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ISO 21013-3

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Cryogenic vessels — Pressure-relief accessories for cryogenic service —

Part 3: **Sizing and capacity determination**

Récipients cryogéniques — Dispositifs de sécurité pour le service cryogénique —

Partie 3: Détermination de la taille et du volume

Reference number
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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 220, *Cryogenic vessels*.

This second edition cancels and replaces the first edition (ISO 21013-3:2006), which has been technically revised.

ISO 21013 consists of the following parts, under the general title *Cryogenic vessels — Pressure-relief accessories for cryogenic service*:

— *Part 1: Reclosable pressure-relief valves*

— *Part 2: Non-reclosable pressure-relief devices*

— *Part 3: Sizing and capacity determination*

— *Part 4: Pressure-relief accessories for cryogenic service*

Cryogenic vessels — Pressure-relief accessories for cryogenic service —

Part 3:
Sizing and capacity determination

1 Scope

This part of ISO 21013 provides separate calculation methods for determining the required mass flow to be relieved for each of the following specified conditions:

— vacuum-insulated vessels with insulation system (outer jacket + insulating material) intact under normal vacuum, outer jacket at ambient temperature, inner vessel at temperature of the contents at the specified relieving pressure;

— vacuum-insulated vessels with insulation system (outer jacket + insulating material) intact under normal vacuum, outer jacket at ambient temperature, inner vessel at temperature of the contents at the specified relieving pressure, pressure regulator of the pressure build-up system functioning at full potential;

— vacuum or non-vacuum-insulated vessels with insulation system remaining in place, but with loss of vacuum in the case of vacuum-insulated vessels, outer jacket at ambient temperature, inner vessel at temperature of the contents at the specified relieving pressure or vacuum or non-vacuum-insulated vessels with insulation system remaining fully or partially in place, but with loss of vacuum in the case of vacuum-insulated vessels, fire engulfment, inner vessel at temperature of the contents at the specified relieving pressure;

— vacuum-insulated vessels containing fluids with saturation temperature below 75 K at 1 bar with insulation system remaining in place, but with loss of vacuum with air or nitrogen in the vacuum space;

— vacuum insulated vessels containing fluids with saturation temperature below 75 K at 1 bar with insulation system remaining in place, but with loss of vacuum with air or nitrogen in the vacuum space with fire engulfment;

— vessels with insulation system totally lost and fire engulfment.

Good engineering practice based on well-established theoretical physical science needs to be adopted to determine the required mass flow where an appropriate calculation method is not provided for an applicable condition.

Recommendations for pressure relief devices for cryostats are given in Annex A.

2 Normative references

There are no normative references in this document.

3 Symbols

A	arithmetic mean of inner and outer surface areas of vessel insulating material	m^2
A_B	actual flow area of a pipe element	m^2
A_e	total outer surface area of pipe network between the outer jacket and location x	m^2
A_F	minimum flow area (reference area) in a pipe network	m^2
A_{Fd}	minimum flow area (reference area) in the pipe network, downstream of relief valve	m^2
A_{Fu}	minimum flow area (reference area) in the pipe network, upstream of relief valve	m^2
A_i	total outside surface area of inner vessel	m^2
A_j	total outer surface area of pipe network between the inner and outer jackets (interspace)	m^2
A_L	larger flow area of a pipe element containing two different flow area sizes	m^2
A_n	cross-sectional area, support, or pipe material	m^2
A_R	area ratio, A_S/A_L	—
A_S	smaller flow area of a pipe element containing two different flow area sizes	m^2
A_V	actual flow (orifice) area of a pressure relief valve	mm^2
A_{Va}	actual flow (orifice) area of pressure relief valve selected for final analysis	mm^2
A_{V1}	minimum required relief valve flow (orifice) area	mm^2
A_2	external heat transfer surface area of ambient air vaporizer	m^2
c_p	constant pressure specific heat capacity at the average of T_n and T_e	kJ/(kg·K)
C_V	experimentally determined flow rate through a pipe element or device	gal/min/psi
e_1	nominal insulating material thickness, normal vacuum, non-fire condition	m
e_3	minimum insulating material thickness, considering loss of vacuum, non-fire condition	m
e_5	insulating material thickness remaining in place during fire conditions	m
f_T	pipe flow friction coefficient	—
h	enthalpy of fluid at conditions of v	kJ/kg
h_r	specific enthalpy at relief valve inlet and outlet	kJ/kg
K_A	flow resistance coefficient of a pipe element in terms of A_F	—
K_B	flow resistance coefficient of a pipe element in terms of A_B	—
K_b	subcritical flow coefficient	—
K_{dr}	derated coefficient of discharge	—

$K_{dr,a}$	derated coefficient of discharge of next largest available valve orifice area greater than A_{V1}	—
$K_{dr,1}$	derated coefficient of discharge of initially analyzed valve	—
k_n	mean thermal conductivity of an individual support or pipe, between T and T_a	W/(m·K)
K_R	flow resistance coefficient of complete pipe network in terms of reference area, A_F	—
K_{RC}	flow resistance coefficient at the transition between critical and subcritical flow	—
K_{Rd}	overall flow resistance coefficient of pipe network, downstream of pressure relief valve	—
K_{Ru}	overall flow resistance coefficient of pipe network, upstream of pressure relief valve	—
K_{SUM}	total flow resistance coefficient of a series or parallel pipe network	—
K_V	experimentally determined flow rate through a pipe element or device	m^3/h/bar
k_1	mean thermal conductivity of insulating material, normal vacuum, non-fire condition	W/(m·K)
k_3	mean thermal conductivity of insulating material with air or gaseous lading, non-fire condition	W/(m·K)
L	latent heat of vaporization of cryogenic liquid at relieving conditions	kJ/kg
l	length, pipe element	m
L_a	latent heat of vaporization of cryogenic liquid at a pressure of 1,013 bar	kJ/kg
l_n	length of support or pipe in vacuum interspace	m
L'	enthalpy-to-volume expansion ratio for critical or all-gas fluid flow conditions	kJ/kg
M	molar mass	kg/mol
m_{max}	maximum mass capacity of vessel	kg
N	normal evaporation rate (NER)	%/day
P	relieving pressure, inner vessel	bar
P_b	pressure, safety relief valve outlet	bar
P_{b10}	pressure at relief valve outlet for a downstream built-up backpressure of 10 %	bar
P_{exit}	pressure at pipe network exit	bar
P_i	pressure, safety relief valve inlet	bar
P_S	pressure relief valve set pressure	bar
Q_m	mass flow rate	kg/h
Q_{ma}	mass flow rate of a relief valve within a given pipe network	kg/h
Q_{mNER}	mass flow rate due to the normal evaporation rate	kg/h

