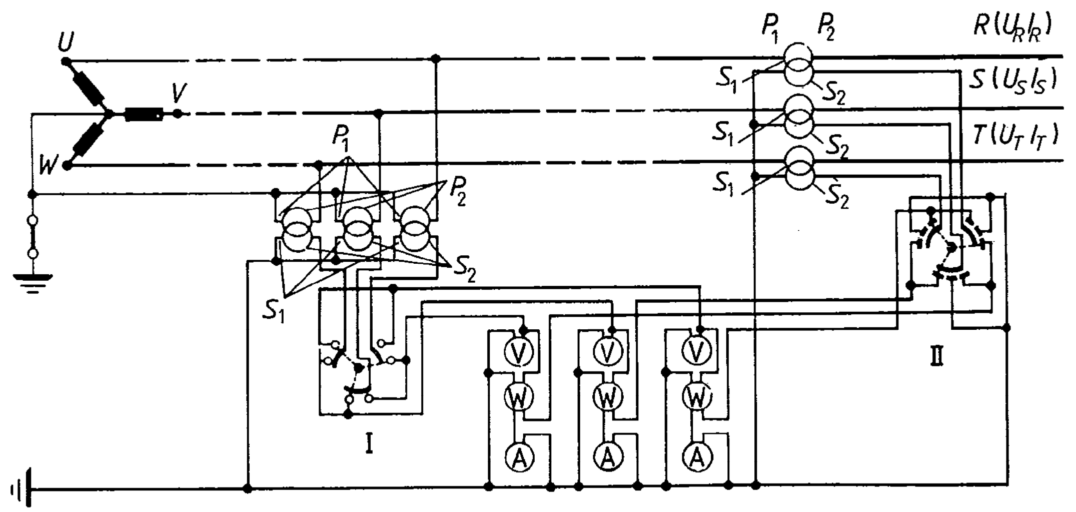
10.2.1 The efficiency of the electric motor shall be determined taking into account all the losses specified in IEC Publication 34-2 (provided that it does not contradict the specifications of this International Standard). When IEC Publication 34-2 does not give details of the procedure to be followed for these measurements, the procedure shall follow the regulations of one of the official national codes in existence, chosen by common accord between the parties at the time the pump is ordered, and taking into account the obligatory requirements of 10.2.2.

Generally the efficiency of an electric motor is determined by indirect measurement, consisting essentially of measuring the aggregate losses of the machine (total losses), and in assuming that these losses represent the difference between the electric power input absorbed and the mechanical power output. In practice, the determination of the above "total losses" is generally accomplished by the individual measurement or calculation of the various categories of losses and by their summation. Thus this method of measuring efficiency is said to be by "separate losses".

10.2.2 Measurement of the electrical power input shall be made at the motor terminals if at all possible. If this cannot be done, the measured power shall be decreased by the losses occurring between the motor terminals and the location of the measuring device; these losses are determined by calculation.

During pump tests, the motor shall operate, as far as possible, at its nominal voltage; in the case of an a.c. machine at its nominal frequency and for a synchronous machine at a power factor equal to unity. If these conditions cannot be fulfilled, due allowance shall be made in calculating the losses and corresponding inputs, and in estimating the probable error in the measurements.

The electric power shall be measured by means of accuracy class wattmeters or by watt-hour meters; they shall be calibrated and fed if necessary by accuracy class instrument transformers. The accuracy of the measurement of the power input to an electric motor on site or on a test rig will not be better than ± 0,2 %, this value depending on the accuracy class of the instrument transformers the accuracy of which shall not be inferior to that of the instruments.



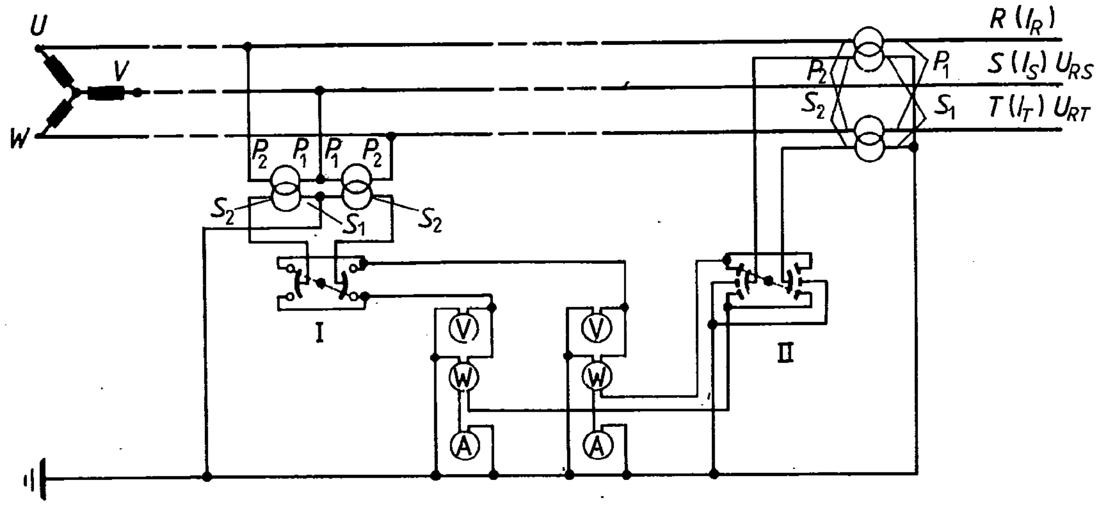
I Potential commutator
II Current commutator

Figure 19 — Measurement of the power at the terminals of a motor: three wattmeter method

The accuracy of these devices shall permit the whole measuring channel to comply with the requirements of table 7.

If the neutral of a three-phase motor is brought out and connected to the network or to earth, it will be obligatory to use the three wattmeter (or watt-hour meter) method (see figure 19).

If the neutral of the motor is brought out but not connected to the network or the earth during the test, either the three wattmeter (or watt-hour meter) method or the two wattmeter (or watt-hour meter) method may be used. The three wattmeter method is recommended. If the neutral of the motor is not brought out, the two wattmeter (or watt-hour meter) method shall be used (see figure 20).



I Potential commutator
II Current commutator

Figure 20 — Measurement of the power at the terminals of a motor: two wattmeter method

It may be necessary to allow for temperature correction in the above instruments. In the case of very great temperature fluctuations, it may be advisable (particularly for watt-hour meters) to place the instruments in a constant-temperature enclosure.

In addition to the measurement of input at the terminals, voltage, current per phase, excitation voltage and excitation current shall be measured by suitable accuracy class instruments. The temperature in the stator winding and other factors necessary to establish the losses and input of the machine under the test conditions shall also be measured. During measurement of the power input of an asynchronous motor, the slip value should be determined (by measuring the leakage flux or by means of stroboscopic measurement).

If the power is measured by direct-reading instruments, the number of readings will depend on the duration of the test and fluctuations in the load. The number of readings shall be sufficient to permit as accurate a calculation as possible of the mean power over the duration of the tests. It is recommended that the various wattmeters used in the measurement of power should be read simultaneously.

If the power is measured by watt-hour meters, they shall be used simultaneously with direct reading wattmeters and checked against them in the course of each measurement. The duration of the recording of the integrating devices shall be measured by means of stop-watches or other time-measuring devices sufficiently accurate to permit the determination of the time to at least 0,1 %. The power shall be measured during the same period in which the flow through the pump is measured.

Because of the possible inaccuracies in shunts used for measuring direct currents of high intensity, the degree of accuracy obtained in the measurement of direct current power may be considerably lower than achieved in the measurement of alternating current.

Because of the accuracy required for the electric measuring instruments (including the instrument transformers), the usual switchboard types are not to be used for precision class tests.

Similarly the instrument transformers supplying the wattmeters, watt-hour meters, or other electrical measuring instruments specially installed for the tests, shall be used solely for that purpose and may not be used to supply at the same time the measuring and protective circuits, etc., of the plant. An exception may be made to this rule only if, by agreement between the parties, it is decided (and possibly checked by calibration) that the same degree of accuracy can be obtained with the use of certain switchboard instrument transformers (in view of their accuracy class, their effective load and their conditions of use), as can be obtained with the use of the independent set of instruments and transformers specially reserved for the test specified above.

10.3 Direct method

The power input to the pump may be measured by torque reaction dynamometer or by torsion dynamometer. Both methods involve the simultaneous measurement of net torque and shaft speed. The torque on the reaction dynamometer is determined by the effective force applied to the dynamometer arm and radius at which it is applied. For the torsion dynamometer (torque tube) the torque shall be computed by means of a previous calibration.

To obtain the true power input, due allowance shall be made for parasitic torque losses as specified in 10.3.2.

10.3.1 The torque reaction dynamometer consists of an electric motor with its casing and field windings mounted on separate bearings from the rotating shaft, so that the whole casing is free to rotate but is restrained by means of a torque-measuring system. The torque delivered by the shaft is balanced by an equal and opposite torque reaction on the casing, and it is this that is measured either by means of a weight or by some other high-accuracy mechanical or electrical system.

10.3.2 Torque errors in torque reaction dynamometers may be avoided if the following precautions are taken.

a) It is necessary to limit the rotational movement of the dynamometer or to have a fixed balance point.

b) The dynamometer shall be so constructed that the cooling fluid enters and leaves so as to avoid torque errors due to tangential velocity components. Similar precautions shall be taken regarding winding. Flexible pipe connections, if used, shall impose no tangential restraint when under pressure. Dash pots, if used, shall be demonstrated to impose equal resistance to motion in either direction.

c) Electrical connections to the dynamometer shall impose no noticeable tangential restraint. Braided flexible copper leads or mercury pots are suitable for this purpose.

d) The effective radius arm of the dynamometer shall be measured with an error not exceeding ± 0,1 %. The inaccuracy of the force-measuring system shall not exceed ± 0,1 % of the reading. It shall be checked against certified weights in the direction of both increasing and decreasing load. In the case of vertical shaft machines, and sometimes others, metal tapes and frictionless pulleys are used for applying the torque balancing weights.

Before and after tests, the dynamometer and linkage shall be carefully checked.

10.3.3 The torsion dynamometer (or torque tube) comprises a length of shafting the torsional strain of which, when rotating at a particular speed and delivering a certain torque, is measured by some convenient method. Some torsion dynamometers use optical techniques to measure angular strain, others use capacitance, inductance or wire resistance strain gauges as electrical transducers. Whatever type of torsion dynamometer is used, it shall be calibrated before and after the tests against some primary method. The design of the dynamometer shall be such that speed and temperature will not influence the torque reading, or such that this influence can be measured quantitatively either by experiment or by means of a special device designed for this purpose.

High accuracy in any measuring equipment is virtually useless unless it can be checked and proved quickly and easily by the user to his own satisfaction. With careful calibration and use, ± 0,25 % of the actual reading can be achieved over the range 15 to 100 % of full scale, improving toward the higher end of the scale. It is generally impossible to check a torsion dynamometer directly against a reliable reference when it is running under load.

Examples of the strain gauged types are torque tubes with slip rings and d.c. excitation and those with inductive couplings and a.c. energization. The slip ring type can provide high accuracy, of the order of 0,1 % of their full load, but require more care and maintenance than the inductive coupling type which are essentially for higher speeds but are also more suitable for permanent installations where the accuracy requirements are not stringent.

The systematic uncertainty of torque measurement is most generally of the order of ± 0,15 % of the maximum torque, arising from the following sources:

- calibration, ± 0,1 %;
- sensitivity, ± 0,1 %;
- reading, ± 0,05 %.

11 Measurement of pump efficiency by the thermodynamic method

11.0 Introduction

This clause serves as a basis for the measurements to be made on pumps and for the computation of pump efficiency, η (see table 1), by applying the thermodynamic method. This method is based on the evaluation of the energy per unit mass of water received by water from a pump shaft. It may be determined by measurements of the performance variables (pressure, temperature, velocity and level) and from the thermodynamic properties of water.

Technological aspects of instrumentation are dealt with in a general way taking into account the fact that the apparatus presently available varies widely and may possibly become obsolete in the future.

The only requirements of instruments are to satisfy conditions stipulated in this International Standard (accuracy, heat exchange, etc.).

Due to the lack of uniformity in values measured at the inlet and outlet sections of the machines, the limitations of measuring equipment and the relatively high magnitude of the correction terms originating from the imperfect measuring conditions, the scope of this method is limited and it can only be used for pump total heads in excess of 100 m. However, under highly favourable conditions, the range could be extended by mutual agreement to cover lower heads subject to an analysis of the accuracy of the measurements.

11.1 Terms, definitions, symbols and units

In addition to the terms defined in table 1, the terms given in table 9 also apply.

Table 9 — Terms, definitions, symbols and units (thermodynamic method)

	Term	Definition	Symbol	Unit
11.1.1	Hydraulic energy per unit mass[1]	The necessary energy per unit mass for the fluid to pass over from state 1 at the pump inlet to pressure p_2 at the pump outlet when the pump is operating without losses. Under experimental conditions allowing the thermodynamic method to be used, the specific hydraulic E_h can be determined by means of the equation : $E_h = V_M (p_2 - p_1) + \frac{\alpha_{a2} U_2^2 - \alpha_{a1} U_1^2}{2} + g (z_2 - z_1)$ The measurement points for determining E_h are marked: 1, 2, in figure 21.	E_h	J/kg
11.1.2	Mechanical energy per unit mass[1]	The energy per unit mass received by water from a pump in the case of actual operation $E_m = \overline{a} (p_{21} - p_{11}) + \overline{c}_p (\theta_{21} - \theta_{11}) + \frac{\alpha_{a2} U_{21}^2 - \alpha_{a1} U_{11}^2}{2} + g (z_{21} - z_{11}) + \Delta E_m$ $= h_{21} - h_{11} + \frac{\alpha_{a2} U_{21}^2 - \alpha_{a1} U_{11}^2}{2} + g (z_{21} - z_{11}) + \Delta E_m$ The measurement points for determining E_m are marked: 11, 21, 22, in figure 21.	E_m	J/kg
11.1.3	Corrective term for energy due to secondary phenomena	ΔE_m is calculated according to the recommendations given in 11.3.	ΔE_m	J/kg
11.1.4	Energy per unit mass corresponding to contractual losses	Energy per unit mass corresponding to contractual losses in the machine which are not removed by water between the measuring sections (for example losses through bearings, where applicable)	E_x	J/kg
11.1.5	Pump efficiency[2]	$\eta = \frac{E_h}{E_m + E_x}$	η	
11.1.6	Volume per unit mass[3]	Volume per unit mass $V_m = \frac{1}{\varrho}$	V_m	m³/kg
11.1.7	Isothermal factor[4]	Factor characterizing a thermodynamic property of water $a = \left(\frac{\partial h}{\partial p}\right)_T = V_m - T \left(\frac{\partial V_m}{\partial T}\right)_p$	a	m³/kg
11.1.8	Specific heat capacity[5]	Specific heat capacity at constant pressure	c_p	J·kg⁻¹·K⁻¹
11.1.9	Mean value of a[6]	Values of a and c_p corresponding to the mean value, $\overline{p}$, where $\overline{p} = \frac{p_{11} + p_{21}}{2}$ and the mean value, $\overline{\theta}$, where $\overline{\theta} = \frac{\theta_{11} + \theta_{21}}{2}$	$\overline{a}$	m³/kg
11.1.10	Mean value of c_p[6]		$\overline{c}_p$	J·kg⁻¹·K⁻¹
11.1.11	Mean value of V_m[6]	Value of V_m corresponding to the mean value $\overline{p}$ and to the mean value $\overline{\theta}$ where: $\overline{p} = \frac{p_1 + p_2}{2}$ and $\overline{\theta} = \frac{\theta_1 + \theta_2}{2}$	$\overline{V}_m$	m³/kg
11.1.12	Shaft power	Shaft power corresponding to mechanical energy per unit mass $P_m = \varrho_2 q_V E_m = q_m E_m$	P_m	W

[1] Use of the term "energy per unit mass" is considered to be preferable to "energy per unit weight" because it offers a more general meaning. Nevertheless, energy per unit weight (i.e. specific head for the installation considered) can be used as a basis. Conversion of numerical values expressing energy per unit mass into head is ensured by dividing the former by g, the mean value for acceleration due to gravity between the extreme levels of the installation.

[2] Under experimental conditions allowing the thermodynamic method to be used, it can normally be assumed that $\alpha_{a1} = \alpha_{a2} = 1$ (see 8.1.1.1).

[3] Values for $\varrho \left(= \frac{1}{V_m}\right)$ are given in table 16.

[4] Values for a are given in table 15.

[5] Values for c_p are given in table 17.

[6] Fractional error in E_m and E_h attributable to the adoption of mean values $\overline{a}$, $\overline{V}_m$ and $\overline{c}_p$ instead to exact integrals [for pressures between 0 and 300 bar (30 MPa) and temperatures between 0 and 150 °C] does not exceed $0{,}4 \times 10^{-3}$.

11.2 Principle

The thermodynamic method results from the application of the principle of conservation of energy (first law of thermodynamics) to a transfer of energy between water and the machine through which it is flowing.

In the case of actual machine operation, the energy per unit mass received by water from a pump shaft may be determined by measurement of the performance variables (pressure, temperature, velocity and level) and from the thermodynamic properties of water. This exchange of energy will be referred to as "mechanical energy per unit mass" (see 11.1.2 and 11.4).

In the case of ideal operation (100 % efficiency), i.e. frictionless flow, the same application can be used for calculating the ideal energy per unit mass received from a pump shaft. Such energy is dependent solely upon the properties of the water and the characteristics of the plant. It is referred to as "hydraulic energy per unit mass" (see 11.1.1 and 11.5).

The need to measure mass rate of flow, which is a difficult and expensive measurement, is eliminated by using the two values of energy per unit mass calculated as above. (Inversely, using the thermodynamic method together with measuring the power input may allow to determine the flow rate without its direct measurement is needed.) An assessment of the flow rate is sufficient for calculating kinetic energies in section 1 and section 2 and secondary corrective terms. A procedure by trial and error can be used, if required, to reduce the uncertainty on flow rate.

The above principle presupposes that all losses in hydraulic machines are dissipated in the main flow. Generally, friction losses in the seals and bearings are dissipated differently and a corresponding correction shall be made to mechanical energy per unit mass (see 11.3.1).

The determination of the hydraulic energy per unit mass uses the computation of the integral $\int V_m \, \mathrm{d}p$ (see 8.1.1.2).

In practice, there are two ways to calculate this integral from the thermodynamic properties of water :

1) $\int_1^2 V_m \, \mathrm{d}p = \overline{V}_m (p_2 - p_1)$

2) $\int_1^{2S} V_m \, \mathrm{d}p = h_{2S} - h_1$

In the range of normal efficiency for pumps covered by this International Standard and in the range of pressures and temperatures defined by the tables given in annex C, the difference between these two calculations is not significant. The approximation $\overline{\theta} = \theta_1$ may similarly be made.

11.3 Correction energy terms

11.3.1 Particular flow arrangements

The equation for the mechanical energy per unit mass, E_m, in table 9 relates to the very simple case where the machine comprises only a single inlet and a single outlet of water. In fact, there can be the following supplementary inlets and outlets :

- leak-off at the balance disc;
- injection into the seals;
- extraction from the seals;
- leak-off at the seals.

It is then convenient to break down the fluid flow into a number of elementary circuits, i, each of them having one inlet (subscript e) and one outlet (subscript s). The correction term ΔE_m to be introduced is then given by the equation

$$\Delta E_\mathrm{m} = \sum_i \varphi_i \left[h_{si} - h_{ei} + \frac{U_{si}^2 - U_{ei}^2}{2} + g\,(z_{si} - z_{ei}) \right]$$

where the difference between enthalpy h_s at the outlet and enthalpy h_e at the inlet is determined from pressure and temperature measurements, either by means of the tables or basic formulations, or by the equation

$$h_\mathrm{s} - h_\mathrm{e} = \overline{a}\,(p_\mathrm{s} - p_\mathrm{e}) + \overline{c}_p\,(\theta_\mathrm{s} - \theta_\mathrm{e})$$

and where φ_i is the ratio of the mass flow rate, q_{mi}, of the circuit involved to the main outlet mass flow rate q_{m2}.

$$\varphi_i = \frac{q_{mi}}{q_{m2}}$$

This calculation takes strictly into account all the frictions between the fluid and the pump shaft at the balance disc or at the seals.

It should be noted that the energy per unit mass corresponding to the losses in the bearings is given by the equation

$$E_\mathrm{x} = \frac{q_{m\mathrm{h}}}{q_{m2}} c_{p\mathrm{h}}\,(\theta_\mathrm{s} - \theta_\mathrm{e})$$

where

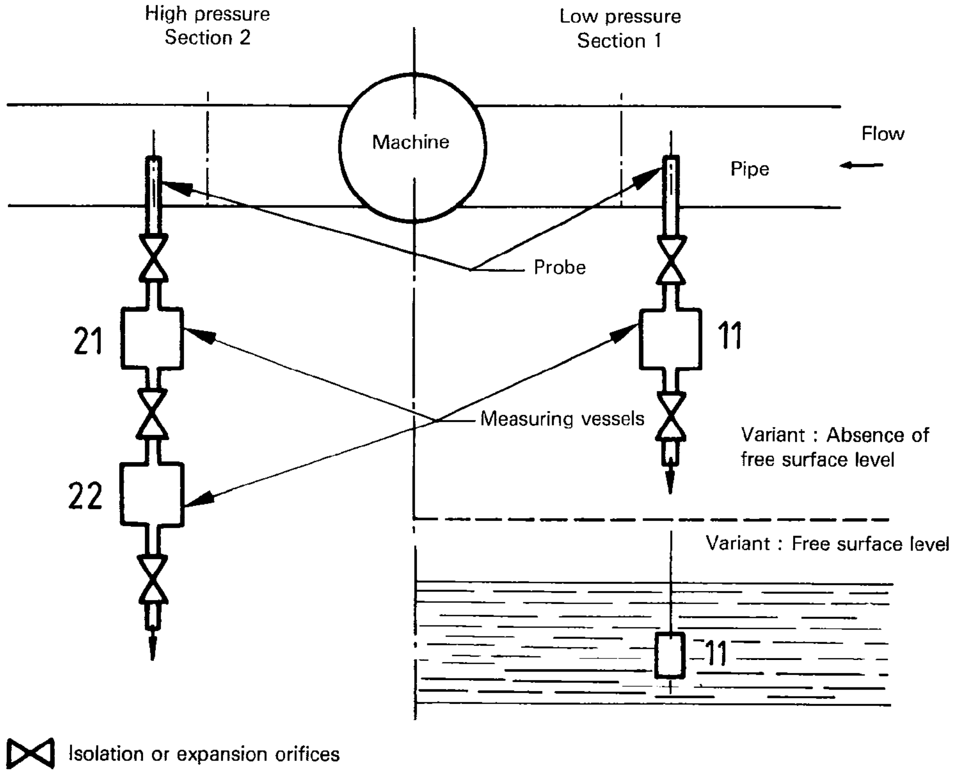
$q_{m\mathrm{h}}$ is the mass flow rate of the oil supplying the pump bearings;

$c_{p\mathrm{h}}$ is its specific heat capacity.

An example of decomposition of the fluid flow in the case of a feed pump of vapour thermal cycle is shown in figure 23 b). The correction energy term ΔE_m and the loss in the bearings E_x are indicated in the legend.

11.3.2 Heat transfer with the surroundings through the walls

Only heat transfers where the water pumped is involved are dealt with here.



NOTE — For use of one or other of the operating procedures for determining mechanical energy per unit mass, see 11.4.

Figure 21 — General schematic diagram of measuring vessels

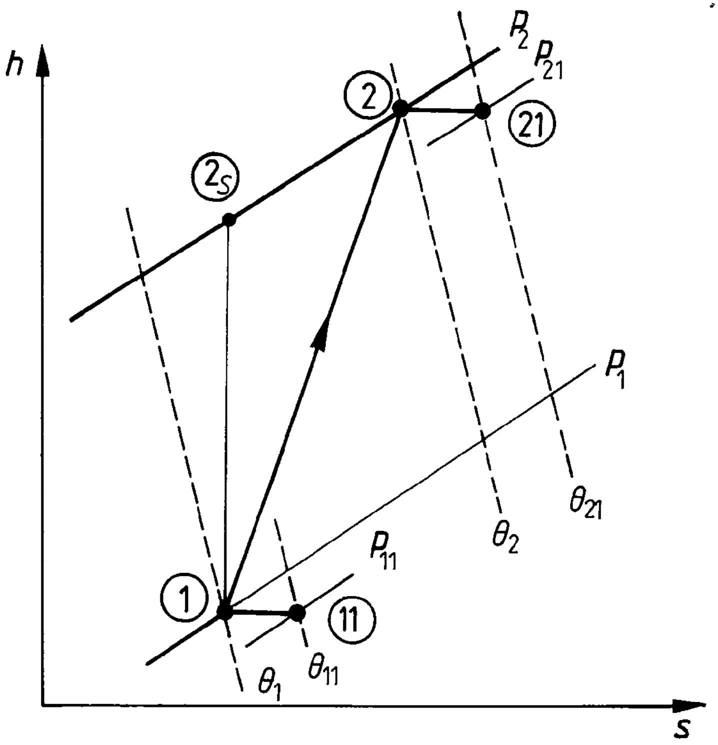
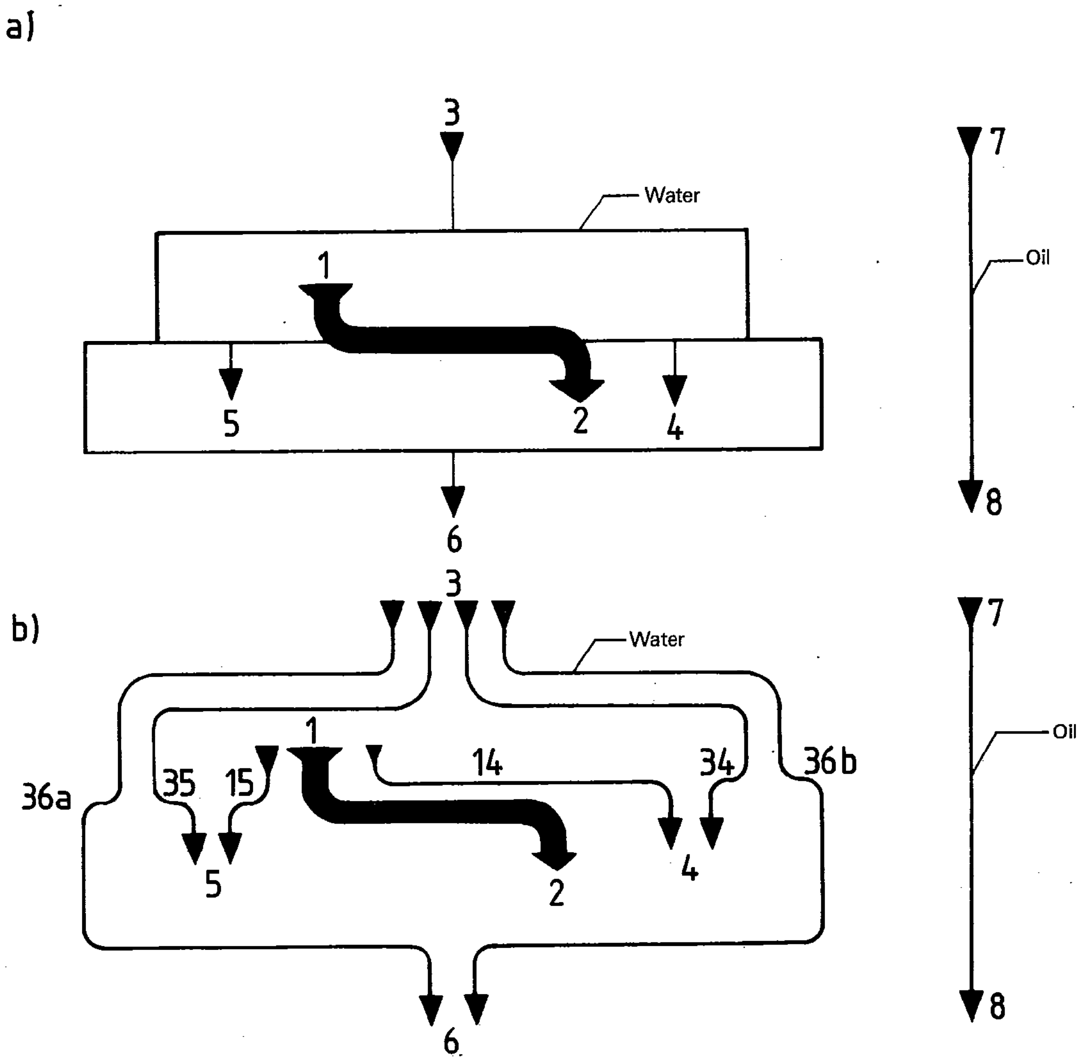


Figure 22 — Enthalpy (h) - entropy (s) - thermodynamic diagram for water



1 pump suction
2 pump discharge
3 injection into the seals
4 leak-off at the balance disc and extraction from the seals HP
5 extraction from the seals BP
6 leak-off at the seals
7 bearings oil inlet
8 bearings oil outlet

Correction energy terms and loss in the bearings, the variations of kinetic and potential energy being neglected:

$$\Delta E_m = \varphi_{14}(h_4 - h_1) + \varphi_{15}(h_5 - h_1) + \varphi_{34}(h_4 - h_3) + \varphi_{35}(h_5 - h_3) + \varphi_{36}(h_6 - h_3)$$

$$E_x = \varphi_{78}(h_8 - h_7)$$

where

$$\varphi_{ij} = \frac{q_{mij}}{q_{m2}}$$

$$\varphi_{36} = \varphi_{36a} + \varphi_{36b}$$

Figure 23 — Example of decomposition of the fluid flow in a pump
(case of a boiler feed pump of vapour thermal cycle)

The heat transfers through the metal walls give rise to the following correction

$$\Delta E_{\mathrm{m}} = \frac{1}{q_{m2}} P' A (\theta_{\mathrm{e}} - \theta_{\mathrm{a}})$$

where

P' is the power, expressed in watts per square metre per kelvin, exchanged; from experience, P' is considered equal to 10 $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$;

q_{m2} is the mass flow rate, expressed in kilograms per second, of the water;

A is the area, in square metres, of the exchange surface;

θ_{a} is the temperature, in degrees Celsius, of the ambient air;

θ_{e} is the temperature, in degrees Celsius, of the water in the pump.

If there is considerable dripping, the resulting increase of heat exchange (in practice always less than about four times) shall either be calculated from the air and water temperatures and the relative air humidity or efficiently depressed by sufficient heat insulation of the metal surfaces by screening jackets.

Calculation of condensation influence can be made with sufficient accuracy by increasing the correction ΔE_{m} for the "dry" heat exchange in the proportion ψ given by the equation

$$\psi = \frac{1}{1 - 2\,490\, \Delta x / \Delta h}$$

where

Δh is the air enthalpy difference, expressed in kilojoules per kilogram;

Δx is the difference in relative water content of the air, expressed in kilograms per kilogram.

The differences are between the condition of the humid air surrounding the pump and that of the saturated air at the metal surface temperature and shall be taken from a normal Mollier diagram for humid air.

11.3.3 Instability of energy at inlet

It is recommended that any inflow of water or energy to the inlet conduit (for example a conduit near a heat source) should be avoided. Moreover, if the same conduit supplies several units, the operating point of the pumps not under test shall be maintained constant.

A slow and continuous variation of temperature of less than 0,005 K/min during one test is admissible. Nevertheless, a suitable correction shall be applied to E_{m} according to the equation

$$\Delta E_{\mathrm{m}} = \bar{c}_p \frac{\mathrm{d}\theta}{\mathrm{d}t} (t - t_1 + t_2)$$

where

$\bar{c}_p$ is the mean specific heat capacity at constant pressure, expressed in joules per kilogram per kelvin;

$\mathrm{d}\theta/\mathrm{d}t$ is the temperature gradient, expressed in kelvins per second;

t is the transit time, in seconds, of water between the inlet and outlet sections of the machine;

t_1 is the transit time, in seconds, of drawn-off water between the inlet section and measuring vessel;

t_2 is the transit time, in seconds, of drawn-off water between the outlet section and measuring vessel.

The cyclic variations of temperature which may be observed in the boiler feed pumps of thermal power stations can reach 0,05 K/min. In such cases, to avoid a large measurement error, measurements shall be taken at intervals of about 1 s.

11.3.4 Limitation of corrections

Measurements shall be considered non-valid whenever the corrections obtained from the measuring procedures or calculations given in 11.3.2 and 11.3.3 exceed the following limits in relation to E_{m}:

a) heat exchange between water in the measuring circuit and surroundings (see 11.3.2) at inlet or outlet: 1 %;

b) sum of the corrections detailed in 11.3.2 and 11.3.3: 1,5 %.

11.4 Procedure for measurement of mechanical energy per unit mass

11.4.1 General

The main difficulty to be overcome in determining the mechanical energy per unit mass lies in the accurate determination of the mean fluid temperatures on both sides of the pump.

It can however be noted that, when the diameters of sections 1 and 2 are similar, the absolute measurement errors do not have a great effect upon the determination of the temperature difference, as long as the measuring probes are of identical design and are similarly set up.

On the other hand, when the diameters of the sections 1 and 2 are very different, the velocities U_1 and U_2 are different and a differential heating may bias the probes. Then it is necessary to apply a correction to take this effect into account at least when the pump total head is low.

Moreover, the flows in conduits being turbulent ones, it is necessary to establish the temperature profiles in the measuring sections in order to determine the mean temperatures of the fluid.

When the temperature difference between inlet and outlet of the pump is sufficiently high, the energy E_m is determined by direct measurements by means of probes mounted in the flow. In this case, pressures p_{11} and p_{21} and temperatures θ_{11} and θ_{21} used in 11.1.2 for the definition of E_m are simply substituted by p_1, p_2, θ_1 and θ_2.

In case of difficulty in carrying out direct measurements in the flow with the required accuracy, the energy E_m is determined by indirect measurements by means of specially designed vessels with tappings for determination of pressure and temperature (see 11.6.2). When the measuring sections are under pressure, the procedure consists of extracting a sample flow, generally of between 0,1 and 0,5 dm^3/s, by a total head probe. The water thus extracted is led to the measuring vessel through an insulated pipe to ensure that the heat exchange with the exterior, estimated in accordance with the procedure described in 11.3.2, gives rise to a correction not exceeding the limit fixed in 11.3.4. This sampling is valid if the recommendations given in 11.6.2.1 regarding extraction points are followed.

The $U^2/2$ and gz terms are of minor importance and their determination calls for no particular remarks. It should be noted that levels z_{11} and z_{21} are those of the middle points of the measuring vessels. Pressure values are expressed with reference to these levels. U_{11} and U_{21} are similarly measured in the vessels.

Other terms defining E_m shall be determined by one of the operating procedures described in 11.4.2 to 11.4.5 which are practical variations of the method. The selection of operating procedure should be based upon machine characteristics and the quality of measuring apparatus available.

At pump inlets, it may be useful, depending upon the selected operating procedure, to reduce water pressure within the measuring vessel to atmospheric pressure.

11.4.2 "Without expansion" operating procedure

This procedure may be used when the temperature difference between inlet and outlet of the pump is sufficiently high.

It brings into play either direct measurements by means of probes mounted in the flow, or indirect measurements by means of vessels supplied by water extractions with minimum expansion between pipe and vessel.

If the enthalpy calculation is not accurate enough, the terms for E_m given in 11.1.2 are determined as follows:

$\bar{a}(p_{21} - p_{11})$	requires a precision manometer (see 11.6.1.2); values of a are given in table 15 (annex C);
$\bar{c}_p\,(\theta_{21} - \theta_{11})$	requires measurement of $\theta_{21} - \theta_{11}$ with requisite accuracy (see 11.6.1.1); values of c_p are given in table 17 (annex C).

The thermometer plays a very important role in this procedure. It shall be very sensitive and reliable, and calibrated beforehand. Whenever this procedure is adopted, "partial expansion" procedure (see 11.4.3) for one test point or *in situ* calibration of the thermometer will be undertaken for checking purposes (see 11.4.6).

$(\theta_{21} - \theta_{11})$ and $(p_{21} - p_{11})$ shall be measured simultaneously and at regular intervals.

The temperature difference between the inlet and outlet of the pump shall be determined to within 0,020 °C when this difference is greater than or equal to 3 °C. It shall be determined to within at least 0,005 °C when this difference is less than or equal to 1 °C.

11.4.3 "Partial expansion" operating procedure

This procedure may only be used when the pressure at the pump inlet is sufficient to ensure that the temperature of the water expanded to atmospheric pressure in the measuring circuit is at least equal to that of the water at the pump outlet.

An expansion valve is located in the sampling circuit between the inlet pipe and the corresponding measuring vessel. The adjustment of the valve should be very fine and stable such that, by partial expansion, temperature equality is achieved in the measuring vessels at the intake and outlet. Thus, in the expression for E_m, the term $\bar{c}_p\,(\theta_{21} - \theta_{11})$ becomes zero and the determination of E_m essentially entails the measurement of $(p_{21} - p_{11})$ with an accurate manometer (see 11.6.2.2). The thermometer shall be highly sensitive and reliable (see 11.6.2.3). Its purpose is to record temperature equality. In practice, it is desirable to establish graphically the correspondence between $(p_{21} - p_{11})$ and $(\theta_{21} - \theta_{11})$. As often as not, p_{11} is practically invariant and only p_{21} need be measured. The pressure value used for calculation is that obtained by graphical extrapolation for a nil difference of temperature.

In all cases where temperature equality cannot be obtained, it is possible to work by graphical extrapolation provided that the range of pressure involved by extrapolation is small compared with the pressure range accurately measured.

11.4.4 "Auxiliary expansion" operating procedure

This procedure is a variant to that described in 11.4.3. But, in contrast, it may be used even if the pump inlet pressure is insufficient.

The pressure p_{11} corresponding to the equality of temperatures θ_{11} and θ_{21} is not measured, but determined on the basis of a comparative expansion of the outlet extracted water in such a way that the temperature variation of the expanded water is equal to that of the water crossing the machine (deviation method).

11.4.5 "Total expansion" operating procedure

This procedure is used mainly when the pump inlet pressure is equal to the atmospheric pressure.

An expansion valve is located in the sampling circuit between the outlet pipe and the corresponding measuring vessel. The adjustment of the valve allows the water expansion until a pressure equal to that at the pump inlet. Thus, in the expression for E_m, the term $\bar{a}\,(p_{21} - p_{11})$ becomes zero and the determination of E_m essentially entails the measurement of $(\theta_{21} - \theta_{11})$.

This operating procedure is generally less accurate because the measurement of the temperature is more difficult than the measurement of the pressure. Moreover, c_p is less well-known.

11.4.6 Expansion procedure for differential thermometer calibration

Two thermometric gauges are placed in two vessels separated by an expansion valve through which water flows after having been withdrawn from the conduit. As the efficiency of the whole of the expander unit is zero, the transfer of mechanical energy per unit mass is zero and thus

$$E_\mathrm{m} = \bar{a}\,(p_{21} - p_{22}) + \bar{c}_p\,(\theta_{21} - \theta_{22}) + \\ + \frac{U_{21}^2 - U_{22}^2}{2} + g\,(z_{21} - z_{22}) = 0$$

or

$$\theta_{22} - \theta_{21} = \frac{\bar{a}\,(p_{21} - p_{22}) + [(U_{21}^2 - U_{22}^2)/2] + g\,(z_{21} - z_{22})}{\bar{c}_p}$$

Thus, the difference in temperature between the two vessels is known and the thermometer may be calibrated for use in the operating procedures described in 11.4.2.

For this procedure, it is essential that expansion shall be progressive and stable, the vessels be perfectly thermally insulated from the exterior, suspended material content in the water shall not exceed 0,1 g/dm^3 and that dissolved gas content shall be below the saturation point. If the expander operation is satisfactory, the calibration is kept when the thermometric gauges are inverted.

11.5 Determination of hydraulic energy per unit mass

This energy per unit mass is represented by the expression given in 11.1 and is determined by separate measurement of the $U^2/2$ and gz terms, and by determining $\overline{V_m}\,(p_2 - p_1)$ or $(h_{2S} - h_1)$. (See 11.2.)

Conditions governing the measurement of p_1 and p_2 are given in 8.4, and g values are given in table 1.

11.6 Measuring apparatus — Recommendations for use

11.6.1 Direct measurements

11.6.1.1 Measurement of main temperatures

11.6.1.1.1 Thermometers directly immersed in the fluid

As far as possible, the thermometers shall be directly immersed in the fluid. Their design shall take into account the characteristics of the fluid and the dynamic solicitations and resonance phenomena liable to involve their breaking. They shall be located far from any pipe irregularity.

Where the temperature distribution at pump inlet and outlet has to be determined, the thermometers shall be in pairs and their settings identical.

11.6.1.1.2 Thermometers protected by thermometric pockets

As fluid pressures are generally high, thermometric probes are often placed in thermometer pockets.

The thermometer pockets and the external insulation of bosses and thermometers shall be identical in pairs in order to eliminate the possible errors in the determination of temperature differences.

For point measurements, care shall be taken to ensure thermal contact between the thermometer end and the pocket bottom, if possible using a support spring.

For exact temperature measurements, the pocket may be filled with a liquid having good thermal properties (water, oil, silicone, etc.).

11.6.1.1.3 Number of temperature measuring points — Temperature distribution

The mean temperature, θ_m, of a fluid of approximately constant density in a cross-section of area A is given by the equation

$$\theta_\mathrm{m} = \frac{\int \theta v_x \,\mathrm{d}A}{\int v_x \,\mathrm{d}A}$$

where v_x is the axial component of the local velocity in the element of section dA.

When the Prandtl number (see 4.1.13) is close to unity and for a small temperature difference between the centre and the wall of the pipe, the velocity and temperature distributions can be considered identical, to a first approximation.

Under such conditions, the value of θ_m can be expressed as the arithmetic mean of the temperatures taken at a given number of points of the profile provided these points are located at well-defined distances, r, from the pipe axis. Thus, for Reynolds numbers greater than 6 000, table 10 gives the ideal positions of the probes when their number varies from one to five.