R	universal gas constant	J/(mol·K)
r	pipe elbow transition radius	m
T	relieving temperature, inner vessel	K
T_a	maximum external ambient temperature, non-fire condition	K
$T_{b,Pb}$	temperature at relief valve outlet	K
T_{b10}	temperature at relief valve outlet for a downstream built-up backpressure of 10 %	K
T_e	external temperature for a given condition	K
$T_{exit,Pb}$	temperature at pipe network exit	K
T_f	external temperature, fire condition	K
T_i	temperature, safety relief valve inlet	K
T_n	temperature of fluid at a given flow start location along the pipe network	K
T_{sat}	saturation temperature of fluid at a pressure of 1 bar	K
T_x	temperature of fluid at a given location x along the pipe network	K
U_p	overall heat transfer coefficient of a pipe network for given temperature conditions	W/ (m^2·K)
U_1	heat transfer coefficient of insulating material, normal vacuum, non-fire condition	W/ (m^2·K)
U_2	overall convective heat transfer coefficient of ambient air vaporizer	W/ (m^2·K)
U_3	heat transfer coefficient of insulating material with air or gaseous lading, non-fire condition	W/ (m^2·K)
U_{3a}	heat transfer coefficient, air or nitrogen condensation, loss of vacuum, non-fire condition	W/m^2
U_5	heat transfer coefficient of insulating material with air or gaseous lading, fire condition	W/ (m^2·K)
U_{5a}	heat transfer coefficient, air or nitrogen condensation, loss of vacuum, fire condition	W/m^2
w_n	heat leak from an individual support or pipe	W/K
W_T	total heat transfer rate for specified conditions	Watt [W]
W_{T1}	total heat transfer rate under normal operation	Watt [W]
W_{T1NER}	total NER heat transfer rate under normal operation	Watt [W]
W_{T2}	total heat transfer rate under normal operation, including pressure build-up device	Watt [W]
W_{T2NER}	total NER heat transfer rate under normal operation, including pressure build-up device	Watt [W]

W_{T3}	total heat transfer rate, loss of vacuum, insulation in place, non-fire condition, $T_{sat} > 75$ K	Watt [W]
W_{T3a}	total heat transfer rate, loss of vacuum, insulation in place, non-fire condition, $T_{sat} \leq 75$ K	Watt [W]
W_{T5}	total heat transfer rate, loss of vacuum, insulation in place, fire condition, $T_{sat} > 75$ K	Watt [W]
W_{T5a}	total heat transfer rate, loss of vacuum, insulation in place, fire condition, $T_{sat} \leq 75$ K	Watt [W]
W_{T6}	total heat transfer rate, loss of vacuum, insulation not in place, fire condition	Watt [W]
W_1	heat transfer rate through insulation system, normal vacuum, non-fire condition	Watt [W]
W_2	heat transfer rate through pressure build-up device, fully open regulator	Watt [W]
W_3	heat transfer rate through insulation system, loss of vacuum, non-fire condition	Watt [W]
W_{3a}	heat transfer rate through air or nitrogen condensation, loss of vacuum, non-fire condition	Watt [W]
W_4	heat transfer rate through interspace supports and piping	Watt [W]
W_5	heat transfer rate through vessel walls, insulation in place, fire condition	Watt [W]
W_{5a}	heat transfer rate through air or nitrogen condensation, loss of vacuum, fire condition	Watt [W]
W_6	heat transfer rate through vessel walls, insulation not in place, fire condition	Watt [W]
x	lengthwise location along a pipe network	m
X	number of insulation layers	—
Y	heat transfer rate U_{3a} or U_{5a}	—
Z_i	compressibility factor at pressure, P_i, and temperature, T_i	—
φ	pressure ratio P_{exit}/P	—
κ	isentropic exponent	—
λ_1	subcritical flow coefficient	—
λ_2	subcritical flow coefficient	—
v	specific volume of critical or all-gas fluid at a given temperature at pressure, P	m^3/kg
v_{b10}	specific volume at relief valve outlet for a downstream built-up backpressure of 10 %	m^3/kg
$v_{b,Pb}$	specific volume at pressure relief valve outlet, evaluated at h_r and a trial value of P_b	m^3/kg
v_{dmax}	maximum average downstream specific volume, as per desired backpressure limit	m^3/kg
v_{d10}	average downstream specific volume, for a downstream built-up backpressure of 10 %	m^3/kg

$v_{exit,Pb}$	specific volume at pipe network exit, evaluated at P_{exit} and $T_{exit,Pb}$	m^3/kg
v_{exit10}	specific volume at pipe network exit for a downstream built-up backpressure of 10 %	m^3/kg
v_g	specific volume of saturated gas at relieving pressure, P	m^3/kg
v_{ga}	specific volume of saturated gas at a pressure of 1,013 bar	m^3/kg
v_i	specific volume, safety relief valve inlet	m^3/kg
v_l	specific volume of saturated liquid at relieving pressure, P	m^3/kg
v_{la}	specific volume of saturated liquid at a pressure of 1,013 bar	m^3/kg
v_u	average specific volume of flowing fluid upstream of pressure relief valve inlet	m^3/kg
ψ	expression for determining Q_m and T for critical or gas-full-vessel fluid flow conditions	$m^{3/2}\cdot kg^{1/2}/kJ$

4 Calculation of the total quantity of heat transferred per unit time from the hot wall (outer jacket) to the cold wall (inner vessel)

4.1 General

P (in bar abs) is the actual relieving pressure inside the vessel which is used for calculating the required mass flow through pressure relief devices.

T_a (in K) is the maximum ambient temperature for conditions other than fire (as specified, for example, by a regulation or standard).

T_f (in K) is the external environment temperature under fire conditions which is taken to be 922 K in this part of ISO 21013.

T (in K) is the relieving temperature in the vessel to be taken into account.

a) For subcritical fluids, T is the saturation temperature of the liquid at pressure, P.

b) For critical or supercritical fluids, T is calculated from 5.2.