Table 10 — Ideal positions of probes

Number of probes	Distance from centre as a fraction of radius, r/R
1	0,72
2	0,46; 0,86
3	0,37; 0,67; 0,91
4	0,34; 0,57; 0,75; 0,93
5	0,27; 0,47; 0,70; 0,80; 0,94

For flow measurements by the velocity area log-linear method, slightly different positions as defined in table 11 have been proposed. By experience, it appears that the difference between mean temperatures calculated in both cases has practically no influence on the test results.

Table 11 — Positions of probes (velocity area log-linear method)

Number of probes	Distance from centre as a fraction of radius, r/R
2	0,42; 0,81
3	0,36; 0,73; 0,94
4	0,31; 0,63; 0,77; 0,96
5	0,28; 0,57; 0,69; 0,85; 0,96

11.6.1.1.4 Types of thermometer

Any sensitive and accurate thermometer can be used for the thermodynamic method provided its calibration and stability ensure the desired accuracy in the measurement of the temperature difference. It is recommended to use a differential thermometer.

This sensitivity and this accuracy shall be between 0,001 °C and 0,020 °C according to the pump total head and the temperature of the water.

They should not be unstable over a range of ± 5 °C about the mean temperature to be measured. This property shall be checked before and after each test.

Measurements have been made with thermocouples, thermistors and quartz thermometers, but resistance thermometers are mostly used.

If measurements are made far from the pump, the resistance thermometers should be of the four wire type to eliminate the resistance of connecting wires in an appropriate bridge mounting.

Special care should be taken, in connecting the wires to the thermometer and measuring bridge, to minimize electromotive contact forces. An a.c. or d.c. bridge can be used provided the direction of current is reversed for each measurement (automatically if possible) in the latter case.

Thermocouples are suitable for measurement of the average temperature by series mounting. Such mountings cannot be used, however, to evaluate energy space instability.

A high speed data acquisition system overcomes the possibility of neglecting possible fluid temperature slidings.

11.6.1.1.5 Thermometer calibration

A calibration accuracy of a few thousandths of a Celsius degree is difficult to obtain, but it is generally sufficient to proceed to relative calibration of the thermometers with respect to each other by comparison in a limited range and, if possible, to group them in pairs.

The stability and homogeneity of calibration baths, of the element of comparison and of the measuring bridge performance shall correspond to the desired measuring accuracy. Each measurement shall be repeated at least once.

11.6.1.2 Pressure measurements

The precision manometer used shall allow an assessment of pressure to an accuracy of at least 0,1 %.

11.6.1.3 Auxiliary measurements for estimation of correction terms

Measurements of temperature, flow rate or pressure in auxiliary circuits do not require as high an accuracy as the previous measurements. For example, calibrated thermocouples can be used for temperature measurements, and differential pressure devices, turbine meters, volumetric tanks, etc., for flow measurements.

11.6.2 Indirect measurements

11.6.2.1 Main measurements

11.6.2.1.1 Sampling water circuits

Water samples from the conduit shall be taken by means of a sampling probe fixed perpendicular to the conduit and protruding into the conduit. This probe shall have a perfectly smooth orifice at its end, of diameter equal to the internal diameter of the probe and pointing upstream. The distance of this orifice from the internal wall of the conduit shall be at least 0,05 m and if possible 0,28 *R* (see 11.6.1.1.3).

At least two sampling points shall be provided, away from any disturbance, up to 1 m in diameter and more for bigger conduits. The depth of the various probes may vary. A mean sampling may also be made by mixing samples taken at various points.

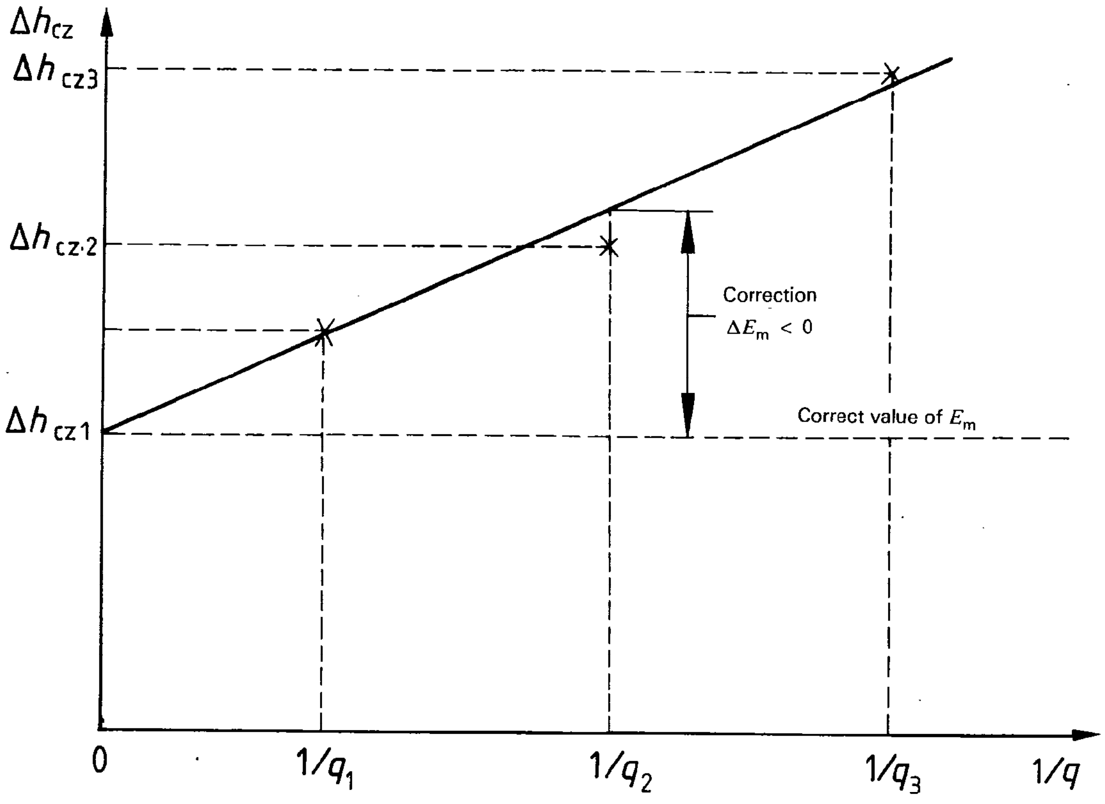
The probe shall be designed to avoid vibration and rupture and marked such that the orifice can be correctly orientated and identified.

The external diameter of the probe in the vicinity of the sampling holes may be chosen in the range 15 to 40 mm, the internal diameter being at least 8 mm. In order to ensure sufficient mechanical strength, the external diameter may be increased gradually towards the wall provided it does not affect the flow essentially.

NOTE — The measuring vessels should be designed so that the kinetic energy of water is converted into pressure energy and that good mixing occurs before the flow passes around the thermometer pockets. Particular construction arrangements are necessary to avoid, as far as possible, heat transfer at the walls of these pockets or by the connecting wires: for example the wires shall be in contact with the walls under the insulation of the vessels.

The expansion orifices shall ensure a high degree of flow stability and when adjustable shall ensure steady progressive variation in discharge.

All the active elements of the sampling circuits (pipes, expanders, vessels) shall be carefully insulated so that the sampling flow is of constant total enthalpy; imperfections in



q is the sampling flow common to all efficiency test points

NOTE — The figure is drawn in the case of heat transfer from the surroundings to the circuit. In the opposite case, the slope of the line should be negative.

Figure 24 — Example of graphic determination of the correction ΔE_m to allow for heat transfer in a sampling circuit

the thermal insulation shall be taken into account by the following procedure:

a) it is assumed, as a first approximation, that the rate of heat exchange with the exterior is constant, so that the value of total enthalpy Δh_{cz} varies linearly with the inverse value of the sampling flow rate;

b) this quantity Δh_{cz} shall be measured for at least three sampling flow rates;

c) a graph of Δh_{cz} as a function of the inverse of the flow rate permits, by interpolation, determination of the correction ΔE_m required to allow for heat transfer (see figure 24).

This check shall be made for all points of the efficiency curve. However, if the correction is less than 0,2 % of E_m, the number of measuring points for which these auxiliary measurements shall be made may be reduced by mutual agreement.

It is recommended that the probe be checked in the following manner, as rupture is always possible, but difficult to see. The total pressure measured in the vessel, considering the probe as a total pressure tapping (when its orifice is located at a distance from the nearest wall equal to about 1/7 of the pipe diameter and with no sampling flow), shall be compared with the sum of the static pressure measured at the wall plus the dynamic pressure, $\varrho(U^2/2)$, measured in the pipe. Any significant difference shall be considered as abnormal.

11.6.2.1.2 Pressure measurements

The manometer used shall permit direct reading of pressure with an accuracy of about 0,1 %. It is recommended that the same manometer shall be used for measuring E_m and E_h to minimize the effect of systematic error of the manometer.

11.6.2.1.3 Temperature difference measurements

The thermometer used shall directly indicate the temperature difference between measurement points. It shall be sensitive and accurate to at least 0,001 °C.

11.6.2.2 Auxiliary measurements

It is necessary to provide an apparatus to check the sampling flow with an accuracy of about 5 %.

The temperature of the water drawn off shall be continuously monitored by thermometers of at least ± 0,05 °C accuracy. The use of a recorder is recommended.

11.7 Accuracy of measurements

11.7.1 Random errors and systematic errors

Errors arising in determining each quantity which occurs in efficiency calculations include random components, the uncertainty of which at 95 % confidence level can be determined, and systematic components, for which only a maximum value can be estimated. Nevertheless it is admissible to treat these errors as if they were all random errors, by associating the systematic errors with an uncertainty equal to half the maximum estimated range of the error. For more details, see ISO 5168.

11.7.2 General expression of uncertainty in efficiency

The relative uncertainty, $\delta\eta/\eta$, in efficiency is obtained from the root mean square of the relative uncertainties in the numerator and denominator of the efficiency expressions given in 11.1.5. Disregarding the error in E_x in these expressions gives

$$\frac{\delta\eta}{\eta} = \left[\left(\frac{\delta E_h}{E_h}\right)^2 + \left(\frac{\delta E_m}{E_m}\right)^2\right]^{1/2}$$

The relative uncertainties in hydraulic and mechanical energy per unit mass themselves arise from several sources :

- determination of the main quantities involved in E_h and E_m;
- determination of corrections allowing for secondary phenomena in the calculation of E_m.

For more detailed information on analysis, propagation and evaluation of these errors, see annex C.

As a guide, it may be assumed that the uncertainty in efficiency measurement carried out by experienced staff in satisfactory experimental conditions lies between 0,5 to 1 %, if the pump total head exceeds 100 m. This limit may be lower if the uncertainty given in table 7 is agreed.

12 Cavitation tests

12.1 General

12.1.1 When a contract specifies a (NPSH) a test may be conducted to verify that the (NPSH) required by the pump is equal to or less than the specified (NPSH).

Whilst primarily the object of cavitation tests specified in this International Standard is the verification of certain performance guarantees, it is recommended that the same principles and methods be applied for research tests.

12.1.2 Cavitation tests will in most cases be conducted with clean cold water. Cavitation tests in water cannot accurately predict the behaviour of the pump with liquids other than clean cold water.

The following methods are for liquids for which the vapour pressure is single-valued. Mixed hydrocarbons and other liquids where vapour pressures cannot be defined by a single value at the test temperature are excluded.

Cavitation may affect the behaviour of a pump in several ways. It may cause noise, vibration, material damage and alteration of performance, as defined by changes of head, rate of flow, efficiency, etc.

In no case shall the cavitation tests be used to ensure that the pump will be free from cavitation erosion during its service life.

Measurements not relating to the hydraulic performance of the pump such as noise and vibrations are not covered by this International Standard.

Assessments of cavitation performance shall be made on a head drop or efficiency drop basis at a given rate of flow or on a drop in rate of flow or efficiency basis at a given total head.

Other methods such as cavitation visualization and sound pressure measurements which are still subject to research and not yet generally accepted, are described in annex D.

12.1.3 There are different types of cavitation tests.

12.1.3.1 A check may be made to show that the hydraulic performance of the pump is not affected by cavitation at the specified duty and (NPSH).

The pump meets the requirement if a test at a higher (NPSH) gives the same total head and efficiency at the same rate of flow.

12.1.3.2 In other cases, cavitation performance is explored more fully by reducing (NPSH) until measurable effects are noted.

This type of test may be conducted either to check the requirement of the pump or as a research test.

From such a test, the behaviour of the pump at various departures from the specified (NPSH) may be judged. For instance, the following cavitation extent may be characterized by corresponding values of the (NPSH) :

a) the beginning of performance alteration, $(\mathrm{NPSH})_d$;

b) $\left(2 + \frac{K}{2}\right)$ % reduction in total head, $(\mathrm{NPSH})_c$;

c) x % reduction in total head, $(\mathrm{NPSH})_H$;

d) x % reduction in efficiency, $(\mathrm{NPSH})_\eta$;

e) blockage of flow rate by fully developed cavitation, $(\mathrm{NPSH})_\mathrm{f}$.

If not otherwise agreed, a drop of $\left(2 + \frac{K}{2}\right)$ % in total head shall be used unless it is shown that comparisons on this basis are invalid.

In the case of multistage pumps, only the head generated by the first stage shall be considered whether actually measured or estimated.

12.2 Test installations

12.2.1 General test conditions

12.2.1.1 General characteristics of the circuit

The circuit shall be such that when cavitation appears in the pump, it shall not occur elsewhere to an extent where it affects the stability or the satisfactory operation of the installation or the measurement of the pump performance.

Cavitation or gas released by cavitation in the pump shall not affect the functioning of the instrumentation, particularly the flow measuring device.

The measuring conditions on the cavitation test rig, whether this be the same as the rig used for the determination of the efficiency curves or not, shall conform to the conditions specified in this International Standard.

The types of installations described in 12.2.2 may necessitate special flow control valves at the inlet and outlet to avoid cavitation in these items influencing results.

Cavitation in the flow through a flow control valve can sometimes be prevented by using two or more control devices connected in series or by arranging for the flow control valve to discharge directly into a closed vessel or a tank of large diameter interposed between the control and the pump inlet.

Baffles and means of extracting air from such a vessel may be needed, especially when the (NPSH) is low.

When a flow control valve is partially closed the pipe shall be full of liquid at the position of the inlet pressure tappings.

12.2.1.2 Viewing conditions

Whatever the type of circuit used, it is recommended where possible that provision be made for visual observation of the condition of the water, with particular reference to the bubble content coming into the pump, and the cleanliness both at the inlet of the pump and upstream of the flow measuring device.

12.2.1.3 Condition of the test liquid

The liquid shall be clean and clear and should not contain solid matter (see table 4).

The total gas content, including both entrained and dissolved gas of the liquid used in the test rig, should be known for the test. It shall be taken at the inlet close to the pump. Present experience in closed circuits indicates that the influence of air content on a cavitation test in water may be neglected if the total air content at standard conditions of pressure and temperature [15° C, absolute pressure 1 bar[1]], is not less than 2 parts by volume in 1 000 and if the pump works in practice with normal industrial water.

Conversely, to avoid degassing in any part of the pump, the liquid of the circuit should not be supersaturated.

De-aeration of liquid used for a cavitation test is necessary if the pump is to be used in practice with de-aerated liquid.

It is possible to examine the influence of gas content by repetition of the same test run under different gas content conditions as permitted by the test installation.

To avoid any degassing in open or closed circuits, an increase of general pressure level may be required (see 12.2.1.1).

12.2.1.4 Flow conditions

The general flow conditions specified in this International Standard, especially at the inlet of the pump, shall be fulfilled.

12.2.2 Types of installation

The following types of installations may be used.

12.2.2.1 For liquids where the error in temperature measurement produces an error in determining the liquid head equivalent to vapour pressure of less than ± 0,10 m or ± 2 % of the measured (NPSH) whichever is the higher, the installations shown in figure 25 are acceptable.

12.2.2.1.1 The pump is installed in a closed pipe loop as shown in figure 25 a) in which the pressure level or, by alteration of temperature, the vapour pressure may be varied without changing the pump head or rate of flow until cavitation occurs in the pump.

Arrangements for cooling or heating the liquid in the loop may be needed in order to maintain the required temperature, and a gas separation tank may be also required.

A liquid recirculation loop may be necessary to avoid unacceptable temperature differences in the test tank.

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[1] 1 bar = 0,1 MPa

The tank shall be of sufficient size and so designed as to prevent the entrainment of gas in the pump inlet flow. Additionally stilling screens may be needed in the tank if the average velocity exceeds 0,25 m/s.

12.2.2.1.2 The pump draws liquid through an unobstructed suction pipe from a sump in which the level of the free liquid surface may be adjusted. [See figure 25 b).]

12.2.2.1.3 The pressure of the liquid entering the pump is adjusted by means of a flow control valve installed in the inlet pipe at the lowest practical level. [See figure 25 c).]

12.2.2.2 For liquids where the error in temperature measurement is greater than that specified in 12.2.2.1, the determination of (NPSH) by direct measurement as described in 12.3.2.4 shall be used by agreement.

12.3 Determination of the (NPSH) required by the pump

12.3.1 Methods of varying (NPSH)

The tests specified in 12.1.3 can be conducted in any of the installations shown in figure 25 and 26 according to one of the different methods indicated in figure 27.

It is possible to vary two control parameters and thus keep flow rate constant during a test, but this is usually more difficult.

12.3.2 Measurement methods

12.3.2.1 Measurement of pump head, flow rate and speed of rotation

The recommended methods in clauses 7 to 9 regarding the measurement of head, outlet flow rate and speed of rotation shall be applied during cavitation tests unless otherwise agreed. For tests in accordance with 12.2.2.2, the (NPSH) shall be directly measured using a liquid column gauge.

Particular care is needed to ensure that in the measurement of flow, cavitation does not affect the accuracy of the flowmeter. Ingress of air through joints and glands should be avoided.

12.3.2.2 Measurement of gas content

Gas content measurement, a requirement of all precision class cavitation tests, may be made by any method shown to give an error in measurement of less than ± 10 % when applied to saturated water.

a) The Winkler method enables the determination by iodometry of the dissolved oxygen content of the water. It is comparatively accurate, but necessitates titrated solutions which are difficult to keep and requires sampling without re-aeration of the specimen. It only yields the value of dissolved air content by calculation.

b) The physical separation or Van Slyke method has the advantage of permitting the extraction of the quantity of air contained, whether in dissolved or occluded form, by cascading the sample under vacuum in an insulated column. The method is relatively rapid, but necessitates working on small volume samples.

c) Gas content recorders (as used in thermal power plants) permit a continuous recording of the total gas content, but must be adapted to the range of use in the laboratory where the water is usually saturated, whereas it is nearly gas-free in a thermal power plant.

NOTE — The above-mentioned methods are hardly operational industrially.

12.3.2.3 Measurement of temperature

For the installations described in 12.2.2.1, the vapour pressure of the test liquid entering the pump shall be determined with sufficient accuracy to comply with 12.3.2.5. When the vapour pressure is derived from standard data and the measurement of the temperature of the liquid entering the pump, the necessary accuracy of temperature measurement may have to be demonstrated.

The active element of a temperature-measuring probe shall be not less than one-eighth of the inlet pipe diameter from the wall of the inlet pipe. If the immersion of the temperature-measuring element in the inlet flow is less than that required by the instrument manufacturer, then a calibration at that immersion depth may be required.

Care shall be taken to ensure that temperature measuring probes inserted into the pump inlet pipe do not influence the measurements of inlet pressure.

12.3.2.4 Determination of (NPSH) by direct measurement

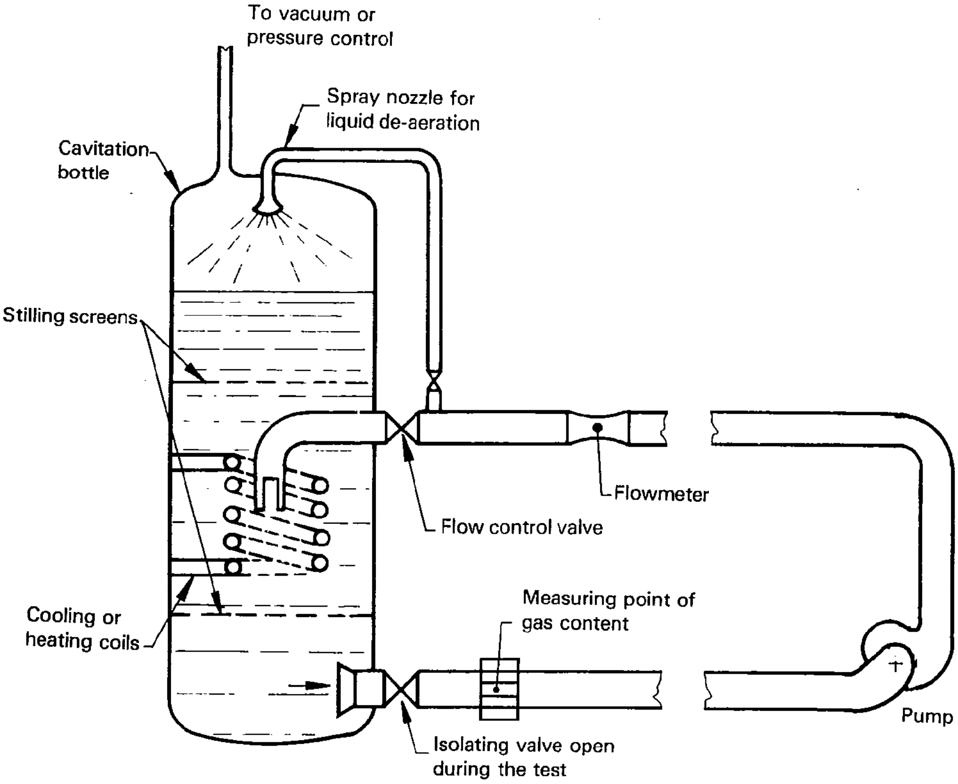
The pump is installed in a closed loop in which a free surface is maintained at vapour pressure by allowing liquid to flash into a tank in a secondary circuit (see figure 26). The (NPSH) is then measured directly on a liquid level column gauge mounted on the cavitation bottle, due account being taken of the inlet pipe head loss which, if below 0,05 m can be considered of negligible influence on the (NPSH) value being measured.

Changes in (NPSH) can be accommodated by bleeding liquid from the cavitation bottle to a separate storage tank. Care needs to be taken, however, when returning such liquid to the main circuit, and adequate mixing shall be allowed to occur so that true vapour pressure conditions are established at the free surface.

12.3.2.5 Limits of error in determination of (NPSH)

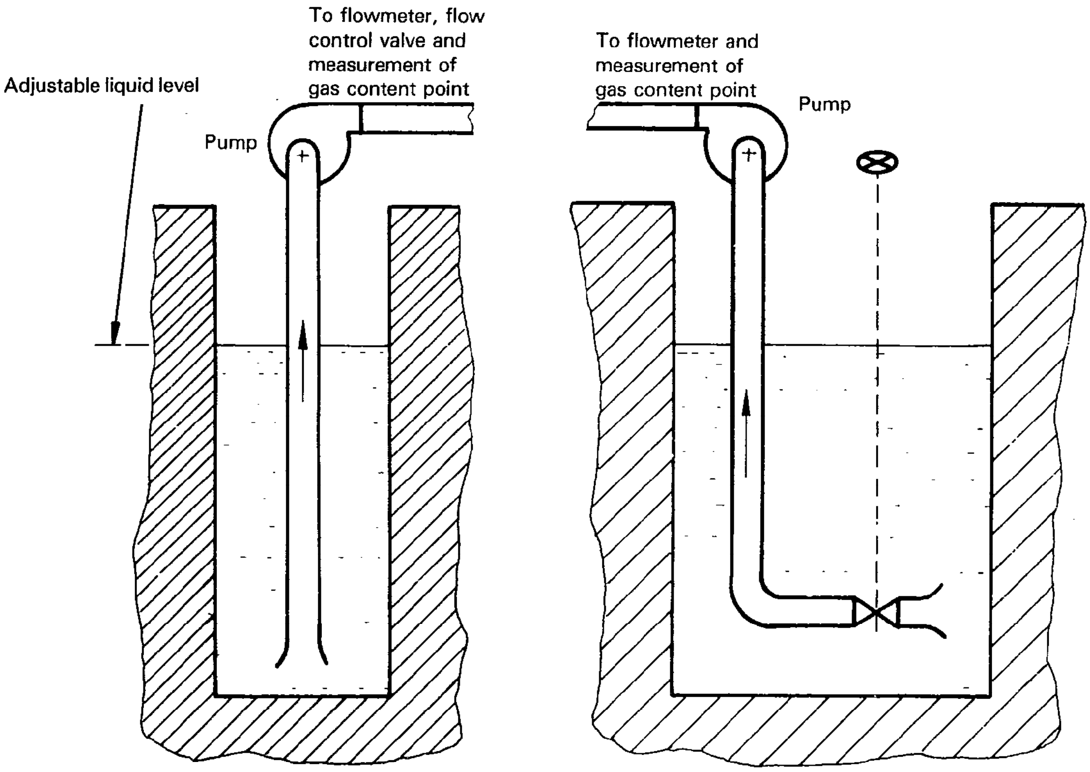
The maximum limits of error in (NPSH) measurements determined by the above methods shall be ± 3 % of the measured (NPSH), or ± 0,15 m whichever is the greater.

For (NPSH) tests with fluid temperature over the saturation temperature at ambient pressure, an exact error calculation shall be made and agreement reached between the manufacturer and the purchaser about the acceptability of the measuring uncertainties obtained.



NOTE — Cooling by means of a coil may be replaced by an injection of cool water above the liquid free surface and an extraction of heated water.

a) Variation of (NPSH) in a closed loop by control of pressure or temperature

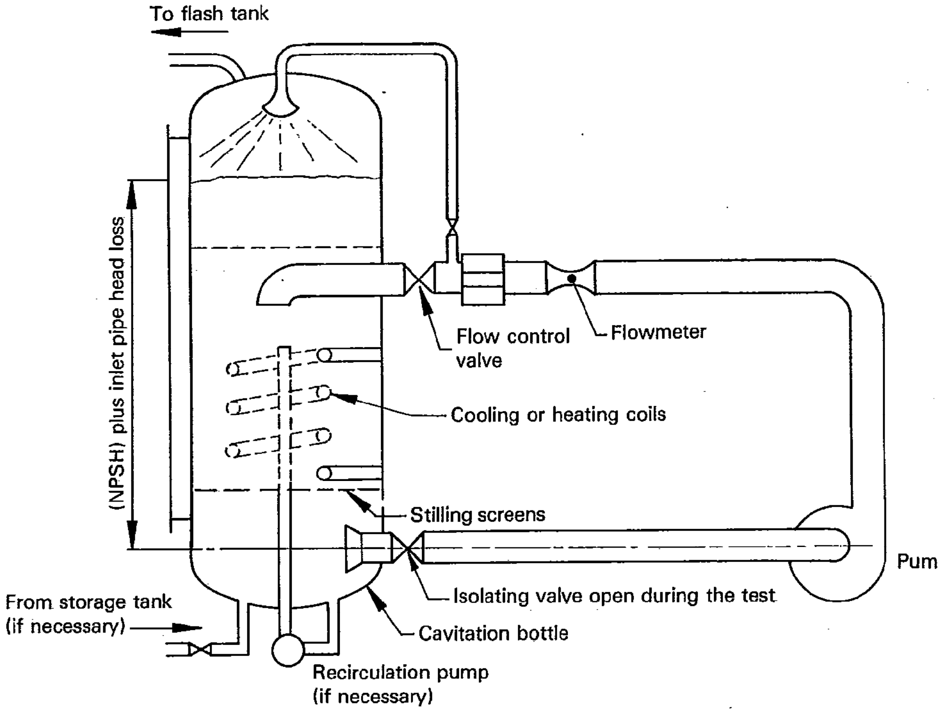


b) Variation of (NPSH) by control of liquid level at inlet

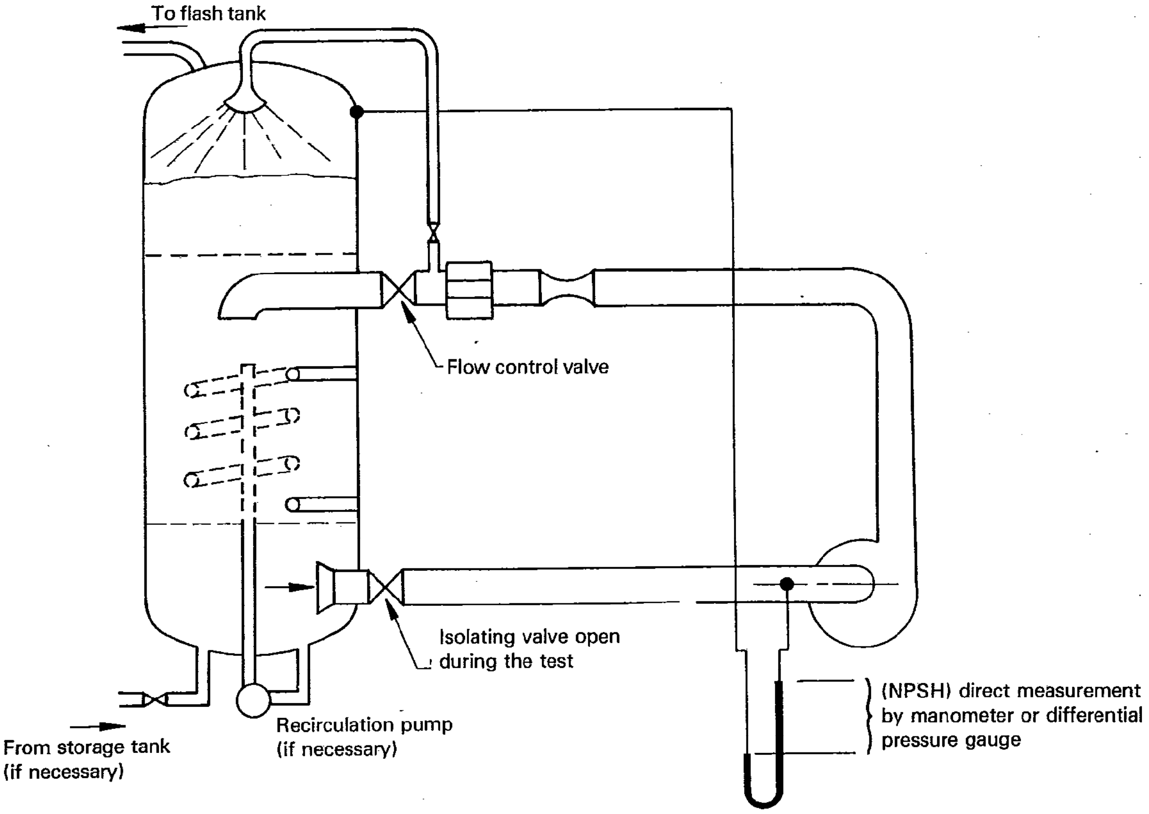
c) Variation of (NPSH) by means of a flow control valve at inlet (to avoid)

NOTE — The drawings show the principle but not full technical details.

Figure 25 — Cavitation tests



a) **Measurement method by level gauge in the cavitation tank**



b) **Measurement method by gauge manometer**

NOTE — The drawings show the principles but not full technical details.

Figure 26 — Cavitation tests — Direct measurement method
[no assessment of (NPSH) from temperature measurement]

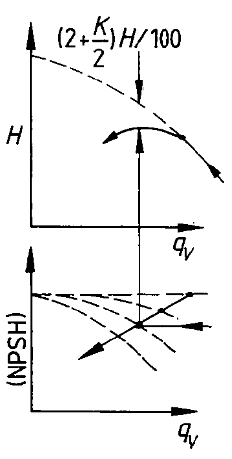
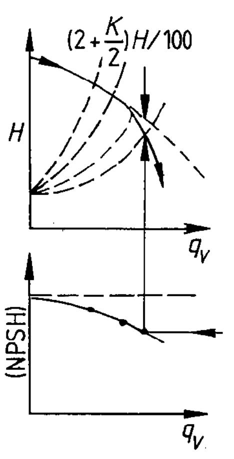
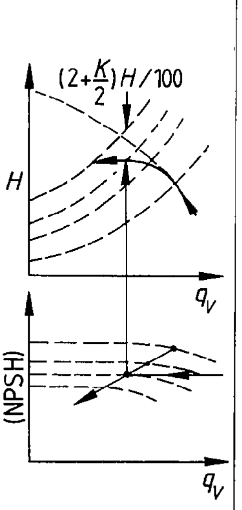
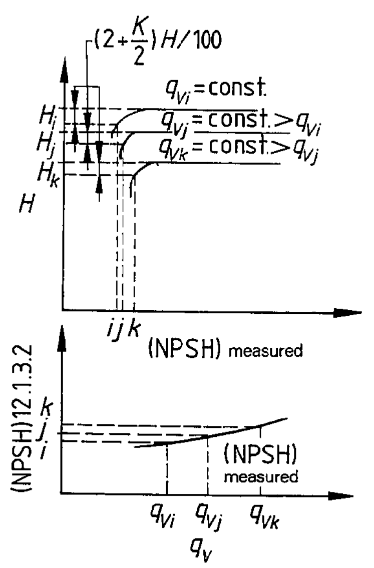
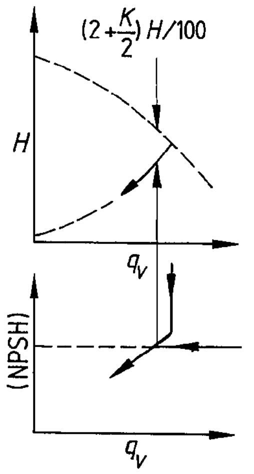
Type of installation	Open sump	Open sump	Open sump	Open sump	Open sump	Closed loop	Closed loop	Closed loop	Closed sump or loop
Independent variable	Inlet flow control valve	Outlet flow control valve	Water level	Inlet flow control valve	Water level	Pressure in the tank	Temperature (vapour pressure)	Pressure reference	Temperature (vapour pressure)
Constant	Outlet flow control valve	Inlet flow control valve	Inlet and outlet flow control valve	Flow rate	Flow rate	Flow rate	Flow rate	Inlet and outlet flow control valve	
Quantities the variation of which is dependent on control	Head, flow rate, (NPSH), water level	Head, flow rate, (NPSH), water level	Head, flow rate, (NPSH)	Outlet flow control valve (for constant flow rate), head, (NPSH)	(NPSH), head, outlet flow control valve	Heat, (NPSH), outlet flow control valve (for constant flow rate, when head begins to drop)	(NPSH), head, outlet flow control valve (for constant flow rate when head begins to drop)	Head, flow rate, (NPSH) { After onset of cavitation	
Head characteristic curve **(NPSH) characteristic curve**									

Figure 27 — Methods of determining required (NPSH) for $\Delta H/H = \left(2 + \frac{K}{2}\right)\%$

Annex A

Estimation and analysis of uncertainties

A.1 General

The degree of uncertainty in any measurement (for example the efficiency of a pump) can properly be found only by a special examination of all the sources and contributory causes of error in the test arrangement and equipment being used, and fluctuations and variations of the phenomenon being measured. It is usually not practicable to make an exhaustive study of this sort for every measurement taken, and so assessments of reliability of measurements will be more or less exact depending on the amount of evidence available and the analysis made. What is required is a conclusion that the value indicated by the measurements is unlikely to have differed from the true value by more than a stated amount.

Both systematic and random experimental errors or uncertainties shall be taken into account, and it is important to remember that observations of unsteady phenomena, such as those encountered in pump testing, are not necessarily exactly repeatable. For this reason, precision class accuracy cannot be guaranteed in advance of the tests, even with the highest standards of instrumentation and calibration. Non-repeatability of results arising from the pump and/or its installation may make it impossible, or meaningless, to represent characteristics by mean lines drawn through the scattered points.

In this case, the contracting parties shall agree on the arrangements to be made (improvement of the test conditions, of the methods, etc.).

A.2 Analysis of errors

This International Standard is mainly concerned with the measurement of the basic quantities, pump head, discharge, torque and shaft speed (or input power) at one set stable test condition at a time.

The concept of a stable test condition implies that during a test these quantities will remain virtually constant until the circuit resistance or speed is deliberately altered. To obtain the pump characteristics, pump head, input power and efficiency are plotted against flowrate, using results from a number of different test conditions. The uncertainties will change for each of these conditions, and repeated sets of readings will be taken for those points for which it is considered important to calculate uncertainties, or where a single measuring point appears to differ from the trend of measuring points taken at other conditions.

This is the normal type of pump test, and this annex deals with the method used to calculate the uncertainties of the results of each test condition studied in such circumstances.

A.3 Estimation of the uncertainty associated with random errors

If the scatter of repeated observations of the same quantity about a mean value occurs in a truly random manner, then a sufficiently large number will tend to be grouped in a pattern known as the normal or Gaussian distribution of error. Other patterns are possible, but in the absence of evidence to the contrary, random variation with the consequent normal distribution will be assumed.

If a set of n repeated observations, x_i ($i = 1, 2, 3 \ldots, n$), of the same quantity is considered, in which the normal distribution of errors occurs, then the arithmetic mean, $\overline{x}$, is given by the equation

$$\overline{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \qquad \ldots (1)$$

and the standard deviation, s, of these observations is:

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \overline{x})^2} \qquad \ldots (2)$$

As n increases, the values of $\overline{x}$ tend to approach the true mean value of the instrument readings within its fundamental limits of precision. For example if a pressure of 50 units is to be measured on a gauge with 1 unit graduations, the true mean value can be established to within approximately ± 0,5 units, but not within say ± 0,05 units for which an instrument of greater precision would have to be used.

If n were sufficiently large and the variations were normally distributed, it would be found that if, *a priori*, a certain percentage (the confidence level) of readings is required to be grouped around the mean value within certain limits (confidence interval), these limits would be related to the standard deviation s given by equation (2). As an example, if the confidence level were 95 % the odds are 19 to 1 that any single one of the observations will lie within these limits.

If the confidence level were 99 %, these limits would be much wider since 99 % of the readings would be required to lie within these limits.

For practical pump tests, a 95 % confidence level is generally accepted as providing sufficient certainty and is used throughout this International Standard. The arithmetic mean of a small number of consecutive measured values of the same quantity will, in general, differ by a greater amount from the true mean value than would the arithmetic mean of a larger number of consecutive readings.

For values of n less than 30, the assumption of a normal distribution becomes invalid; however, small (or exact) sampling theory may be applied. Student's t distribution gives the probability of the mean value of n readings lying between chosen limits $\pm\, ts/\sqrt{n}$ where t is a function on n as given in table 12, for a 95 % confidence level.

Table 12 — Values of Student's t distribution

n	t
3	4,30
4	3,18
5	2,78
6	2,57
7	2,45
8	2,36
9	2,31
10	2,26
11	2,23
12	2,20
13	2,18
14	2,16
15	2,14
16	2,13
17	2,12
18	2,11
19	2,10
20	2,09

The procedure, therefore, to determine the uncertainty at a 95 % confidence level due to the scatter of experimental results about the mean is as follows:

a) determine the mean value, $\overline{x}$, of the readings, using equation (1);

b) calculate the standard deviation, s, from the value of $\overline{x}$ so obtained, and using equation (2);

c) multiply this value of s by the appropriate value of $t/\sqrt{n}$.

The answer so obtained will indicate within what limits 95 out of 100 mean values obtained under identical conditions might be expected to lie with respect to the true mean indicated values of the instrument being used.

The random uncertainty $ts/\sqrt{n}$ is denoted by e_r.

In order, therefore, to check the random error for a single stable test condition, a number (at least three) of readings of each quantity should be made at that condition.

The readings should be synchronized, i.e. head, flow, torque and speed readings should be made simultaneously. If one or more of the readings are being time-averaged mechanically or electrically over a period (for example weightank or revolution counter), the other readings should be observed over the same period, and their average for that period recorded.

In order to restrict the number of repeated readings, it is helpful to have previous agreement between the parties to the test concerning the amount of uncertainty arising from scatter that can be tolerated. If the measurements or results are contained within a specified band, they may be accepted without further repetition or analyses.

If the agreed random error tolerance is ± ε then a permissible standard deviation can be expressed for different numbers of test points by applying the condition

$$\frac{ts}{\sqrt{n}} < \varepsilon$$

that is

$$s < \frac{\varepsilon\sqrt{n}}{t} \qquad \dots (3)$$

Values of $\sqrt{n}/t$ are given in table 13.

Table 13 — Values of $\sqrt{n}/t$

n	$\sqrt{n}/t$
3	0,403
4	0,629
5	0,804
6	0,953
7	1,080
8	1,198
9	1,299
10	1,399
11	1,487
12	1,575
13	1,653
14	1,732
15	1,810
16	1,878
17	1,945
18	2,011
19	2,076
20	2,140

The possibility exists that one reading may deviate much more widely from the mean than the remainder in the set. Suppose the value of this reading is x_r. The following test should be used to determine whether or not it may be rejected.

a) Estimate the mean, $\overline{x}$ and the standard deviation, s, for the whole set, including the suspect reading.

b) Calculate the ratio $R = (x_r - \overline{x})/s$ between the deviation of the suspect reading from the mean, $\overline{x}$, and the standard deviation, s (i.e. calculate the "number of standard deviations" by which the suspect reading differs from the mean).

Only if this ratio ("number of standard deviations") exceeds the value given in table 14 may the suspect reading be rejected. Note that if a reading is rejected, n is then reduced by 1, and $\overline{x}$ and s shall be recalculated. The final value of n shall not be less than 3.

Table 14 — Maximum permissible value of ratio R (number of standard deviations)

n	R
3	1,15
4	1,48
5	1,71
6	1,89
7	2,02
8	2,13
9	2,21
10	2,29
11	2,36
12	2,41
13	2,46
14	2,51
15	2,55
16	2,59
17	2,62
18	2,65
19	2,68
20	2,71

It is preferable, whenever possible, to estimate random errors from repeated readings at one or more selected stable test condition, as described here, rather than to try to deduce them from the scatter about a mean line of points taken from single sets of readings at a number of test conditions. Clause A.6 gives general guidance on procedures for curve-fitting.