4.2 Under conditions other than fire

4.2.1 Vacuum-insulated vessels under normal vacuum

W_1 is the quantity of heat transferred per unit time (in watts) by heat leak through the insulation system.

$$W_1 = (U_1 \cdot A)(T_a - T) \quad (1)$$

where

U_1 is the overall heat transfer coefficient of the insulating material under normal vacuum, in W/(m²·K);

$$U_1 = \frac{k_1}{e_1};$$

k_1 is the mean thermal conductivity of the insulating material under normal vacuum, between T and T_a, in W/(m·K);

e_1 is the nominal insulating material thickness, in metres;

A is the arithmetic mean of the inner and outer surface areas of the vessel insulating material, in m².

4.2.2 Pressure build-up device

W_2 is the quantity of heat transferred per unit time (in watts) by the pressure build-up device circuit with the regulator fully open. W_2 is determined from the type (ambient air, water or steam, electrical, etc.) and design of the pressure build-up device circuit. For example, in the case of an ambient air vaporizer.

$$W_2 = (U_2 \cdot A_2)(T_a - T) \tag{2}$$

where

U_2 is the overall convective heat transfer coefficient of the ambient air vaporizer, in W/(m²·K);

A_2 is the external heat transfer surface area of the vaporizer, in m².

As a first approximation, the following may be used:

$$U_2(T_a - T) = 19\,000 \text{ W/m}^2 \text{ for } T \le 75 \text{K} \tag{3}$$

$$U_2(T_a - T) = 2\,850 \text{ W/m}^2 \text{ for } T > 75 \text{K} \tag{4}$$

4.2.3 Vacuum-insulated vessels in the case of loss of vacuum and non-vacuum insulated vessels

W_3 is the quantity of heat transferred per unit time (in watts) by heat leak through the insulating material.

$$W_3 = (U_3 \cdot A)(T_a - T) \tag{5}$$

where

If the insulation is fully effective for conduction, convection, and radiation heat transfer at 328 K, U_3 may be calculated using Formula (6).

$$U_3 = \frac{k_3}{e_3} \quad (6)$$

U_3 is the overall heat transfer coefficient of the insulating material when saturated with gaseous lading or air at atmospheric pressure, whichever is greater, in W/(m²·K);

k_3 is the mean thermal conductivity of the insulating material saturated with gaseous lading or air at atmospheric pressure, whichever provides the greater coefficient, between T and T_a, in W/(m·K). Values of k_3 for gases are listed in Table 1;

e_3 is the minimum insulating material thickness taking into account the manufacturing tolerances or effects of sudden loss of vacuum, in metres.

NOTE This formula might not be applicable at temperatures below 75 K with a small thickness of insulating material as the maximum heat transfer coefficient would be given by air condensation.

Vacuum space, gas space, or space occupied by the deteriorated insulation shall not be included in the thickness of the insulation. The effectiveness of these spaces or deteriorated insulation in reducing conduction, convection, or radiation heat transfer may be evaluated separately and included in the overall heat transfer coefficient, U_3, using methods found in published heat transfer literature. Deterioration of the insulation can be caused by the following:

— moisture condensation;

— air condensation;

— increase in the density of the insulation due to a sudden loss of vacuum.

Table 1 — Thermal conductivity for refrigerated (cryogenic) fluids at the mean temperature between saturation and 328 K (k_3) and 922 K (k_5) at 1 bar

Fluid	k_3 [W/(m·K)]	k_5 [W/(m·K)]
Air	0,019	0,043
Argon	0,013	0,027
Carbon dioxide	0,017	0,039
Carbon monoxide	0,020	0,039
Helium	0,104	0,211
Hydrogen	0,116	0,217
Methane	0,024	0,074
Neon	0,034	0,067
Nitrogen	0,019	0,040
Oxygen	0,019	0,043
Krypton	0,007	0,015
Xenon	0,005	0,009
Ethane	0,016	0,064
Trifluoromethane	0,012	0,027
Ethylene (ethene)	0,015	0,056
Nitrous oxide	0,014	0,038

4.2.4 Supports and piping

W_4 is the quantity of heat transferred per unit time (in watts) by supports and piping located in the interspace.

$$W_4 = (w_1 + w_2 + w_3 + \ldots + w_n)(T_a - T) \quad (7)$$

where

w_n is the heat leak per degree K contributed by one of the supports or the pipes, in W/K.

$$w_n = k_n \left(\frac{A_n}{l_n} \right) \quad (8)$$

k_n is the mean thermal conductivity of the support or pipe material between T and T_a, in W/(m·K);

A_n is the support or pipe section area, in m^2;

l_n is the support or pipe length in the vacuum interspace, in metres.

4.3 Under fire conditions

4.3.1 Insulation system remains fully or partially in place during fire conditions

W_5 is the quantity of heat transferred per unit time (in watts) by heat leak through the vessel walls.

$$W_5 = 2{,}6 \cdot (922 - T) \cdot U_5 \cdot A^{0{,}82} \quad (9)$$

where

If the insulation is fully effective for conduction, convection, and radiation heat transfer for an external temperature of 922 K, U_5 may be calculated using Formula (10).

$$U_5 = \frac{k_5}{e_5} \quad (10)$$

U_5 is the overall heat transfer coefficient of the container-insulating material when saturated with gaseous lading or air at atmospheric pressure, whichever is greater, in W/(m^2·K);

k_5 is the mean thermal conductivity of the insulating material saturated with gaseous lading or air at atmospheric pressure, whichever provides the greater coefficient, between T and 922 K, in W/(m·K). Values of k_5 for gases are listed in Table 1;

e_5 is the thickness of the insulating material remaining in place during fire conditions, in metres;

A is the arithmetic mean of the inner and outer surface areas of the insulating material remaining in place during fire conditions, in m^2.

Vacuum space, gas space, or space occupied by the deteriorated insulation shall not be included in the thickness of the insulation. The effectiveness of these spaces or deteriorated insulation in reducing conduction, convection, or radiation heat transfer may be evaluated separately and included in the overall heat transfer coefficient, U_5, using methods found in published heat transfer literature. Deterioration of the insulation can be caused by the following:

— moisture condensation;

— air condensation;

— increase in the density of the insulation due to a sudden loss of vacuum;

— degradation due to heat.

If the outer jacket remains in place during fire conditions, but the insulating material is entirely destroyed, U_5 is equal to the overall heat transfer coefficient with gaseous lading or air at atmospheric pressure in the space between the outer jacket and the inner vessel, whichever provides the greater coefficient, between T and 922 K. A is equal to the mean surface area of the interspace.