A.4 Estimation of uncertainty associated with systematic errors

All known corrections may be applied to the value of an instrument reading taken in perfectly steady conditions without any observer error, and yet it may still differ from the true value of the quantity being measured. This residual uncertainty is called systematic error, and arises from the limitations of calibration, change of installation compared with calibration conditions, and inherent and constructional limitations of the instrument itself.

The uncertainty associated with systematic errors cannot be assessed experimentally without changing the equipment or conditions of measurement. Whenever possible this should be done since the alternative is to make a subjective judgement on the basis of experience and consideration of equipment involved.

The first step in the estimation of systematic uncertainty is to identify those aspects of the measurement that can affect its value; the second step is to allocate uncertainty limits to allow for each of these effects. For example if the independent variables (such as density, temperature, datum height, velocity head) for calculating the head, H, are denoted $X_1, X_2, ..., X_n$, then:

$$H = f(X_1, X_2, ..., X_n) \qquad \ldots (4)$$

Then the standard deviation, s_H, of H, due to the standard deviations arising from uncertainties in the individual variables, is given by:

$$s_H = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial H}{\partial X_i}\right)^2 s_{Xi}^2} \qquad \ldots (5)$$

provided the variables are mutually independent.

If f is a linear function

$$s_H = \sqrt{\sum_{i=1}^{n} s_{Xi}^2} \qquad \ldots (6)$$

and thus the confidence limits, e_s, of systematic error at a 95 % confidence level, are given by

$$e_{sH} = \sqrt{\sum_{i=1}^{n} e_{sXi}^2} \qquad \ldots (7)$$

where $e_{sH} = 1{,}96\, s_H$

In practice it is necessary to draw largely from past experience and published data to arrive at an estimate of systematic uncertainty in the measurement of any one quantity. Often it is possible to have an instrument calibrated by a recognized national authority who will include, with the calibration certificate, the uncertainty at the 95 % confidence level or the standard deviation of the results of the calibration.

Even if the instrument is calibrated locally, it must be against some secondary standard the limits of error of which must be known if the calibration is to be meaningful.

At least two calibrations are necessary, one before and one after the test, but it is preferable to have a history of a number of calibrations than to rely on only previous calibration.

Alternatively some instruments such as differential pressure flowmeters are covered by national and International Standards which give details of construction and use, together with coefficients, corrections, and uncertainties.

Values given in clauses 7 to 12 are based on experience and judgement and are the likely ranges of the systematic uncertainty, at a 95 % confidence level, for the methods employed. These should be used only as a guide for the estimation of the systematic uncertainties and read in conjunction with the appropriate clauses of this International Standard and the relevant standards for each method.

A.5 Combination of random and systematic uncertainties

There is no universally accepted method of combining random and systematic uncertainties. Although it is of value to list systematic and random uncertainties separately, this would be confusing when related to specified conditions. The overall error in any one quantity shall be obtained using the square law propagation method

$$e = \sqrt{e_s^2 + e_r^2} \qquad \ldots (8)$$

The systematic error is entirely controlled by the choice of measuring method and the characteristics of the installation, for example the value of the kinetic energy calculated using the mean velocity can differ from its true value if the velocity distribution of the measuring section is not sufficiently regular. Random error is, however, influenced by the care taken during measurement, the number of measurements taken and the site conditions.

A.6 Estimation of errors from scatter around a fitted curve

Computer programs are available for fitting curves to test data, and these may be used to advantage in a contractual situation where two or more people have interests in the interpretation of the test results.

Fitting a mathematical curve to such data imposes constraints over and above those implicit in the data, and the choice of curve itself may therefore become the subject of conflicting interests.

With a limited number of test conditions, especially if none are repeated, a complicated curve passing through each of the points may well be a worse estimate of the true mean curve than a simpler expression about which the test data are scattered.

Curve fitting for acceptance test purposes is best confined to a fairly narrow range of duties (say ± 10 %) around the condition specified for acceptance. As many repeats, or near repeats, as are technically and/or economically feasible should be made within this range. Usually it will be found that, within such a range, simple low order polynomials may be fitted, such that the fitting of a polynomial one or more order higher results in no advantage with respect to the confidence limits obtained at the specified duty point.

End conditions can be imposed on such a curve by "spline-fit" programs linking a simple curve covering one range to similar curves over adjacent ranges on either side.

If it becomes apparent that the range selected contains characteristics with inflexions, discontinuities, or other singularities, it may be necessary to narrow or shift the range so as to investigate thoroughly the true curve shape. Figure 28 gives an example.

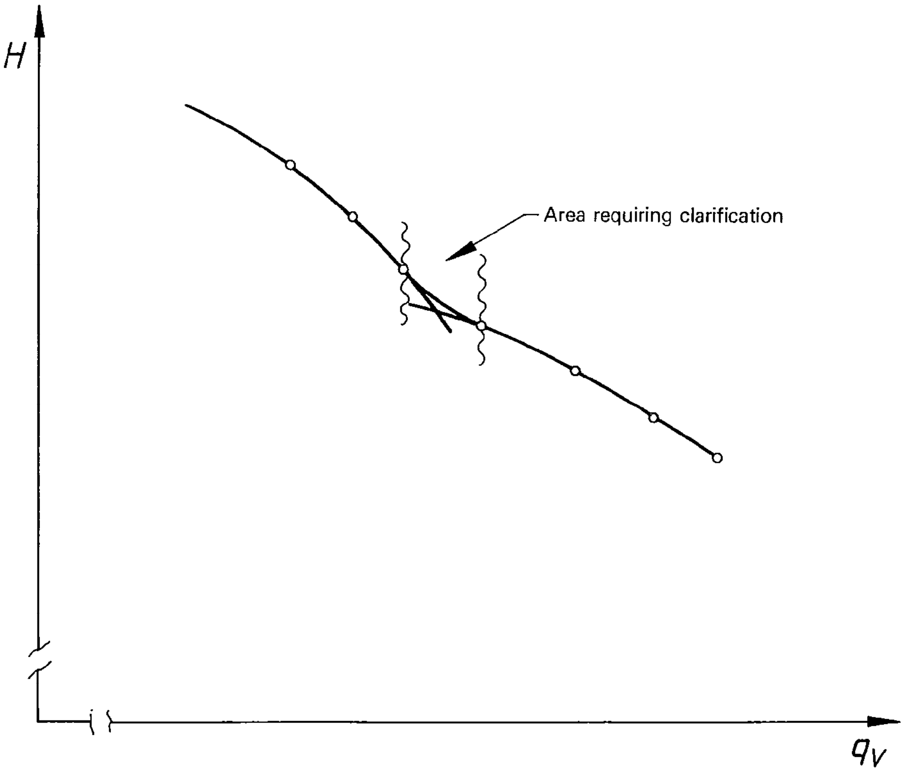


Figure 28 — Example of a discontinuity

Annex B

Comparison of test results with specified duty

B.0 Introduction

This International Standard does not specify any constructional tolerance nor any global tolerance for acceptance purposes.

Nevertheless, after these points have been agreed in the contract, it remains necessary to compare the results of measurements with the specified duty, taking into account both the uncertainties of measurement and the agreed tolerances. This annex gives different possible methods of comparison which may be used as a guide. Positive and negative tolerances have been used though this may not always be the case.

B.1 Comparison of test results with specified quantities at a given flow rate

B.1.1 Pump total head

The specification on head is met if, on the graph of $H(q_V)$, the band of measurement as defined in 6.5.3 intersects or touches the line AB shown in figure 29, where t_H is the agreed tolerance on the total head, H.

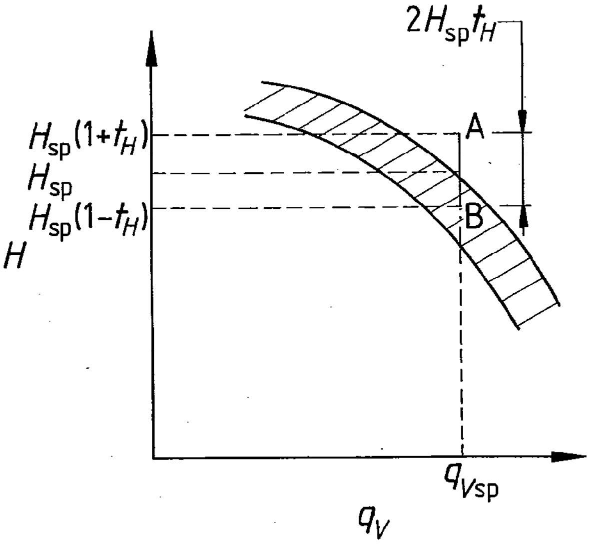


Figure 29 — Graph of comparison of measured total head with that specified at a given flow rate

B.1.2 Efficiency

The specification on efficiency is met if, on the graph of $\eta(q_V)$, the band of measurement as defined in 6.5.3 intersects, touches or is higher than the line AB shown in figure 30, where t_η is the agreed tolerance on efficiency, η.

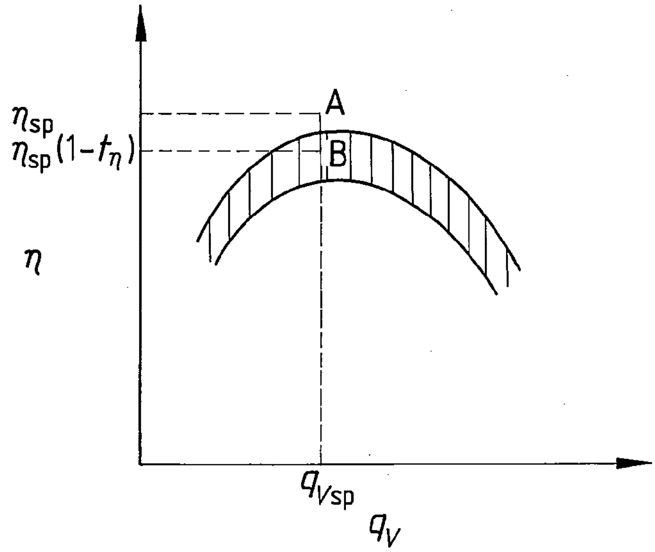


Figure 30 — Graph for comparison of measured efficiency with that specified at a given flow rate

B.1.3 Power input

The specification on power input is met if, on the graph of $P(q_V)$, the band of measurement as defined in 6.5.3 intersects, touches or is lower than the line AB shown in figure 31, where t_P is the agreed tolerance on power input, P.

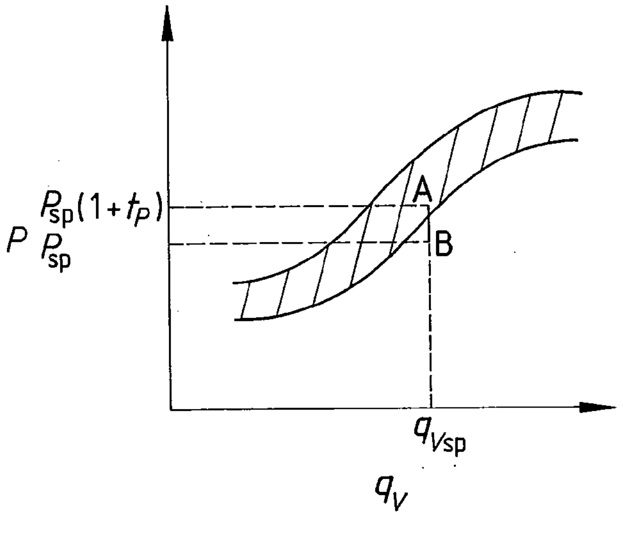


Figure 31 — Graph for comparison of measured power input with that specified at a given flow rate

B.2 Comparison of test results with the specified quantities at a given total head

B.2.1 Flow rate

The specification on flow rate is met if, on the graph of $H(q_V)$, the band of measurement as defined in 6.5.3 intersects or touches the line AB shown in figure 32, where t_q is the agreed tolerance on flow rate, q_V.

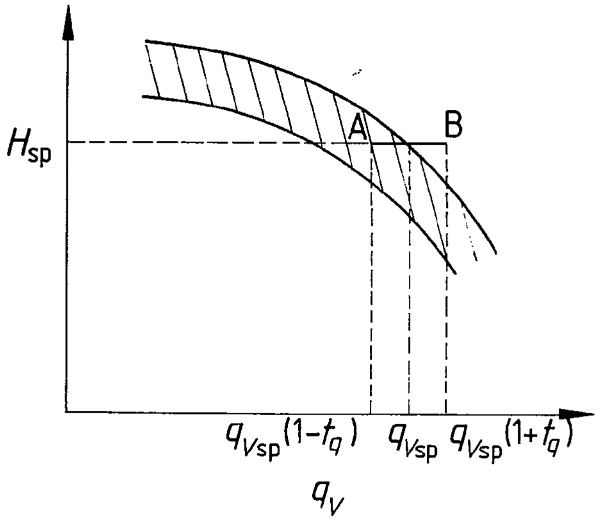


Figure 32 — Graph for comparison of measured flow rate with that specified at a given total head

B.2.2 Efficiency

The specification on efficiency is met if, on the graph of $H(\eta)$, the band of measurement as defined in 6.5.3 intersects, touches or is to the right of the line AB shown in figure 33, where t_η is the agreed tolerance on efficiency, η.

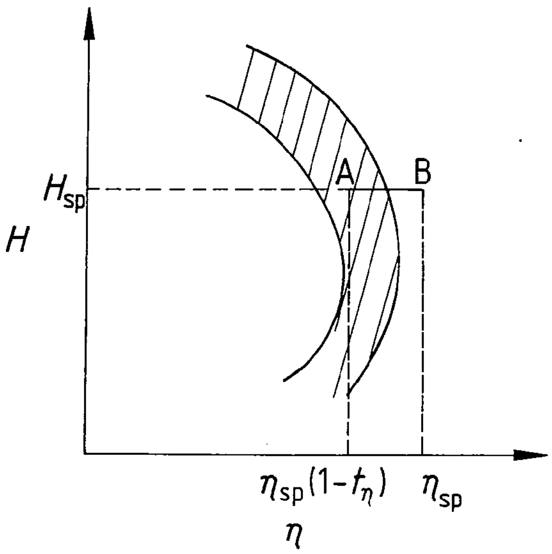


Figure 33 — Graph for comparison of measured efficiency with that specified at a given total head

B.2.3 Power input

The specification on power input is met if, on the graph of $H(P)$, the band of measurement as defined in 6.5.3 intersects, touches or is to the left of the line AB shown in figure 34, where t_P is the agreed tolerance on power input, P.

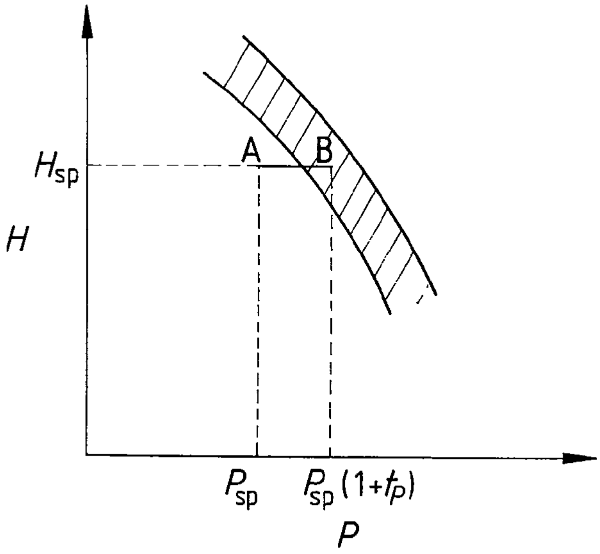


Figure 34 — Graph for comparison of measured power input with that specified at a given total head

B.3 Comparison of test results with a specified duty point

B.3.1 Flow rate and total head

The specification on the duty point (q_{Vsp}, H_{sp}) is met if, on the graph of $H(q_V)$, the band of measurement as defined in 6.5.3 intersects or touches the rectangle ABCD shown in figure 35, where t_q and t_H are agreed tolerances on flow rate, q_V, and total head, H, respectively.

All points which lie simultaneously in the band of measurement and in the rectangle ABCD are delimited by DEF of figure 35. All the points of this zone are equally valid and conform to the specification.

B.3.2 Efficiency

The zone DEF delimited in figure 35 determines a range of flow rate. That part of the band of measurement on the graph of $\eta(q_V)$, situated in this range of flow rate delimits a zone GHIJ. All points of this zone are equally valid.

The specification on efficiency is met if the zone GHIJ intersects or touches or is higher than the rectangle A'B'C'D' shown in figure 36, where t_q and t_η are agreed tolerances on flow rate, q_V, and efficiency, η respectively.

B.3.3 Power input

The zone DEF delimited in figure 35 determines a range of flow rate. That part of the band of measurement on the graph of $P(q_V)$, situated in this range of flow rate delimits a zone KLMN. All the points of this zone are equally valid.

The specification on power input is met if the zone KLMN intersects, touches or is lower than the rectangle ABCD shown in figure 37, where t_q and t_P are agreed tolerances on flow rate, q_V, and power input, P, respectively.

NOTE — In the case where is no agreed tolerance, the line AB in figures 29 to 34 or the rectangle ABCD in figures 35 to 37 is reduced to a point.

The relevant specification is met if this point lies within the corresponding band of measurement or on the upper or lower limiting curve of the band.

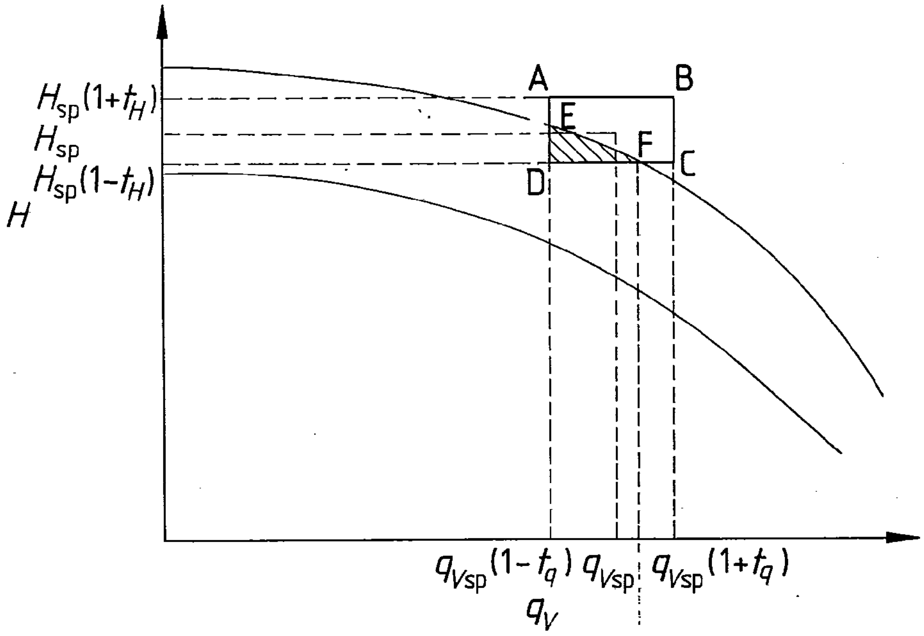


Figure 35 — Graph for comparison of flow rate and total head with a specified duty point

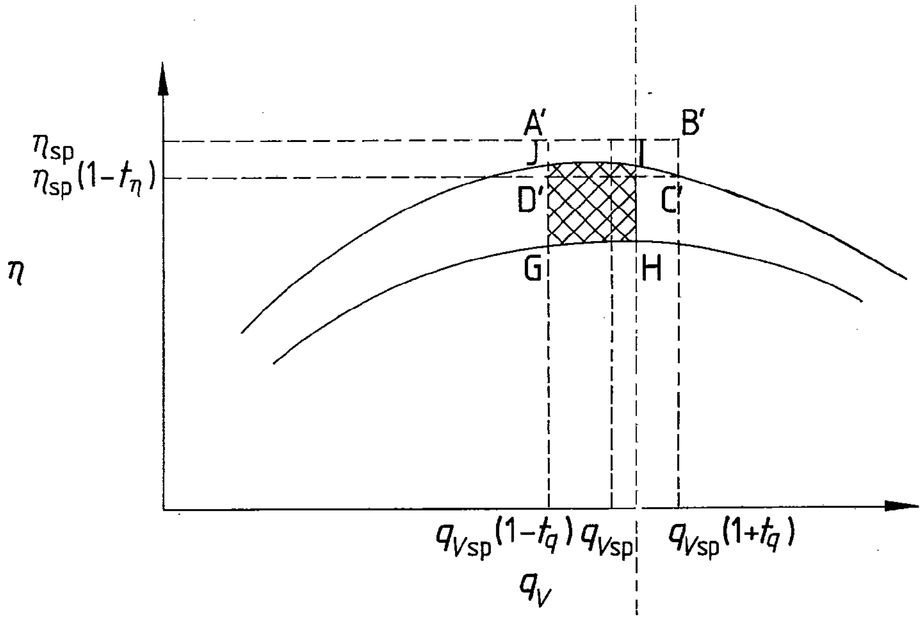


Figure 36 — Graph for comparison of flow rate and efficiency with a specified duty point

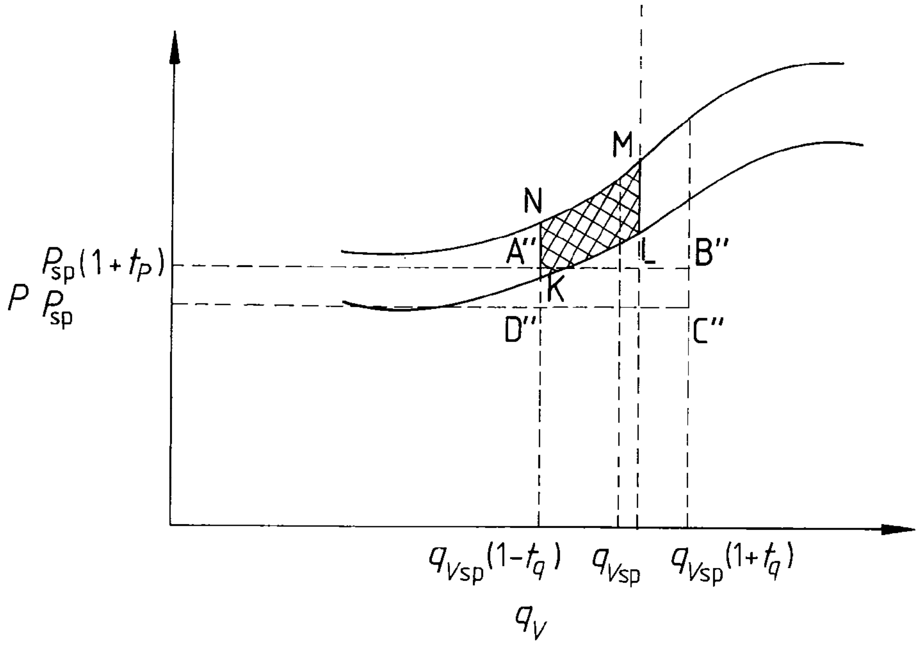


Figure 37 — Graph for comparison of flow rate and power input with a specified duty point

Annex C

Thermodynamic properties of water and assessment of the accuracy of efficiency measurements by the thermodynamic method

C.1 Tables of thermodynamic properties of water

Values of coefficients a, ϱ and c_p are given in tables 15 to 17 as a function of temperature and pressure at intervals from 0 to 275 °C and from 1 to 300 bar[1].

Table 15 — Isothermal coefficient, a (10^{-3} m^3/kg)

Pressure bar \ Temperature °C	0	5	10	15	20	25	30	35
0	1,018 6	0,995 9	0,975 4	0,957 1	0,941 1	0,926 5	0,912 4	0,899 0
20	1,015 3	0,993 2	0,973 1	0,955 2	0,939 4	0,925 0	0,911 1	0,897 9
40	1,012 1	0,990 5	0,970 8	0,953 2	0,937 7	0,923 5	0,909 8	0,896 7
60	1,008 9	0,987 8	0,968 6	0,951 3	0,936 0	0,922 0	0,908 6	0,895 6
80	1,005 8	0,985 2	0,966 3	0,949 4	0,934 3	0,920 6	0,907 3	0,894 5
100	1,002 7	0,982 6	0,964 1	0,947 4	0,932 7	0,919 1	0,906 0	0,893 4
120	0,999 7	0,980 0	0,961 9	0,945 6	0,931 0	0,917 6	0,904 7	0,892 3
140	0,996 8	0,977 4	0,959 7	0,943 7	0,929 4	0,916 2	0,903 5	0,891 2
160	0,993 8	0,974 9	0,957 6	0,941 8	0,927 7	0,914 7	0,902 2	0,890 1
180	0,990 9	0,972 4	0,955 4	0,940 0	0,926 1	0,913 3	0,900 9	0,889 0
200	0,988 1	0,970 0	0,953 3	0,938 1	0,924 5	0,911 9	0,899 7	0,887 9
220	0,985 3	0,967 6	0,951 2	0,936 3	0,922 9	0,910 5	0,898 5	0,886 9
240	0,982 5	0,965 2	0,949 1	0,934 5	0,921 3	0,909 1	0,897 2	0,885 8
260	0,979 8	0,962 8	0,947 1	0,932 7	0,919 7	0,907 7	0,896 0	0,884 7
280	0,977 2	0,960 5	0,945 1	0,930 9	0,918 2	0,906 3	0,894 8	0,883 7
300	0,974 5	0,958 2	0,943 0	0,929 2	0,916 6	0,904 9	0,893 6	0,882 6

---

1) 1 bar = 0,1 MPa

Table 15 — Isothermal coefficient, *a* (10^{-3} m^3/kg) (*continued*)

Temperature °C Pressure bar	40	45	50	55	60	65	70	75
0	0,886 1	0,873 9	0,862 3	0,851 1	0,840 0	0,828 8	0,817 8	0,806 7
20	0,885 2	0,873 1	0,861 7	0,850 6	0,839 5	0,828 5	0,817 6	0,806 7
40	0,884 2	0,872 3	0,861 0	0,850 0	0,839 1	0,828 2	0,817 4	0,806 6
60	0,883 3	0,871 5	0,860 3	0,849 5	0,838 7	0,827 9	0,817 2	0,806 6
80	0,882 3	0,870 7	0,859 7	0,848 9	0,838 3	0,827 6	0,817 1	0,806 5
100	0,881 4	0,869 9	0,859 0	0,848 4	0,837 8	0,827 3	0,816 9	0,806 4
120	0,880 4	0,869 1	0,858 3	0,847 8	0,837 4	0,827 0	0,816 7	0,806 4
140	0,879 5	0,868 3	0,857 6	0,847 3	0,837 0	0,826 7	0,816 5	0,806 3
160	0,878 5	0,867 5	0,857 0	0,846 7	0,836 5	0,826 4	0,816 3	0,806 2
180	0,877 6	0,866 7	0,856 3	0,846 2	0,836 1	0,826 1	0,816 0	0,806 1
200	0,876 7	0,865 9	0,855 6	0,845 6	0,835 7	0,825 7	0,815 8	0,806 0
220	0,875 7	0,865 1	0,855 0	0,845 1	0,835 2	0,825 4	0,815 6	0,805 9
240	0,874 8	0,864 3	0,854 3	0,844 5	0,834 8	0,825 1	0,815 4	0,805 7
260	0,873 9	0,863 5	0,853 6	0,844 0	0,834 3	0,824 7	0,815 1	0,805 6
280	0,873 0	0,862 7	0,853 0	0,843 4	0,833 9	0,824 4	0,814 9	0,805 5
300	0,872 1	0,862 0	0,852 3	0,842 8	0,833 4	0,824 0	0,814 7	0,805 3

Temperature °C Pressure bar	80	85	90	95	100	105	110	115
0	0,795 8	0,784 9	0,774 1	0,763 1	0,751 8	—	—	—
20	0,795 9	0,785 1	0,774 4	0,763 6	0,752 4	0,740 8	0,728 9	0,716 6
40	0,795 9	0,785 3	0,774 7	0,764 0	0,753 0	0,741 6	0,729 8	0,717 7
60	0,796 0	0,785 5	0,775 0	0,764 4	0,753 5	0,742 3	0,730 7	0,718 7
80	0,796 0	0,785 6	0,775 3	0,764 8	0,754 1	0,742 9	0,731 5	0,719 7
100	0,796 1	0,785 8	0,775 6	0,765 2	0,754 6	0,743 6	0,732 3	0,720 6
120	0,796 1	0,785 9	0,775 8	0,765 6	0,755 1	0,744 2	0,733 0	0,721 5
140	0,796 2	0,786 1	0,776 1	0,766 0	0,755 5	0,744 8	0,733 8	0,722 4
160	0,796 2	0,786 2	0,776 3	0,766 3	0,756 0	0,745 4	0,734 5	0,723 3
180	0,796 2	0,786 3	0,776 5	0,766 6	0,756 5	0,746 0	0,735 2	0,724 1
200	0,796 2	0,786 4	0,776 8	0,767 0	0,756 9	0,746 5	0,735 9	0,724 9
220	0,796 2	0,786 5	0,776 9	0,767 3	0,757 3	0,747 1	0,736 5	0,725 7
240	0,796 2	0,786 6	0,777 1	0,767 6	0,757 7	0,747 6	0,737 2	0,726 5
260	0,796 1	0,786 7	0,777 3	0,767 8	0,758 1	0,748 1	0,737 8	0,727 3
280	0,796 1	0,786 8	0,777 5	0,768 1	0,758 5	0,748 6	0,738 4	0,728 0
300	0,796 1	0,786 8	0,777 6	0,768 3	0,758 8	0,749 0	0,739 0	0,728 7

Table 15 — Isothermal coefficient, a (10^{-3} m^3/kg) (*continued*)

Temperature °C / Pressure bar	120	125	130	135	140	145	150	155
0	—	—	—	—	—	—	—	—
20	0,704 0	0,690 9	0,677 5	0,663 6	0,649 4	0,634 6	0,618 9	0,602 5
40	0,705 2	0,692 3	0,679 1	0,665 4	0,651 4	0,636 8	0,621 5	0,605 3
60	0,706 4	0,693 7	0,680 6	0,667 2	0,653 4	0,639 0	0,623 9	0,608 1
80	0,707 5	0,695 0	0,682 1	0,668 9	0,655 3	0,641 1	0,626 3	0,610 7
100	0,708 6	0,696 3	0,683 6	0,670 5	0,657 1	0,643 2	0,628 6	0,613 3
120	0,709 7	0,697 5	0,685 0	0,672 1	0,658 9	0,645 2	0,630 9	0,615 8
140	0,710 7	0,698 7	0,686 4	0,673 7	0,660 7	0,647 2	0,633 0	0,618 2
160	0,711 8	0,699 9	0,687 7	0,675 2	0,662 4	0,649 1	0,635 2	0,620 6
180	0,712 7	0,701 1	0,689 0	0,676 7	0,664 1	0,651 0	0,637 3	0,622 9
200	0,713 7	0,702 2	0,690 3	0,678 2	0,665 7	0,652 8	0,639 3	0,625 2
220	0,714 6	0,703 3	0,691 6	0,679 6	0,667 3	0,654 6	0,641 3	0,627 4
240	0,715 6	0,704 3	0,692 8	0,681 0	0,668 8	0,656 3	0,643 2	0,629 6
260	0,716 4	0,705 3	0,694 0	0,682 3	0,670 3	0,658 0	0,645 1	0,631 6
280	0,717 3	0,706 3	0,695 1	0,683 6	0,671 8	0,659 6	0,646 9	0,633 7
300	0,718 1	0,707 3	0,696 2	0,684 9	0,673 2	0,661 2	0,648 7	0,635 7

Temperature °C / Pressure bar	160	165	170	175	180	185	190	195
0	—	—	—	—	—	—	—	—
20	0,585 3	0,567 2	0,548 3	0,528 5	0,507 4	0,484 3	0,459 4	0,432 5
40	0,588 4	0,570 7	0,552 1	0,532 8	0,512 1	0,489 6	0,465 4	0,439 2
60	0,591 4	0,574 1	0,555 9	0,536 9	0,516 7	0,494 8	0,471 1	0,445 6
80	0,594 4	0,577 3	0,559 5	0,540 9	0,521 1	0,499 7	0,476 6	0,451 8
100	0,597 3	0,580 5	0,563 0	0,544 8	0,525 4	0,504 5	0,481 9	0,457 8
120	0,600 1	0,583 6	0,566 5	0,548 6	0,529 6	0,509 1	0,487 1	0,463 5
140	0,602 8	0,586 6	0,569 8	0,552 2	0,533 6	0,513 6	0,492 1	0,469 1
160	0,605 4	0,589 6	0,573 0	0,555 8	0,537 6	0,518 0	0,496 9	0,474 5
180	0,608 0	0,592 4	0,576 2	0,559 3	0,541 4	0,522 2	0,501 7	0,479 7
200	0,610 5	0,595 2	0,579 2	0,562 7	0,545 1	0,526 3	0,506 2	0,484 8
220	0,613 0	0,597 9	0,582 2	0,565 9	0,548 7	0,530 3	0,510 7	0,479 7
240	0,615 3	0,600 5	0,585 1	0,569 1	0,552 3	0,534 2	0,515 0	0,494 5
260	0,617 7	0,603 1	0,588 0	0,572 3	0,555 7	0,538 0	0,519 2	0,499 2
280	0,619 9	0,605 6	0,590 7	0,575 3	0,559 0	0,541 7	0,523 2	0,503 7
300	0,622 1	0,608 0	0,593 4	0,578 2	0,562 3	0,545 3	0,527 2	0,508 0

Table 15 — Isothermal coefficient, *a* (10^{-3} m^3/kg) (*concluded*)

Temperature °C / Pressure bar	200	205	210	215	220	225	230	235
0	—	—	—	—	—	—	—	—
20	0,403 7	0,372 8	0,339 9	—	—	—	—	—
40	0,411 2	0,381 3	0,349 4	0,315 5	0,279 5	0,241 5	0,199 4	0,150 9
60	0,418 4	0,389 3	0,358 4	0,325 5	0,290 7	0,254 0	0,213 3	0,166 9
80	0,425 3	0,397 0	0,367 0	0,335 1	0,301 4	0,265 8	0,226 6	0,182 0
100	0,432 0	0,404 5	0,375 3	0,344 3	0,311 6	0,277 1	0,239 2	0,196 4
120	0,438 4	0,411 6	0,383 2	0,353 2	0,321 4	0,288 0	0,251 3	0,210 1
140	0,444 6	0,418 5	0,390 9	0,361 7	0,330 9	0,298 4	0,262 9	0,223 2
160	0,450 6	0,425 2	0,398 3	0,369 9	0,340 0	0,308 4	0,274 1	0,235 7
180	0,456 4	0,431 7	0,405 5	0,377 9	0,348 7	0,318 1	0,284 8	0,247 7
200	0,462 1	0,437 9	0,412 4	0,385 5	0,357 2	0,327 4	0,295 1	0,259 3
220	0,467 5	0,444 0	0,419 2	0,392 9	0,365 4	0,336 4	0,305 0	0,270 4
240	0,472 8	0,449 9	0,425 6	0,400 1	0,373 3	0,345 1	0,314 6	0,281 1
260	0,478 0	0,455 6	0,431 9	0,407 0	0,380 9	0,353 4	0,323 9	0,291 4
280	0,482 9	0,461 1	0,438 0	0,413 7	0,388 2	0,361 5	0,332 8	0,301 3
300	0,487 8	0,466 4	0,443 9	0,420 2	0,395 4	0,369 3	0,341 4	0,310 8

Temperature °C / Pressure bar	240	245	250	255	260	265	270	275
0	—	—	—	—	—	—	—	—
20	—	—	—	—	—	—	—	—
40	0,095 9	0,034 4	—	—	—	—	—	—
60	0,114 5	0,056 1	− 0,008 4	− 0,079 2	− 0,156 3	− 0,239 9	—	—
80	0,132 0	0,076 4	0,015 2	− 0,051 8	− 0,124 6	− 0,203 4	− 0,288 3	− 0,379 3
100	0,148 5	0,095 5	0,037 2	− 0,026 4	− 0,095 4	− 0,169 9	− 0,250 0	− 0,335 8
120	0,164 2	0,113 5	0,057 9	− 0,002 6	− 0,068 1	− 0,138 8	− 0,214 6	− 0,295 7
140	0,179 1	0,130 5	0,077 4	0,019 8	− 0,042 6	− 0,109 7	− 0,181 7	− 0,258 6
160	0,193 3	0,146 7	0,095 9	0,040 8	− 0,018 6	− 0,082 6	− 0,151 0	− 0,224 0
180	0,206 9	0,162 2	0,113 5	0,060 8	0,004 0	− 0,057 0	− 0,122 2	− 0,191 7
200	0,219 9	0,176 9	0,130 2	0,079 7	0,025 3	− 0,032 9	− 0,095 1	− 0,161 3
220	0,232 4	0,191 0	0,146 1	0,097 6	0,045 6	− 0,010 1	− 0,069 5	− 0,132 7
240	0,244 4	0,204 5	0,161 3	0,114 8	0,064 8	0,011 5	− 0,045 4	− 0,105 8
260	0,255 9	0,217 4	0,175 8	0,131 1	0,083 1	0,031 9	− 0,022 5	− 0,080 4
280	0,267 0	0,229 8	0,189 7	0,146 6	0,100 5	0,051 4	− 0,000 9	− 0,056 3
300	0,277 6	0,241 6	0,202 9	0,161 4	0,117 1	0,069 8	0,019 7	− 0,033 5

Table 16 — Density, ϱ (kg/m^3)

Temperature °C Pressure bar	0	5	10	15	20	25	30	35
0	999,8	999,9	999,7	999,1	998,2	997,0	995,6	994,0
20	1 000,8	1 000,9	1 000,6	1 000,0	999,1	997,9	996,5	994,9
40	1 001,8	1 001,9	1 001,6	1 000,9	1 000,0	998,8	997,4	995,8
60	1 002,8	1 002,8	1 002,5	1 001,8	1 000,9	999,7	998,3	996,6
80	1 003,8	1 003,8	1 003,4	1 002,7	1 001,8	1 000,6	999,1	997,5
100	1 004,8	1 004,8	1 004,4	1 003,7	1 002,7	1 001,5	1 000,0	998,4
120	1 005,8	1 005,7	1 005,3	1 004,6	1 003,6	1 002,3	1 000,9	999,2
140	1 006,8	1 006,7	1 006,2	1 005,5	1 004,5	1 003,2	1 001,7	1 000,1
160	1 007,8	1 007,6	1 007,2	1 006,4	1 005,4	1 004,1	1 002,6	1 000,9
180	1 008,8	1 008,6	1 008,1	1 007,3	1 006,2	1 005,0	1 003,5	1 001,8
200	1 009,7	1 009,5	1 009,0	1 008,2	1 007,1	1 005,8	1 004,3	1 002,6
220	1 010,7	1 010,5	1 009,9	1 009,1	1 008,0	1 006,7	1 005,2	1 003,5
240	1 011,7	1 011,4	1 010,8	1 010,0	1 008,9	1 007,6	1 006,0	1 004,3
260	1 012,6	1 012,3	1 011,7	1 010,9	1 009,7	1 008,4	1 006,9	1 005,2
280	1 013,6	1 013,3	1 012,6	1 011,7	1,010,6	1 009,3	1 007,7	1 006,0
300	1 014,6	1 014,2	1 013,5	1 012,6	1 011,5	1 010,1	1 008,6	1 006,8

Temperature °C Pressure bar	40	45	50	55	60	65	70	75
0	992,2	990,2	988,0	985,7	983,2	980,5	977,7	974,8
20	993,1	991,0	988,9	986,5	984,0	981,4	978,6	975,7
40	993,9	991,9	989,7	987,4	984,9	982,3	979,5	976,6
60	994,8	992,8	990,6	988,2	985,8	983,1	980,4	977,4
80	995,7	993,6	991,4	989,1	986,6	984,0	981,2	978,3
100	996,5	994,5	992,3	990,0	987,5	984,8	982,1	979,2
120	997,4	995,3	993,2	990,8	988,3	985,7	982,9	980,1
140	998,2	996,2	994,0	991,7	989,2	986,6	983,8	980,9
160	999,1	997,0	994,8	992,5	990,0	987,4	984,6	981,8
180	999,9	997,9	995,7	993,3	990,9	988,2	985,5	982,6
200	1 000,8	998,7	996,5	994,2	991,7	989,1	986,3	983,5
220	1 001,6	999,6	997,4	995,0	992,5	989,9	987,2	984,3
240	1 002,4	1 000,4	998,2	995,8	993,4	990,8	988,0	985,2
260	1 003,3	1 001,2	999,0	996,7	994,2	991,6	988,9	986,0
280	1 004,1	1 002,0	999,8	997,5	995,0	992,4	989,7	986,8
300	1 004,9	1 002,9	1 000,7	998,3	995,8	993,2	990,5	987,7

Table 16 — Density, ϱ (kg/m^3) *(continued)*

Temperature °C / Pressure bar	80	85	90	95	100	105	110	115
0	971,7	968,6	965,3	961,8	958,3	—	—	—
20	972,6	969,5	966,2	962,8	959,2	955,6	951,9	948,0
40	973,5	970,4	967,1	963,7	960,2	956,6	952,8	949,0
60	974,4	971,3	968,0	964,6	961,1	957,5	953,8	950,0
80	975,3	972,1	968,9	965,5	962,0	958,4	954,7	950,9
100	976,2	973,0	969,8	966,4	962,9	959,4	955,7	951,9
120	977,0	973,9	970,7	967,3	963,8	960,3	956,6	952,8
140	977,9	974,8	971,5	968,2	964,8	961,2	957,5	953,8
160	978,8	975,7	972,4	969,1	965,7	962,1	958,5	954,7
180	979,6	976,5	973,3	970,0	966,5	963,0	959,4	955,6
200	980,5	977,4	974,2	970,9	967,4	963,9	960,3	956,6
220	981,3	978,2	975,0	971,7	968,3	964,8	961,2	957,5
240	982,2	979,1	975,9	972,6	969,2	965,7	962,1	958,4
260	983,0	980,0	976,8	973,5	970,1	966,6	963,0	959,3
280	983,9	980,8	977,6	974,3	971,0	967,5	963,9	960,2
300	984,7	981,6	978,5	975,2	971,8	968,4	964,8	961,1