4.3.2 Insulation system does not remain in place during fire conditions

W_6 is the quantity of heat transferred per unit time (in watts) by heat leak through the vessel walls.

$$W_6 = 7{,}1 \cdot 10^4 \cdot A_i^{0{,}82} \tag{11}$$

where

A_i is the total outside surface area of the inner vessel, in m^2.

The heat transferred by supports and piping located in the interspace can be neglected in this case.

4.4 Air or Nitrogen condensation

4.4.1 General

The air or nitrogen condensation case for the loss of vacuum condition shall be considered for fluids with a saturation temperature below 75 K at 1 bar.

Air condensation, for the case of loss of vacuum to the atmosphere on a vacuum insulated container, is highly dependent on the type of insulation and how the insulation is designed. Since air condensation occurs primarily below 75 K, and fluids with saturation temperatures below 75 K are generally stored and transported in containers insulated with multi-layer insulation, this part of ISO 21013 covers air condensation on multi-layer insulated containers only. In the absence of pertinent reliable data on perlite insulated vessels, 4.2.3, 4.3.1, and 4.3.2 shall be used with thermal conductivity values shown in Table 1 increased by a factor of two in Formula (6) for k_3 and Formula (10) for k_5, respectively.

Condensation of air on a multi-layer insulated surface below 75 K will depend on the rate of air access to the insulated surface. On a multi-layer insulated container, the air condensation rate can vary depending on the number of layers and the air access allowed by the design of the insulation.

Figure 1 provides heat transfer rates from air condensation to the stored fluid as a function of the number of layers of insulation. The fire engulfment curve is an extrapolation for 922 K ambient temperature. Unless heat transfer rates under the loss of vacuum condition from air condensation can be determined for the same type and design of multi-layer insulation from prototype tests or actual incidents, heat transfer rates from Figure 1 shall be used.

4.4.2 Loss of vacuum with air and nitrogen

W_{3a} is the quantity of heat transferred per unit time (in watts) through air or nitrogen condensation for vacuum-insulated vessels in the case of a loss of vacuum with air or nitrogen.

$$W_{3a} = U_{3a} \cdot A_i \tag{12}$$

where

U_{3a} is the heat transfer through air or nitrogen condensation, in watts per square metre of the inner vessel outer surface area, from Figure 1.

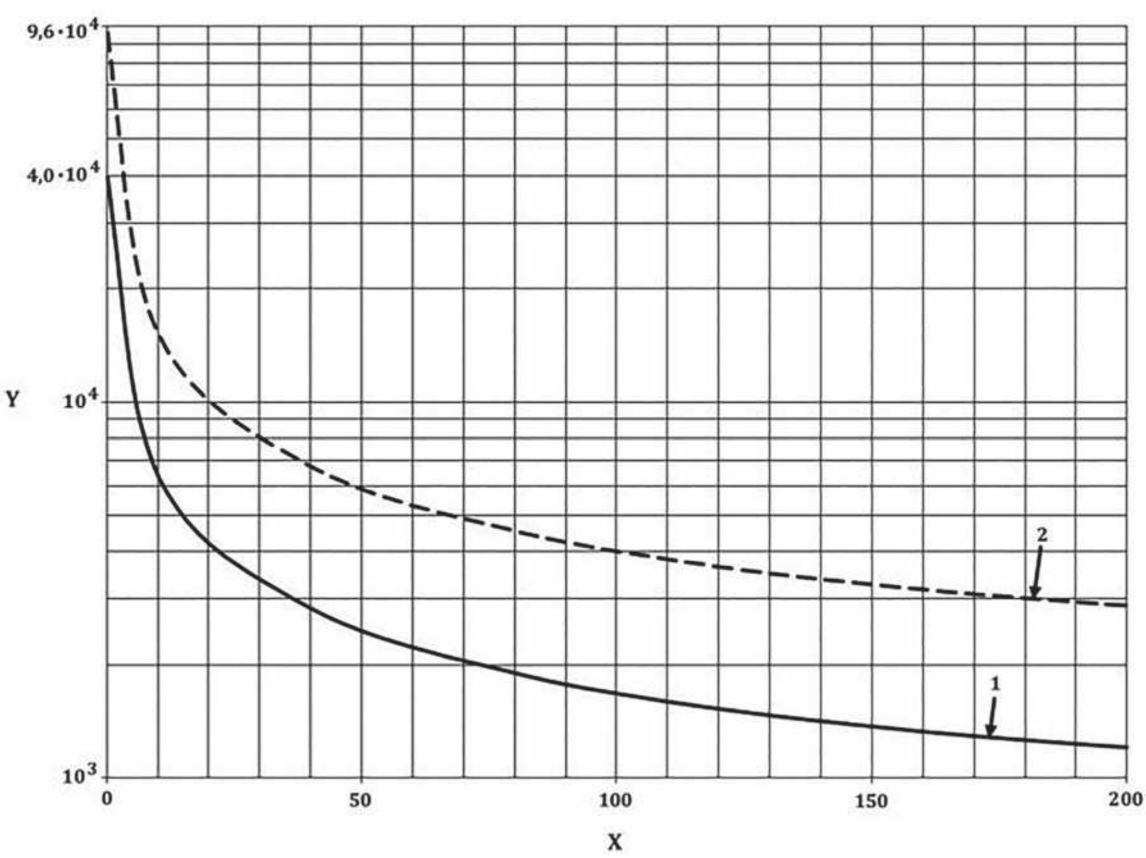
4.4.3 Fire with loss of vacuum with air or nitrogen

W_{5a} is the quantity of heat transferred per unit time (in watts) through air or nitrogen condensation for vacuum-insulated vessels in the case of a fire and loss of vacuum with air or nitrogen.

$$W_{5a} = 1{,}95 \cdot U_{5a} \cdot A_i^{0{,}82} \qquad (13)$$

where

U_{5a} is the heat transfer through air or nitrogen condensation during fire conditions, in watts per square metre of the inner vessel surface area, from Figure 1.



Key

X number of insulation layers

Y heat transfer [W/m²]

1 $U_{3a} = Y = \dfrac{38\,400 + 420 \cdot X^{0{,}73}}{0{,}96 + X^{0{,}73}}$

2 $U_{5a} = Y = \dfrac{92\,160 + 1\,000 \cdot X^{0{,}73}}{0{,}96 + X^{0{,}73}}$

Figure 1 — Heat transfer rate for air or nitrogen condensation

4.5 Heat transfer per unit time (watts)

4.5.1 General

The required mass flow rate, Q_m, to be relieved can be calculated from the heat transfer, W_T, for the following specified conditions, where W_T is the total heat transfer applicable to the specified condition.