Temperature °C / Pressure bar	120	125	130	135	140	145	150	155
0	—	—	—	—	—	—	—	—
20	944,0	940,0	935,8	931,5	927,0	922,5	917,9	913,2
40	945,0	941,0	936,8	932,5	928,1	923,6	919,0	914,3
60	946,0	943,0	937,8	933,6	929,2	924,7	920,1	915,5
80	947,0	943,0	938,8	934,6	930,2	925,8	921,2	916,6
100	948,0	944,0	939,8	935,6	931,3	926,9	922,3	917,7
120	948,9	944,9	940,8	936,6	932,3	927,9	923,4	918,8
140	949,9	945,9	941,8	937,7	933,4	929,0	924,5	919,9
160	950,8	946,9	942,8	938,7	934,4	930,0	925,6	921,0
180	951,8	947,9	943,8	939,7	935,4	931,1	926,7	922,1
200	952,7	948,8	944,8	940,7	936,4	932,1	927,7	923,2
220	953,7	949,8	945,8	941,7	937,5	933,2	928,8	924,3
240	954,6	950,7	946,7	942,6	938,5	934,2	929,8	925,3
260	955,5	951,7	947,7	943,6	939,4	935,2	930,8	926,4
280	956,5	952,6	948,6	944,6	940,4	936,2	931,9	927,5
300	957,4	953,5	949,6	945,5	941,4	937,2	932,9	928,5

Table 16 — Density, ϱ (kg/m^3) (*continued*)

Temperature °C / Pressure bar	160	165	170	175	180	185	190	195
0	—	—	—	—	—	—	—	—
20	908,3	903,3	898,3	893,1	887,7	882,3	876,7	871,0
40	909,5	904,6	889,5	894,3	889,1	883,6	878,1	872,4
60	910,7	905,8	900,7	895,6	890,4	885,0	879,5	873,9
80	911,8	906,9	902,0	896,9	891,7	886,3	880,9	875,3
100	913,0	908,1	903,2	898,1	892,9	887,6	882,2	876,7
120	914,1	909,3	904,4	899,3	894,2	889,0	883,6	878,1
140	915,3	910,5	905,6	900,6	895,5	890,3	884,9	879,5
160	916,4	911,6	906,8	901,8	896,7	891,5	886,2	880,8
180	917,5	912,8	907,9	903,0	897,9	892,8	887,5	882,2
200	918,6	913,9	909,1	904,2	899,2	894,1	888,8	883,5
220	919,7	915,0	910,2	905,4	900,4	895,3	890,1	884,8
240	920,8	916,1	911,4	906,5	901,6	896,5	891,4	886,1
260	921,9	917,2	912,5	907,7	902,8	897,8	892,6	887,4
280	922,9	918,3	913,6	908,8	904,0	899,0	893,9	888,7
300	924,0	919,4	914,8	910,0	905,1	900,2	895,1	890,0

Temperature °C / Pressure bar	200	205	210	215	220	225	230	235
0	—	—	—	—	—	—	—	—
20	865,1	859,1	852,9	—	—	—	—	—
40	866,6	860,6	854,5	848,2	841,8	835,2	828,4	821,4
60	868,1	862,2	856,1	849,9	843,5	837,0	830,3	823,4
80	869,6	863,7	857,7	851,5	845,2	838,8	832,1	825,3
100	871,0	865,2	859,3	853,2	846,9	840,5	834,0	827,2
120	872,5	866,7	860,8	854,8	848,6	842,2	835,8	829,1
140	873,9	868,2	862,3	856,3	850,2	843,9	837,5	831,0
160	875,3	869,6	863,8	857,9	851,8	845,6	839,3	832,8
180	876,7	871,1	865,3	859,4	853,4	847,3	841,0	834,6
200	878,1	872,5	866,8	860,9	855,0	848,9	842,7	836,3
220	879,4	873,9	868,2	862,4	856,5	850,5	844,4	838,1
240	880,8	875,3	869,7	863,9	858,1	852,1	846,0	839,8
260	882,1	876,6	871,1	865,4	859,6	853,7	847,6	841,4
280	883,4	878,0	872,5	866,8	861,1	855,2	849,2	843,1
300	884,7	879,3	873,9	868,3	862,6	856,7	850,8	844,7

Table 16 — Density, ϱ (kg/m^3) (*concluded*)

Temperature °C / Pressure bar	240	245	250	255	260	265	270	275
0	—	—	—	—	—	—	—	—
20	—	—	—	—	—	—	—	—
40	814,2	806,8	—	—	—	—	—	—
60	816,3	809,0	801,4	793,6	785,4	777,0	—	—
80	818,3	811,1	803,7	795,9	788,0	779,7	771,2	762,3
100	820,3	813,2	805,9	798,3	790,4	782,3	773,9	765,3
120	822,3	815,3	808,0	800,5	792,8	784,9	776,6	768,2
140	824,2	817,3	810,1	802,7	795,2	787,3	779,3	770,9
160	826,1	819,2	812,2	804,9	797,4	789,7	781,8	773,6
180	828,0	821,2	814,2	807,1	799,7	792,1	784,3	776,3
200	829,8	823,1	816,2	809,1	801,9	794,4	786,7	778,8
220	831,6	825,0	818,2	811,2	804,0	796,7	789,1	781,3
240	833,4	826,8	820,1	813,2	806,1	798,9	791,4	783,8
260	835,1	828,6	822,0	815,2	808,2	801,1	793,7	786,2
280	836,8	830,4	823,9	817,1	810,3	803,2	795,9	788,5
300	838,5	832,2	825,7	819,1	812,3	805,3	798,1	790,8

Table 17 — Specific heat capacity per unit mass at constant pressure, c_p [J/(kg·K)]

Temperature °C / Pressure bar	0	5	10	15	20	25	30	35
0	4 207,5	4 202,7	4 196,7	4 189,7	4 181,6	4 182,1	4 182,0	4 181,6
20	4 198,1	4 194,1	4 189,0	4 182,9	4 175,7	4 176,4	4 176,6	4 176,3
40	4 189,0	4 185,8	4 181,5	4 176,2	4 169,9	4 170,8	4 171,2	4 171,2
60	4 180,1	4 177,6	4 174,1	4 169,6	4 164,2	4 165,3	4 165,9	4 166,1
80	4 171,4	4 169,6	4 166,9	4 163,1	4 158,5	4 159,8	4 160,6	4 161,1
100	4 162,9	4 161,8	4 159,8	4 156,8	4 153,0	4 154,4	4 155,4	4 156,1
120	4 154,6	4 154,2	4 152,8	4 150,5	4 147,5	4 149,1	4 150,3	4 151,2
140	4 146,4	4 146,7	4 146,0	4 144,4	4 142,1	4 143,9	4 145,3	4 146,4
160	4 138,5	4 139,3	4 139,3	4 138,4	4 136,8	4 138,8	4 140,4	4 141,6
180	4 130,7	4 132,2	4 132,7	4 132,5	4 131,5	4 133,7	4 135,5	4 136,9
200	4 123,1	4 125,1	4 126,3	4 126,7	4 126,3	4 128,7	4 130,6	4 132,3
220	4 115,7	4 118,2	4 120,0	4 120,9	4 121,2	4 123,8	4 125,9	4 127,7
240	4 108,4	4 111,5	4 113,8	4 115,3	4 116,2	4 118,9	4 121,2	4 123,2
260	4 101,2	4 104,9	4 107,7	4 109,8	4 111,3	4 114,1	4 116,6	4 118,8
280	4 094,2	4 098,4	4 101,7	4 104,4	4 106,4	4 109,4	4 112,0	4 114,4
300	4 087,4	4 092,0	4 095,9	4 099,0	4 101,6	4 104,8	4 107,5	4 110,0

Table 17 — **Specific heat capacity per unit mass at constant pressure,** c_p [J/(kg·K)] *(continued)*

Temperature °C / Pressure bar	40	45	50	55	60	65	70	75
0	4 180,8	4 179,8	4 178,8	4 181,3	4 183,7	4 186,2	4 188,8	4 191,6
20	4 175,8	4 175,1	4 174,3	4 176,8	4 179,3	4 181,8	4 184,4	4 187,2
40	4 170,9	4 170,4	4 169,9	4 172,4	4 174,9	4 177,4	4 180,1	4 182,9
60	4 166,1	4 165,8	4 165,5	4 168,1	4 170,6	4 173,1	4 175,8	4 178,6
80	4 161,3	4 161,3	4 161,2	4 163,8	4 166,3	4 168,9	4 171,5	4 174,4
100	4 156,5	4 156,8	4 156,9	4 159,5	4 162,1	4 164,6	4 167,3	4 170,2
120	4 151,8	4 152,3	4 152,7	4 155,3	4 157,9	4 160,5	4 163,2	4 166,1
140	4 147,2	4 147,9	4 148,5	4 151,2	4 153,7	4 156,3	4 159,1	4 162,0
160	4 142,7	4 143,6	4 144,4	4 147,1	4 149,6	4 152,3	4 155,0	4 157,9
180	4 138,2	4 139,3	4 140,4	4 143,0	4 145,6	4 148,2	4 151,0	4 153,9
200	4 133,7	4 135,0	4 136,3	4 139,0	4 141,6	4 144,2	4 147,0	4 150,0
220	4 129,3	4 130,9	4 132,4	4 135,0	4 137,6	4 140,3	4 143,1	4 146,1
240	4 125,0	4 126,7	4 128,4	4 131,1	4 133,7	4 136,4	4 139,2	4 142,2
260	4 120,7	4 122,6	4 124,5	4 127,2	4 129,8	4 132,5	4 135,4	4 138,4
280	4 116,5	4 118,6	4 120,7	4 123,4	4 126,0	4 128,7	4 131,6	4 134,6
300	4 112,4	4 114,6	4 116,9	4 119,6	4 122,2	4 124,9	4 127,8	4 130,9

Temperature °C / Pressure bar	80	85	90	95	100	105	110	115
0	4 194,6	4 198,0	4 201,8	4 208,4	4 215,2	—	—	—
20	4 190,2	4 193,6	4 197,5	4 204,0	4 210,6	4 217,4	4 224,6	4 232,0
40	4 185,9	4 189,4	4 193,2	4 199,6	4 206,1	4 212,8	4 219,8	4 227,1
60	4 181,7	4 185,2	4 189,1	4 195,3	4 201,6	4 208,2	4 215,0	4 222,2
80	4 177,5	4 181,0	4 184,9	4 191,0	4 197,2	4 203,6	4 210,3	4 217,4
100	4 173,3	4 176,9	4 180,8	4 186,8	4 192,8	4 199,1	4 205,7	4 212,6
120	4 169,2	4 172,8	4 176,8	4 182,6	4 188,5	4 194,7	4 201,1	4 207,9
140	4 165,2	4 168,7	4 172,8	4 178,4	4 184,3	4 190,3	4 196,6	4 203,3
160	4 161,2	4 164,8	4 168,8	4 174,4	4 180,1	4 186,0	4 192,2	4 198,7
180	4 157,2	4 160,8	4 164,9	4 170,3	4 175,9	4 181,7	4 187,8	4 194,2
200	4 153,3	4 156,9	4 161,0	4 166,3	4 171,8	4 177,5	4 183,4	4 189,7
220	4 149,4	4 153,0	4 157,2	4 162,4	4 167,7	4 173,3	4 179,1	4 185,3
240	4 145,5	4 149,2	4 153,4	4 158,5	4 163,7	4 169,2	4 174,9	4 181,0
260	4 141,7	4 145,4	4 149,6	4 154,6	4 159,8	4 165,1	4 170,7	4 176,7
280	4 137,9	4 141,7	4 145,9	4 150,8	4 155,8	4 161,1	4 166,6	4 172,4
300	4 134,2	4 138,0	4 142,2	4 147,0	4 151,9	4 157,1	4 162,5	4 168,2

Table 17 — Specific heat capacity per unit mass at constant pressure, c_p [J/(kg·K)] *(continued)*

Temperature °C Pressure bar	120	125	130	135	140	145	150	155
0	—	—	—	—	—	—	—	—
20	4 239,9	4 248,3	4 257,2	4 266,7	4 276,8	4 289,4	4 302,5	4 316,4
40	4 234,8	4 243,0	4 251,8	4 261,1	4 271,1	4 283,3	4 296,2	4 309,7
60	4 229,8	4 237,8	4 246,4	4 255,6	4 265,4	4 277,4	4 289,9	4 303,2
80	4 224,8	4 232,7	4 241,2	4 250,2	4 259,9	4 271,5	4 283,8	4 296,7
100	4 219,9	4 227,7	4 236,0	4 244,9	4 254,4	4 265,8	4 277,8	4 290,4
120	4 215,1	4 222,7	4 230,9	4 239,6	4 249,0	4 260,1	4 271,8	4 284,2
140	4 210,3	4 217,8	4 225,8	4 234,4	4 243,7	4 254,6	4 266,0	4 278,1
160	4 205,6	4 213,0	4 220,9	4 229,3	4 238,5	4 249,1	4 260,3	4 272,1
180	4 201,0	4 208,2	4 216,0	4 224,3	4 233,3	4 243,7	4 254,6	4 266,2
200	4 196,4	4 203,5	4 211,1	4 219,4	4 228,2	4 238,3	4 249,1	4 260,4
220	4 191,9	4 198,9	4 206,4	4 214,5	4 223,2	4 233,1	4 243,6	4 254,7
240	4 187,4	4 194,3	4 201,7	4 209,6	4 218,3	4 227,9	4 238,2	4 249,0
260	4 183,0	4 189,7	4 197,0	4 204,9	4 213,4	4 222,9	4 232,9	4 243,5
280	4 178,6	4 185,3	4 192,5	4 200,2	4 208,6	4 217,8	4 227,7	4 238,1
300	4 174,3	4 180,9	4 187,9	4 195,6	4 203,8	4 212,9	4 222,5	4 232,7

Temperature °C Pressure bar	160	165	170	175	180	185	190	195
0	—	—	—	—	—	—	—	—
20	4 330,9	4 346,2	4 362,3	4 379,4	4 401,4	4 424,1	4 447,6	4 471,8
40	4 323,9	4 338,9	4 354,7	4 371,4	4 392,7	4 414,7	4 437,4	4 460,8
60	4 317,1	4 331,7	4 347,2	4 363,5	4 384,1	4 405,4	4 427,4	4 450,2
80	4 310,3	4 324,7	4 339,8	4 355,8	4 375,8	4 396,4	4 417,7	4 439,8
100	4 303,7	4 317,8	4 332,6	4 348,3	4 367,7	4 387,6	4 408,3	4 429,6
120	4 297,2	4 311,0	4 325,5	4 341,0	4 359,7	4 379,0	4 399,0	4 419,8
140	4 290,8	4 304,3	4 318,6	4 333,7	4 351,9	4 370,6	4 390,0	4 410,2
160	4 284,6	4 297,8	4 311,8	4 326,6	4 344,2	4 362,4	4 381,2	4 400,8
180	4 278,4	4 291,4	4 305,1	4 319,7	4 336,7	4 354,4	4 372,7	4 391,6
200	4 272,3	4 285,1	4 298,5	4 312,9	4 329,4	4 346,5	4 364,3	4 382,7
220	4 266,4	4 278,9	4 292,1	4 306,2	4 322,2	4 338,8	4 356,1	4 374,0
240	4 260,5	4 272,8	4 285,8	4 299,6	4 315,1	4 331,3	4 348,0	4 365,4
260	4 254,8	4 266,8	4 279,5	4 293,1	4 308,2	4 323,9	4 340,2	4 357,1
280	4 249,1	4 260,9	4 273,4	4 286,8	4 301,4	4 316,7	4 332,5	4 349,0
300	4 243,5	4 255,1	4 267,4	4 280,5	4 294,8	4 309,6	4 325,0	4 341,0

Table 17 — Specific heat capacity per unit mass at constant pressure, c_p [J/(kg·K)] (*concluded*)

Temperature °C / Pressure bar	200	205	210	215	220	225	230	235
0	—	—	—	—	—	—	—	—
20	4 496,9	4 522,8	4 549,6	—	—	—	—	—
40	4 485,1	4 510,2	4 536,3	4 563,2	4 591,1	4 620,1	4 664,7	4 712,3
60	4 473,7	4 498,1	4 523,3	4 549,5	4 576,6	4 604,7	4 646,9	4 692,1
80	4 462,6	4 486,2	4 510,7	4 536,1	4 562,5	4 589,8	4 629,8	4 672,8
100	4 451,8	4 474,7	4 498,5	4 523,2	4 548,8	4 575,4	4 613,4	4 654,2
120	4 441,3	4 463,6	4 486,7	4 510,7	4 535,6	4 561,5	4 597,6	4 636,5
140	4 431,0	4 452,7	4 475,1	4 498,5	4 522,8	4 548,0	4 582,3	4 619,4
160	4 421,0	4 442,1	4 463,9	4 486,7	4 510,3	4 534,8	4 567,5	4 602,9
180	4 411,3	4 431,8	4 453,0	4 475,1	4 498,1	4 522,1	4 553,2	4 587,1
200	4 401,8	4 421,7	4 442,4	4 463,9	4 486,3	4 509,7	4 539,4	4 571,8
220	4 392,6	4 411,9	4 432,1	4 453,0	4 474,9	4 497,6	4 526,0	4 557,0
240	4 383,5	4 402,4	4 422,0	4 442,4	4 463,7	4 485,9	4 513,0	4 542,7
260	4 374,7	4 393,0	4 412,2	4 432,1	4 452,9	4 474,5	4 500,4	4 528,9
280	4 366,1	4 383,9	4 402,6	4 422,0	4 442,3	4 463,4	4 488,2	4 515,5
300	4 357,7	4 375,1	4 393,2	4 412,2	4 432,0	4 452,6	4 476,3	4 502,6

Temperature °C / Pressure bar	240	245	250	255	260	265	270	275
0	—	—	—	—	—	—	—	—
20	—	—	—	—	—	—	—	—
40	4 763,0	4 817,0	—	—	—	—	—	—
60	4 740,3	4 791,7	4 846,3	4 904,3	4 965,7	—	—	—
80	4 718,7	4 767,8	4 820,0	4 875,6	4 934,5	4 996,9	5 062,8	5 132,4
100	4 698,1	4 745,0	4 795,0	4 848,3	4 905,0	4 965,1	5 028,7	5 095,9
120	4 678,3	4 723,2	4 771,2	4 822,5	4 877,0	4 935,0	4 996,4	5 061,4
140	4 659,4	4 702,4	4 748,6	4 797,9	4 850,5	4 906,4	4 965,8	5 028,8
160	4 641,3	4 682,6	4 726,9	4 774,4	4 825,2	4 879,3	4 936,8	4 997,9
180	4 623,8	4 663,5	4 706,2	4 752,0	4 801,1	4 853,5	4 909,2	4 968,5
200	4 607,0	4 645,2	4 686,3	4 730,6	4 778,1	4 828,8	4 882,9	4 940,5
220	4 590,8	4 627,6	4 667,3	4 710,1	4 756,1	4 805,3	4 857,9	4 913,9
240	4 575,2	4 610,6	4 649,0	4 690,4	4 735,0	4 782,8	4 833,9	4 888,4
260	4 560,2	4 594,3	4 631,4	4 671,5	4 714,7	4 761,2	4 810,9	4 864,1
280	4 545,6	4 578,6	4 614,5	4 653,3	4 695,3	4 740,5	4 788,9	4 840,8
300	4 531,6	4 563,4	4 598,1	4 635,8	4 676,6	4 720,6	4 767,8	4 818,4

C.2 Accuracy of measurements

The general principles for estimating the uncertainties in efficiency measurement by the thermodynamic method are given in 11.7. Complementary information on the evaluation and propagation of the individual components of the errors is given in C.2.1 and C.2.2.

C.2.1 Estimation of the uncertainty in the determination of the energies per unit mass

C.2.1.1 Hydraulic energy per unit mass

Errors arising are:

a) the relative error in the pressure difference measurement $(p_2 - p_1)$: $\delta\Delta p/\Delta p$;

b) the relative error in the determination of the mean value of the volume per unit mass: $\delta\bar{V}_m/\bar{V}_m$

Therefore the relative uncertainty $\delta E_h/E_h$ is given by the equation

$$\left(\frac{\delta E_h}{E_h}\right) = \sqrt{\left(\frac{\delta\Delta p}{\Delta p}\right)^2 + \left(\frac{\delta\bar{V}_m}{\bar{V}_m}\right)^2}$$

C.2.1.2 Mechanical energy per unit mass

C.2.1.2.1 First equation in 11.1.2

Errors arising are:

a) the relative error in the pressure difference measurement $(p_{21} - p_{11})$: $\delta\Delta p/\Delta p$;

b) the relative error in the mean isothermal factor: $\delta\bar{a}/\bar{a}$;

c) the relative error in the temperature difference: $\delta\Delta\theta/\Delta\theta$;

d) the relative error in the mean specific heat capacity: $\delta\bar{c}_p/\bar{c}_p$;

e) the relative error in the corrections due to secondary phenomena: $\delta\Delta E_m/E_m$.

The absolute uncertainty in E_m, δE_m, is given by the equation

$$(\delta E_m)^2 = (\Delta p \cdot \delta\bar{a})^2 + (\bar{a} \cdot \delta\Delta p)^2 + (\Delta\theta \cdot \delta\bar{c}_p)^2 + (\bar{c}_p \cdot \delta\Delta\theta)^2$$

Whence the relative uncertainty, $\dfrac{\delta E_m}{E_m}$, can be derived

$$\left(\frac{\delta E_m}{E_m}\right)^2 = \frac{1}{\left(1 + \dfrac{\bar{c}_p\Delta\theta}{\bar{a}\Delta p}\right)^2}\left[\left(\frac{\delta\bar{a}}{\bar{a}}\right)^2 + \left(\frac{\delta\Delta p}{\Delta p}\right)^2\right] + \frac{1}{\left(1 + \dfrac{\bar{a}\Delta p}{\bar{c}_p\Delta\theta}\right)^2}\left[\left(\frac{\delta\bar{c}_p}{\bar{c}_p}\right)^2 + \left(\frac{\delta\Delta\theta}{\Delta\theta}\right)^2\right] + \left(\frac{\delta\Delta E_m}{E_m}\right)^2$$

C.2.1.2.2 Second equation in 11.1.2

Errors arising are:

a) the relative uncertainty in the enthalpy difference: $\delta(h_{21} - h_{11})/(h_{21} - h_{11})$;

b) the relative uncertainty in the corrections due to the secondary phenomena: $\delta\Delta E_m/E_m$.

As previously, the uncertainty in the enthalpy difference takes into account the combination of the uncertainties in temperature measurements (errors in calibration, of measuring bridge, in reading), of those in pressure measurements and in determination of the enthalpies.

Let δh be the absolute total uncertainty in the determination of enthalpy, h. The relative uncertainty in the enthalpy difference is then

$$\frac{\delta(h_{21} - h_{11})}{h_{21} - h_{11}} = \left[\frac{2\,\delta h}{h_{21} - h_{11}}\right]_{\theta pd}$$

The uncertainties in the velocity and altitude terms have generally a very small effect.

C.2.1.3 Estimation of the uncertainty in corrections due to the secondary phenomena

These phenomena are:

a) heat exchange between surroundings and measurement circuits at inlet and outlet;

b) instability of energy at inlet;

c) parasitic exchanges.

It may be estimated that each correction is biased by an uncertainty equal to 10 % of its value and each corresponding relative uncertainty shall be evaluated by reference to E_m, i.e:

$$\frac{\delta f_1}{E_m}, \frac{\delta f_2}{E_m}, \ldots$$

These residual errors being independent of each other, they shall be combined by the root sum square method. An estimation of the uncertainty in the mechanical energy per unit mass due to corrections is thus obtained :

$$\frac{\delta\Delta E_m}{E_m} = \sqrt{\left(\frac{\delta f_1}{E_m}\right)^2 + \left(\frac{\delta f_2}{E_m}\right)^2 + \ldots}$$

C.2.2 Relative uncertainty in efficiency

The relative uncertainty, $\delta\eta/\eta$, in the determination of the efficiency is then

$$\frac{\delta\eta}{\eta} = \sqrt{\left(\frac{\delta E_h}{E_h}\right)^2 + \left(\frac{\delta E_m}{E_m}\right)^2}$$

Thus

$$\frac{\delta\eta}{\eta} = \left\{ \left(\frac{\delta\overline{V}_{\mathrm{m}}}{\overline{V}_{\mathrm{m}}}\right)^2 + \left[1 + \frac{1}{\left(1 + \frac{\overline{c}_p\Delta\theta}{\overline{a}\Delta p}\right)^2}\right] \left(\frac{\delta\Delta p}{\Delta p}\right)^2 + \frac{1}{\left(1 + \frac{\overline{c}_p\Delta\theta}{\overline{a}\Delta p}\right)^2} \left(\frac{\delta\overline{a}}{\overline{a}}\right)^2 + \frac{1}{\left(1 + \frac{\overline{a}\Delta p}{\overline{c}_p\Delta\theta}\right)^2} \left[\left(\frac{\delta\Delta\theta}{\Delta\theta}\right)^2 + \left(\frac{\delta\overline{c}_p}{\overline{c}_p}\right)^2\right] + \left(\frac{\delta\Delta E_{\mathrm{m}}}{E_{\mathrm{m}}}\right)^2 \right\}^{1/2}$$

In the case of the partial expansion operating procedure, where the temperatures are equalized, the above equation reduces to

$$\frac{\delta\eta}{\eta} = \left[\left(\frac{\delta\overline{V}_{\mathrm{m}}}{\overline{V}_{\mathrm{m}}}\right)^2 + \left(\frac{\delta\overline{a}}{\overline{a}}\right)^2 + 2\left(\frac{\delta\Delta p}{\Delta p}\right)^2 + \left(\frac{\delta\Delta E_{\mathrm{m}}}{E_{\mathrm{m}}}\right)^2\right]^{1/2}$$

Annex D

Other cavitation tests

D.0 Introduction

The purpose of other cavitation tests is to allow the evaluation of the development of the cavitation from other criteria than the pump total head drop, i.e.:

- development of cavitation cavities significantly extended;
- significant changes in sound-pressure level.

The appearance of the phenomenon or of the detected effect generally arises at various (NPSH) values according to the criterion selected, as shown schematically in figure 38.

It should be noted that the (NPSH) associated with each criterion allows the detection of the early effects of the cavitation and the sensitivity of a given impeller design to the cavitation under various flow conditions, but that no criterion is at this time available allowing connection of the (NPSH) values so defined with other effects such as erosion or vibrations.

During these tests, the speed of rotation shall be kept constant within measurement errors.

D.1 Cavitation appearance visual test

The net positive suction head associated with a defined onset of cavitation appearance visually detected, is denoted $(\mathrm{NPSH})_{\mathrm{vis}}$.

In cavitation appearance visual tests, cavitation is induced by reducing (NPSH) or other changes progressively until cavities appear which have a significant characteristic length (a few millimetres), the length of the cavities being measured in the general direction of flow.

Stroboscopic observations may be sufficient in many instances. For more accurate observations of cavitation appearance, photographic or high speed cinematographic techniques may be used.

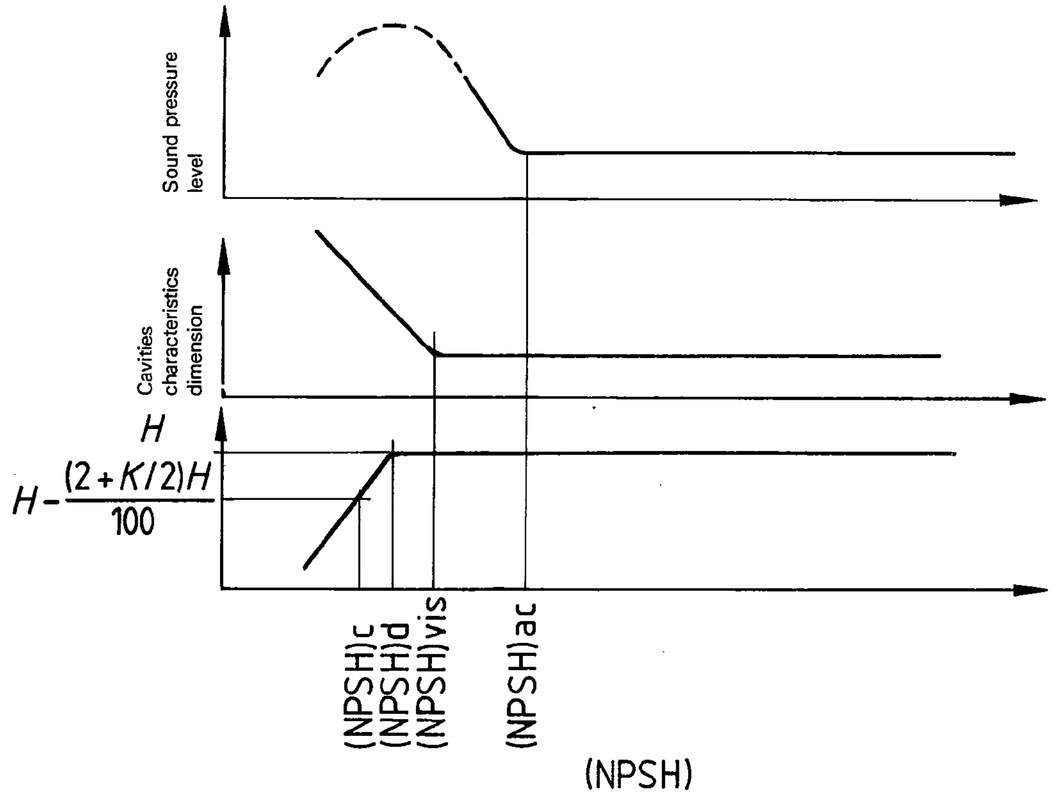


Figure 38 — Detected effect at various (NPSH) values according to criterion selected

Cavitation appearance tests necessitate some components of the pump or of the circuit being constructed of transparent materials at appropriate areas. For most pump designs, the test is usually only effective at flow below best efficiency point, the cavitation being difficult to observe on the pressure side of the impeller at higher flows.

For the cavitation appearance tests described, the speed of rotation may deviate from the specified speed by ± 20 %. Nevertheless, taking into account the qualitative nature of the cavitation appearance criterion, a higher deviation may be admitted by mutual agreement. Translation of results to the specified speed may be made using the relationship

$$(\mathrm{NPSH})_T = (\mathrm{NPSH}) \left(\frac{n_{sp}}{n} \right)^2$$

D.2 Cavitation onset determination by sound-pressure level measurement

The net positive suction head associated with a significant change in the sound-pressure level is denoted $(\mathrm{NPSH})_{ac}$ [frequency or frequency bands to be quoted with such (NPSH) figures]. When such a test is required, the amount of the sound-pressure change shall be specified in the contract.

In these tests, cavitation varies in intensity by progressively varying the (NPSH) whilst maintaining a constant flow rate. The sound-pressure level in a given frequency band or at a given frequency is measured with each change of (NPSH).

To avoid the results being invalidated by mechanical or hydraulic phenomena related to the pump but not to cavitation, sound-pressure level tests should preferably be conducted above 10 kHz or at least five times the passing frequency that an impeller blade makes with a volute tongue, diffuser blades, or similar hydraulic passage.

For arbitrary comparisons of cavitation performance on a sound-pressure level basis, octave bands with centre frequencies of 16 kHz and 31,5 kHz should preferably be used, unless it is shown that comparisons on this basis are invalid. In such cases, a smaller bandwidth (third octave), higher frequency band, or higher discrete frequency analysis may be used.

Particular care is needed in these tests to ensure that cavitation noise from other parts of the test rig does not influence the assessments made from the test data. Cavitation may occur in areas such as wear rings, between shroud and casing, or at the impeller tip. This may produce changes in sound-pressure level which appear before, or dominate, the sound-pressure level associated with the cavitation effect being investigated, which is generally located on the impeller blades.

A hydrophone having a suitable frequency response for the tests to be carried out may be used. It should be mounted flush with the wall of the inlet pipe, preferably at a distance of one inlet diameter away from the pump suction.

If no special acoustical method and/or arrangement are used, sound pressure level measurement may only be made for arbitrary comparisons of cavitation performance (see 12.1). The use of hydrophones mounted in pipe wall recesses or externally mounted sound probes are acceptable. It should be noted that these methods may only be valid in measuring changes in sound-pressure and not absolute values because there are reflections and disturbances associated with the recess or effects of pipe wall stiffness and pipe system characteristics.

Sound-pressure level measurement shall be made with an apparatus the sensitivity and accuracy of which are consistent with the change in sound-pressure level to be measured.

The value of the sound-pressure level cannot be translated to a speed of rotation other than the speed at which the measurement has been made, but the value of $(\mathrm{NPSH})_{ac}$ can be translated in the same way as in D.1.

Annex E

Friction losses

The equations given in 8.2.5 for calculating head loss due to friction involve a lengthy calculation which would lead in many cases to the conclusion that a correction need not be applied.

Figure 39 may be used as a preliminary check as to whether a calculation needs to be made. It applies to straight steel or wrought iron pipes of constant circular cross-section, handling cold water. Outlet and inlet pipes are assumed of equal diameter, and measuring points two diameters upstream and downstream of the inlet and outlet flanges, respectively. If the pipes are of different diameters, the diameter of the smaller pipe should be used.

Then if "no correction" is indicated, the calculation need not be made.

If correction is needed, the Moody graph (see figure 40) may be used, or the appropriate equations for λ solved (see 8.2.5). For the pipe roughness k the values given in table 20 may be used.

Table 20 — Typical values of equivalent uniform roughness k for pipes

(Source: MARKS, L.S. *Mechanical Engineer's Handbook*, McGraw-Hill, 1958.)

Commercial pipe (new) material	Typical values of equivalent uniform roughness k of the surface
	mm
Glass, drawn brass, copper or lead	0
Steel (wrought)	0,05
Asphalted cast iron	0,12
Galvanized iron	0,15
Cast iron	0,25
Concrete	0,3 to 3,0
Riveted steel	1,0 to 10,0

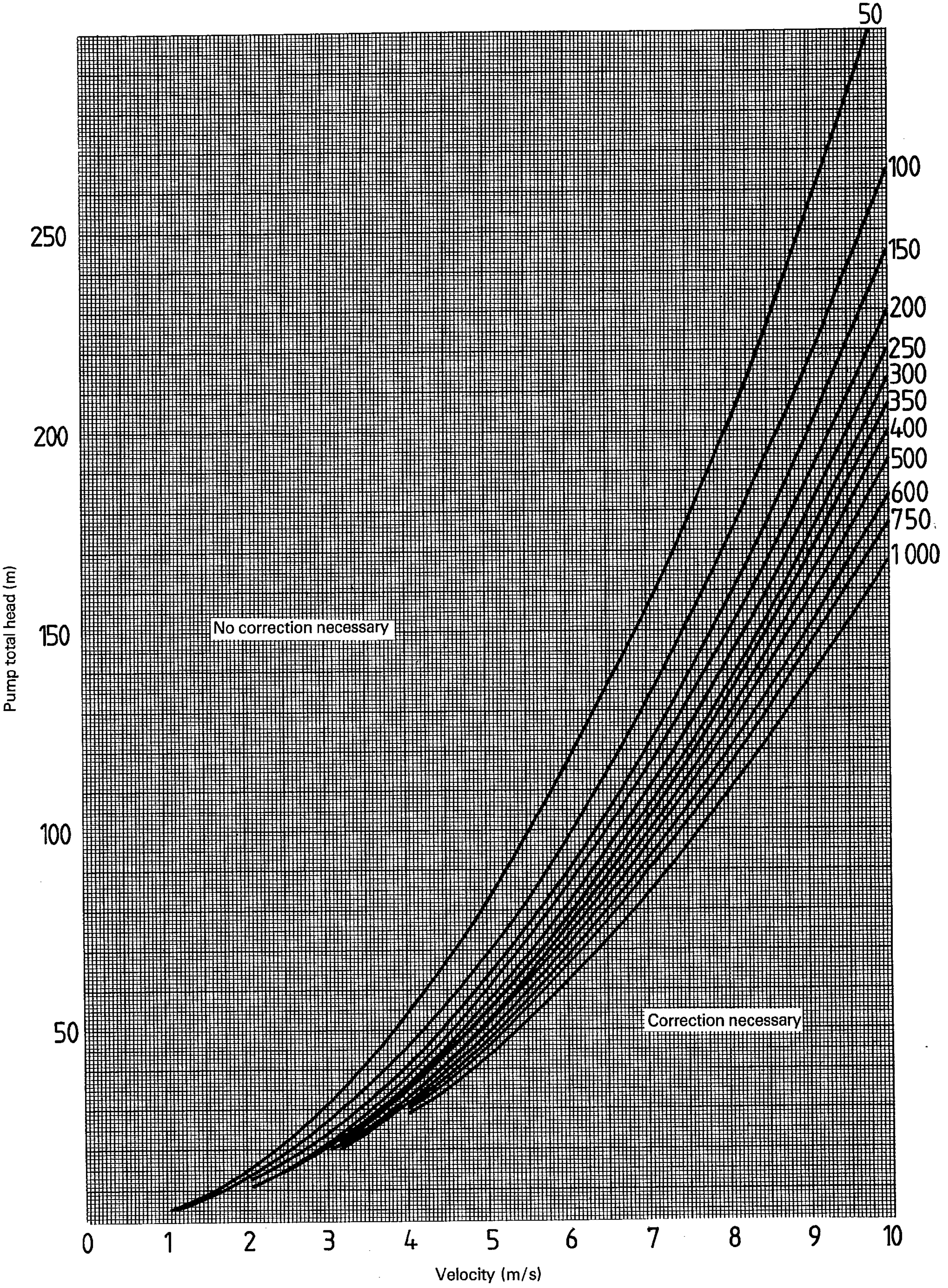


Figure 39 — Graph showing velocities above which loss corrections are required

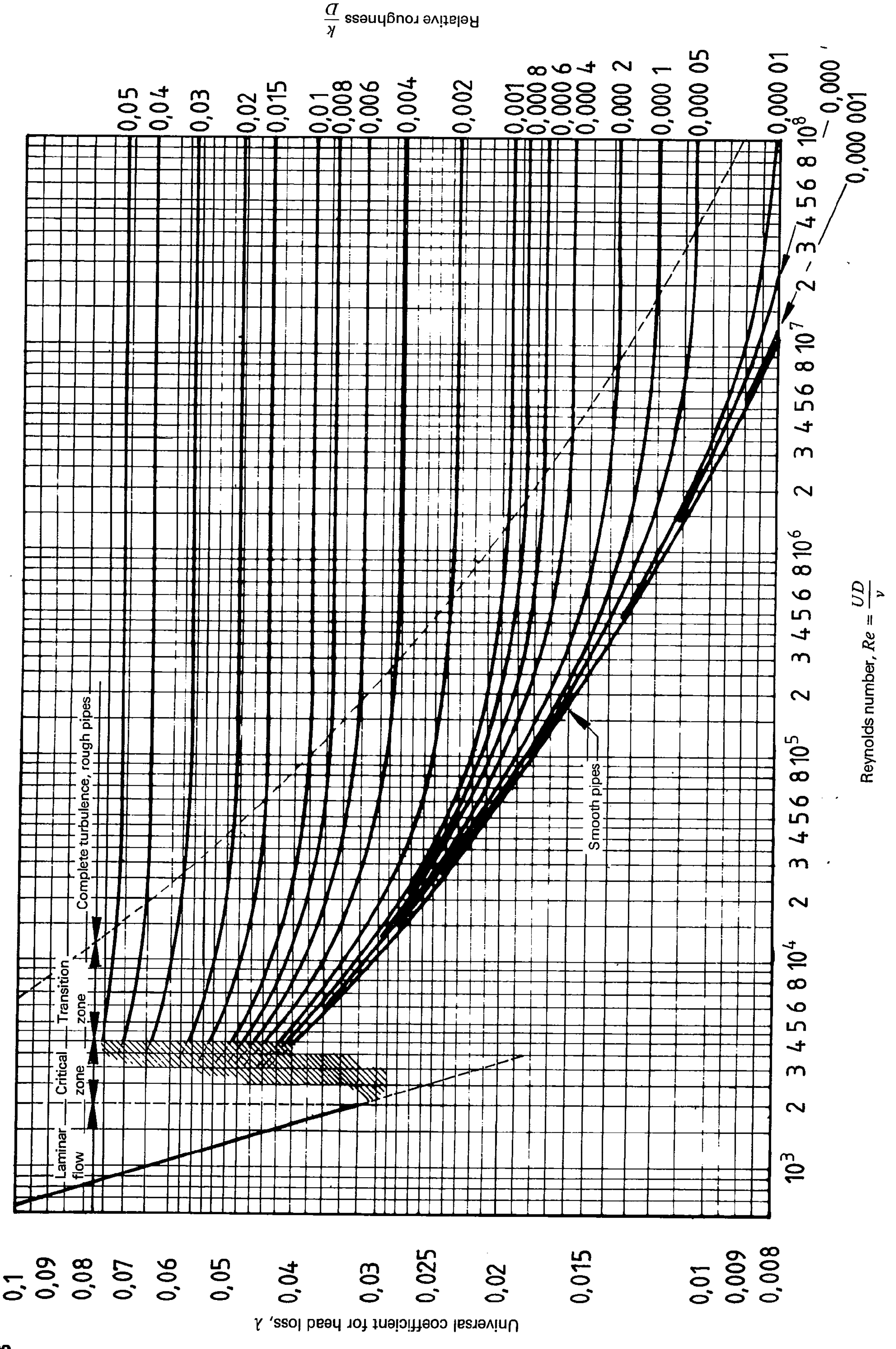


Figure 40 — Values of universal coefficient for head loss λ (Moody graph)

UDC 621.671.001.4 : 532.52

Descriptors : pumps, centrifugal pumps, tests, performance tests.

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