4.5.2 Normal operation

$$W_{T1} = W_1 + W_4 \tag{14}$$

Alternatively, the heat transfer rate, W_{T1NER}, can be determined from the normal evaporation rate (NER).

$$W_{T1NER} = \left(\frac{Q_{mNER} \cdot L_a}{3,6} \right) \left(\frac{v_{ga}}{v_{ga} - v_{la}} \right) \tag{15}$$

where

Q_{mNER} is the mass flow rate due to the normal evaporation rate, in kg/h;

L_a is the latent heat of vaporization of the cryogenic liquid at a pressure of 1,013 bar, in kJ/kg;

v_{ga} is the specific volume of saturated gas at a saturation pressure of 1,013 bar, in m^3/kg;

v_{la} is the specific volume of saturated liquid at a saturation pressure of 1,013 bar, in m^3/kg;

W_{T1NER} is the total heat leak calculated from the experimentally determined normal evaporation rate, in watts.

4.5.3 Pressure build up regulator fully open

$$W_{T2} = W_{T1} + W_2 \tag{16}$$

Or for the NER method:

$$W_{T2NER} = W_{T1NER} + W_2 \tag{17}$$

4.5.4 Loss of vacuum condition

The heat transfer rate is to be the larger of W_{T3} or W_{T3a}.

$$W_{T3} = W_3 + W_4 \tag{18}$$

$$W_{T3a} = W_{3a} + W_4 \tag{19}$$

where

W_{T3} is the total heat transfer rate if the saturation temperature of the fluid is greater than or equal to 75 K at 1 bar;

W_{T3a} is the total heat transfer rate if the saturation temperature of the fluid is less than 75 K at 1 bar.

Alternatively, W_{T3} may be calculated using Formula (20)

$$W_{T3} = W_{T1} + W_3 \tag{20}$$

or approximately, using Formula (21)

$$W_{T3} = W_{T1NER} + W_3 \tag{21}$$

W_{T3a} may be calculated using Formula (22)

$$W_{T3a} = W_{T1} + W_{3a} \tag{22}$$

or approximately, using Formula (23)

$$W_{T3a} = W_{T1NER} + W_{3a} \tag{23}$$

4.5.5 Fire condition with loss of vacuum, vacuum jacket, and insulation fully or partially in place

The heat transfer rate is to be the larger of W_{T5} or W_{T5a}.

where

W_{T5} is equal to the heat transfer rate, W_5, if the saturation temperature of the fluid is greater than or equal to 75 K at 1 bar

W_{T5a} is equal to the heat transfer rate, W_{5a}, if the saturation temperature of the fluid is less than 75 K at 1 bar

4.5.6 Fire condition with loss of vacuum, insulation not in place

The heat transfer rate is to be the larger of W_{T6} = W_6 or W_{T5} = W_{5a}, where W_{5a} is calculated with U_{5a} for the bare surface condition from Figure 1.

4.5.7 Total heat transfer rate

W_T is the total heat transfer rate and is equal to W_{T1}, W_{T1NER}, W_{T2}, W_{T2NER}, W_{T3}, W_{T3a}, W_{T5}, W_{T5a}, or W_{T6}, as applicable.

5 Calculation of the mass flow to be relieved by pressure relief devices

5.1 Relieving pressure, *P*, less than the critical pressure

For a relieving pressure, *P*, less than the critical pressure, the discharge mass flow rate Q_m (in kg/h) is calculated on the basis of either the heat input, W_T, or the normal evaporation rate, Q_{mNER} (in kg/h).

For heat input W_T

$$Q_m = 3{,}6\left(\frac{v_g - v_l}{v_g}\right)\left(\frac{W_T}{L}\right) \tag{24}$$

where

v_g is the specific volume of saturated gas at the relieving pressure, P, in m^3/kg;

v_l is the specific volume of saturated liquid at the relieving pressure, P, in m^3/kg;

L is the latent heat of vaporization of the cryogenic liquid at the relieving conditions, in kJ/kg.

For normal evaporation rate, Q_{mNER}

$$Q_m = Q_{mNER} = \frac{N \cdot m_{max}}{2\,400} \quad (25)$$

where

N is the normal evaporation rate (NER), in percent per day;

m_{max} is the maximum mass capacity of the vessel, in kg.

5.2 Relieving pressure, *P*, equal to or greater than the critical pressure

For a relieving pressure, P, equal to or greater than the critical pressure, the discharge mass flow rate Q_m is given by Formula (26).

$$Q_m = 3{,}6\left(\frac{W_T}{L'}\right) \quad (26)$$

where

$$L' = v\left[\frac{\partial h}{\partial v}\right]_P \quad (27)$$

L' (kJ/kg) is evaluated at the relieving pressure, P, and inner vessel flow exit temperature, T (K). The value of T and its corresponding value of L' are found by tabulating values of ψ using thermophysical property tables and finding the values of T and L' associated with the maximum value found for ψ, where ψ is given by Formula (28).

$$\psi = \frac{\sqrt{v}}{v\left[\frac{\partial h}{\partial v}\right]_P} = \frac{\sqrt{v}}{L'} \quad (28)$$

where

v is the specific volume of critical or subcritical fluid (gas-full condition) at the relieving pressure, P, in the vessel at the temperature of consideration, in m^3/kg;

h is the enthalpy of the fluid at the same conditions as v, in kJ/kg.

5.3 Example

Calculate the values of L' and T to be used for liquid hydrogen relieving at pressure, P = 13,8 bar, as given in Table 2.

Table 2 — Determination of relieving temperature, *T*

Temperature [K]	v [m³/kg]	$L' = v\left[\frac{\partial h}{\partial v}\right]_P$	$\psi = \frac{\sqrt{v}}{v\left[\frac{\partial h}{\partial v}\right]_P}$
33,3	0,027 16	214,09	0,000 769 7
34,7	0,0583 0	236,56	0,001 102 06
34,8	0,0588 5	237,49	0,001 0214 max
34,9	0,0593 5	238,65	0,001 020 8
38,9	0,0855 4	304,53	0,000 960 3
44,4	0,1109 7	384,77	0,000 865 7

At P = 13,8 bar, the maximum value of ψ occurs at T = 34,8 K for hydrogen. For this condition, L' = 237,49 kJ/kg.

6 Piping for pressure relief devices

6.1 Pressure drop

6.1.1 General

If the piping between the outer jacket and safety relief device is longer than 0,6 m, heat transfer to the released flow shall be taken into account. This heat transfer reduces the product density and consequently reduces the effective discharge rate of the relief system.

When fittings and piping are used on the upstream or downstream sides of pressure relief devices, the passages shall be designed such that the flow capacity of the pressure relief system is not reduced below the capacity required for the container on which the pressure relief system is installed.

6.1.2 Relief valves

Pressure drops associated with the flow resistance of the pipe network are to be considered when sizing relief valves. In order to avoid resonance ("chatter") in conventional direct acting relief valves, it is recommended that the maximum pressure drop across the upstream pipe network at the flow capacity, Q_{ma}, of the valve within the given system configuration be less than or equal to 3 % of the relief valve set pressure (bar, gauge). Additionally, it is recommended that the differential pressure drop between the relief valve outlet and the system outlet that develops as a result of flow after the pressure relief device opens ("built-up back pressure") be limited to 10 % of the valve set pressure (bar, gauge). The sizing and balancing of the upstream and downstream pipe network designs shall be optimized whenever possible to satisfy these pressure drop conditions. Furthermore, internally pressure-balanced or externally pilot-operated valves may be used to mitigate valve chatter in system designs which exceed these pressure drops.

More detailed engineering analysis may allow for higher pressure drops as long as the capacity of the system is demonstrated to meet or exceed the requirements of the vessel and that performance is not compromised by valve chatter.

6.1.3 Bursting discs

Built-up back pressure associated with flow resistance through the pipe network shall be considered with respect to the flow capacity of the pipe network and pressure requirements of the inner vessel.

6.2 Back pressure consideration

When adding up flow capacities of multiple pressure relief devices to satisfy the total required discharge capacity, the effect of back pressure from open relief devices on other open or closed relief devices shall be taken into account. Closing of reclosable pressure relief devices by opening of non-reclosable pressure relief devices and reduction of flow capacities due to higher back pressures shall be evaluated. Consideration shall also be made for the opening of reclosable relief devices and the effect that this may have on increasing the bursting pressure of bursting discs due to the elevated back pressure.

6.3 Heat transfer

For loss of vacuum and fire engulfment cases (with or without air condensation), the adjusted flow temperature T_x [K] at a given location along the pipe network is determined to account for heat transfer into the pipe network.

$$T_x = T_e - \left[\frac{T_e - T_n}{e^{\left[\frac{3{,}6 \cdot U_p}{Q_m \cdot c_p}\right] \cdot \left[\left(\frac{T_e + T_n}{2 \cdot T_e}\right)(A_j) + A_e\right]}} \right] \quad (29)$$

where

T_e is T_a for the non-fire case or T_f for the fire case;

T_n is the fluid temperature [K] at the flow start location under consideration. $T_n = T$ when evaluating the temperature rise between the inner vessel and a location x (at temperature, T_x) in the pipe network. $T_n = T_b$ when evaluating the temperature rise between a pressure relief valve and a downstream location x (at temperature, T_x) in the pipe network;

U_p is 105 [W/(m^2·K)] for $T_e = T_f$;

U_p is 78,5 [W/(m^2·K)] for $T_e = T_a$ and T_n less than or equal to 75 K;

U_p is 16,5 [W/(m^2·K)] for $T_e = T_a$ and T_n is greater than 75 K;

A_j is the total outer surface area of the pipe network containing flow of fluid between the inner and outer jackets, in m^2;

A_e is the total outer surface area of the pipe network containing flow of fluid, from the outer jacket up to the flow temperature location x under consideration, in m^2;

c_p is the constant pressure specific heat capacity at the average of temperature, T_n and T_e, in kJ/kg·K. Values of c_p are listed in Table 3.

Table 3 — Specific heat for refrigerated (cryogenic) fluids at the mean temperature between saturation and 328 K and 922 K at 1 bar

Fluid	c_p [kJ/(kg·K)] for T_e = 328 K	c_p [kJ/(kg·K)] for T_e = 922 K
Air	1,014	1,038
Argon	0,523	0,521
Carbon dioxide	0,826	1,059
Carbon monoxide	1,044	1,065
Helium	5,193	5,193
Hydrogen	13,12	14,51
Methane	2,115	2,963

Table 3 *(continued)*

Fluid	c_p [kJ/(kg·K)] for T_e = 328 K	c_p [kJ/(kg·K)] for T_e = 922 K
Neon	1,031	1,030
Nitrogen	1,043	1,056
Oxygen	0,914	0,974
Krypton	0,251	0,248
Xenon	0,162	0,159
Ethane	1,604	2,799
Trifluoromethane	0,687	1,069
Ethylene (ethene)	1,390	2,397
Nitrous oxide	0,842	1,075

7 Sizing of pressure relief devices

7.1 General

For all pressure relief devices which have to discharge together the mass flow, Q_m, at the same relieving pressure, P, the sum of the relieving capacities of all of the individual relief devices shall be equal to or greater than Q_m. Inlet pressure drops and back pressure distribution should be taken into account when calculating combined capacity.

It is not permitted to calculate the capacity at a lower overpressure than that at which the tests to determine flow characteristics were carried out, although it is permissible to calculate the capacity at any higher overpressure.

NOTE 1 Valves having a certified (derated) coefficient of discharge established on critical flow at the test backpressure might not have the same certified (derated) coefficient of discharge at a higher backpressure.

NOTE 2 Due to variations in the use of the term coefficient of discharge internationally (derated) is included in this part of ISO 21013 to remind users that K_{dr} or (derated) coefficient of discharge is 0,9 times the experimentally determined coefficient of discharge. If the factor 0,9 is already included in the coefficient of discharge, then $K_{dr} = K_d$.

7.2 Sizing of pressure relief valves

7.2.1 Discharge capacity

The flow of a gas or vapour through an orifice, such as the flow area of a safety valve, increases as the upstream pressure (P_i) is increased until critical flow is achieved. Further, decrease in safety relief valve outlet pressure (P_b) will not result in any further increase in flow.

7.2.2 Determination of critical vs. subcritical flow for gases

Critical flow occurs when

$$\frac{P_b}{P_i} \leq \left(\frac{2}{\kappa+1}\right)^{\left(\frac{\kappa}{\kappa-1}\right)} \tag{30}$$

and subcritical flow occurs when

$$\frac{P_b}{P_i} > \left(\frac{2}{\kappa+1}\right)^{\left(\frac{\kappa}{\kappa-1}\right)} \tag{31}$$

where

κ is the isentropic exponent (the ratio of the specific heat capacity at constant pressure to the specific heat capacity at constant volume).

7.2.3 Critical flow

For critical flow, the minimum required valve flow area is given by Formula (32).

$$A_V = \frac{Q_m}{31{,}62 \cdot P_i \cdot C \cdot K_{dr} \cdot \sqrt{\frac{M}{Z_i \cdot T_i}}} = \frac{Q_m}{0{,}2\,883 \cdot C \cdot K_{dr} \cdot \sqrt{\frac{P_i}{v_i}}} \tag{32}$$

where

A_V is the valve flow area (actual orifice area, not curtain area), in square millimetres;

Q_m is the mass flow to be relieved by the device, in kg/h;

P_i is the pressure at the inlet of the pressure relief valve, in bar absolute;

K_{dr} is the derated coefficient of discharge;

M is the molar mass of the gas, in kg/mol;

T_i is the temperature at the inlet of the pressure relief valve, in K;

v_i is the specific volume at the inlet of the pressure relief valve, in m^3/kg;

Z_i is the compressibility factor at pressure, P_i and temperature, T_i.

And the coefficient, C, is given by Formula (33).

$$C = 3{,}948\sqrt{\kappa\left(\frac{2}{\kappa+1}\right)^{\frac{(\kappa+1)}{(\kappa-1)}}} \tag{33}$$

NOTE 1 $3{,}948 = \dfrac{3\,600}{\sqrt{\left(10^5\right)R}}$

NOTE 2 $0{,}2\,883 = 0{,}1\sqrt{R}$

NOTE 3 $R = 8{,}314\,\text{J} / \text{mol} \cdot \text{K}$

The values of C in Table 4, where κ is at standard conditions, shall be used. Alternatively, the value of κ used to determine C may be based on the actual flowing conditions at the relief valve inlet, potentially yielding less conservative results near saturation. Values within ±5 % of the critical point should be used for evaluations close to the critical state of the fluid.

Table 4 — Coefficient, C vs isentropic exponent, κ

κ	C	κ	C	κ	C
1,001	2,395	1,26	2,605	1,52	2,780
1,02	2,412	1,28	2,620	1,54	2,793
1,04	2,430	1,30	2,634	1,56	2,805
1,06	2,447	1,32	2,649	1,58	2,817
1,08	2,464	1,34	2,663	1,60	2,829
1,10	2,481	1,36	2,676	1,62	2,840
1,12	2,497	1,38	2,690	1,64	2,852
1,14	2,513	1,40	2,703	1,66	2,863
1,16	2,529	1,42	2,713	1,68	2,874
1,18	2,545	1,44	2,730	1,70	2,886
1,20	2,560	1,46	2,743	2,00	3,039
1,22	2,576	1,48	2,755	2,20	3,129
1,24	2,591	1,50	2,768	2,50	3,249

7.2.4 Subcritical flow

For subcritical flow of gases, the minimum required valve flow area is given by Formula (34).

$$A_V = \frac{Q_m}{31{,}62 \cdot P_i \cdot C \cdot K_{dr} \cdot K_b \cdot \sqrt{\frac{M}{Z_i \cdot T_i}}} = \frac{Q_m}{0{,}2883 \cdot C \cdot K_{dr} \cdot K_b \cdot \sqrt{\frac{P_i}{v_i}}} \qquad (34)$$

where

$$K_b = \sqrt{\frac{\left[\frac{2 \cdot \kappa}{\kappa - 1}\right]\left[\left(\frac{P_b}{P_i}\right)^{\frac{2}{\kappa}} - \left(\frac{P_b}{P_i}\right)^{\frac{\kappa+1}{\kappa}}\right]}{\kappa\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{\kappa-1}}}};$$

P_b is the pressure at the outlet of the pressure relief valve, in bar absolute.

For non-flashing liquids in the turbulent zone where the Reynolds Number, Re, is greater than or equal to 80 000.

$$Q_m = 1{,}61 \cdot K_{dr} \cdot A_v \cdot \sqrt{\frac{P_i - P_b}{v_i}} \qquad (35)$$

NOTE $1{,}61 = \frac{3\ 600\sqrt{2}}{10\sqrt{10^5}}$

7.2.5 Recommended analysis method

7.2.5.1 Upstream pipe network — Determination of relief valve inlet conditions

a) Determine inlet temperature, T_i, using the temperature equation (6.3) by evaluating the heat input into the pipe network from the inner jacket (at temperature, T) to the pressure relief valve inlet.

b) Determine the average upstream specific volume, v_u, using relieving pressure, P, and evaluating the average of the specific volumes at temperatures T and T_i.

c) Calculate the inlet pressure P_i.

$$P_i = P - \frac{3{,}857 \cdot 10^{-13} \cdot Q_m{}^2 \cdot v_u \cdot K_{Ru}}{A_{Fu}{}^2} \tag{36}$$

where

K_{Ru} is the upstream pipe network flow resistance coefficient in terms of the minimum reference area, A_{Fu} (determined using the methodology described in 7.3.5.1);

A_{Fu} is the minimum cross-sectional flow area (reference area) in the upstream pipe network, in m^2.

d) Verify that (P-P_i) is less than or equal to 3 % of (P_S-1,013).

where

P_S is the relief valve set pressure, in bar absolute.

e) Determine the specific volume v_i (P_i, T_i) and specific enthalpy h_r (P_i, T_i) at the inlet (for a constant enthalpy expansion through the relief valve, the enthalpies at the inlet and outlet sides of the valve are equal).

7.2.5.2 Downstream pipe network — Determination of relief valve outlet conditions

a) Assuming an upper-limit case of built-up back pressure of 10 %, calculate the associated relief valve outlet pressure P_{b10}.

$$P_{b10} = P_{exit} + 0{,}1\left(P_S - 1{,}013\right) \tag{37}$$

where

P_{exit} is the system exit pressure, in bar absolute, and is equal to the static pressure that exists at the outlet of the relief valve at the time the device is required to operate.

b) Determine the relief valve outlet specific volume and temperature [v_{b10} (P_{b10}, h_r), T_{b10} (P_{b10}, h_r)].

c) Determine the system exit temperature, T_{exit10}, by using Formula (29) and evaluating the heat input into the pipe network from the relief valve outlet (T_n = T_{b10}) to the system exit.

d) Determine the system exit specific volume [v_{exit10} (P_{exit}, T_{exit10})].

e) Calculate the average downstream specific volume, v_{d10}.

$$v_{d10} = \frac{v_{b10} + v_{exit10}}{2} \tag{38}$$

f) For the prescribed downstream pipe network geometry and flow, calculate the maximum desirable average downstream specific volume v_{dmax}

$$v_{\text{dmax}} = \frac{A_{\text{Fd}}{}^{2} \cdot \left[0{,}1\left(P_{\text{S}} - 1{,}013\right)\right]}{3{,}857 \cdot 10^{-13} \cdot Q_{\text{m}}{}^{2} \cdot K_{\text{Rd}}} \tag{39}$$

where

K_{Rd} is the downstream pipe network flow resistance coefficient in terms of the minimum reference area, A_{Fd} (determined using the methodology described in 7.3.5.1);

A_{Fd} is the minimum cross-sectional flow area (reference area) in the downstream pipe network, in m^2.

g) Compare v_{d10} and v_{dmax}.

If v_{d10} is greater than v_{dmax}, then excessive built-up back pressure exists and design iteration is required.

If v_{d10} is less than or equal to v_{dmax}, then the back pressure at the relief valve outlet is acceptable and P_b can be determined.

h) Determine relief valve back pressure, P_b.

With P_b known to be within the desired limits (greater than P_{exit} and less than P_{b10}), iteration within these limits can be performed to solve for P_b. P_b will be found when a trial value of P_b between these limits produces the same result for P_b according to Formula (40).

$$P_{\text{b}} = \frac{1{,}929 \cdot 10^{-13} \cdot Q_{\text{m}}{}^{2} \cdot K_{\text{Rd}}\left(v_{\text{b,Pb}} + v_{\text{exit,Pb}}\right)}{A_{\text{Fd}}{}^{2}} + P_{\text{exit}} \tag{40}$$

where

$v_{b,Pb}$ is the specific volume at the relief valve outlet evaluated at enthalpy, h_r, and the trial value of P_b;

$v_{exit,Pb}$ is the specific volume at the system exit evaluated at system exit pressure, P_{exit}, and temperature, $T_{exit,Pb}$;

$T_{exit,Pb}$ is determined by evaluating the temperature at the relief valve outlet [$T_{b,Pb}$ (P_b, h_r)] and then applying the temperature equation (6.3) to the downstream pipe network.

7.2.5.3 Determine if flow is critical or subcritical

Using the results obtained for P_b and P_i, calculate the ratio (P_b/P_i) and compare to the relations in 7.2.2 to determine if the flow is critical or subcritical.

7.2.5.4 Determine orifice area and valve selection

a) Calculate the minimum required valve orifice area, A_{V1}, by substituting values into the appropriate area formula for critical or subcritical flow (7.2.3 and 7.2.4), where $A_V = A_{V1}$.

b) Select a valve with the next largest available orifice area greater than A_{V1} and calculate its flow capacity, Q_{ma}, in the system.

$$Q_{\text{ma}} = Q_{\text{m}}\left(\frac{A_{\text{Va}} \cdot K_{\text{dr,a}}}{A_{\text{V1}} \cdot K_{\text{dr,1}}}\right) \tag{41}$$

where

A_{Va} is the next largest available valve orifice area greater than A_{V1};

$K_{dr,a}$ is the derated coefficient of discharge of the next largest available valve orifice area greater than A_{V1};

$K_{dr,1}$ is the derated coefficient of discharge of the initially analysed valve.

NOTE For cases in which the next available valve orifice area above A_{V1} is the initially analyzed valve orifice area, $K_{dr,a} = K_{dr,1}$, and A_{Va} is equal to the initially analyzed valve orifice area.

c) Verify that the upstream and downstream pressure drops are acceptable by repeating the analysis (7.2.5.1 to 7.2.5.3) with $Q_m = Q_{ma}$ substituted into the applicable formulae.

7.2.6 Example

For a loss of vacuum under ambient conditions, determine if the selected relief valve for the system depicted in Figure 2 is adequately sized for the following known conditions:

— relief valve: 12,05 bar set pressure, 0,007 m diameter orifice, $K_{dr} = K_{dr,1} = 0{,}82$;

— liquid hydrogen in inner vessel with a relieving pressure of 13,25 bar;

— upstream and downstream piping: 0,0266 m inner diameter × 0,0334 outer diameter;

— diverter valve flow coefficient $C_V = 10$;

— required mass flow rate based on inner vessel heat input: 172 kg/h;

— discharge at exit to atmosphere.

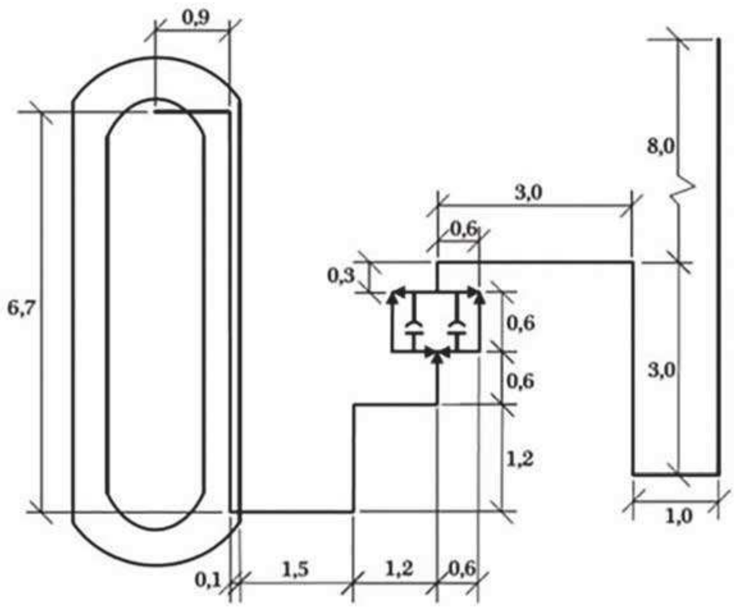


Figure 2 — Relief valve system

a) Determine relief valve inlet conditions.

1) Determine inlet temperature, T_i.

As described in Table 2, the relieving temperature associated with relieving pressure P = 13,25 bar is determined by finding the indicated maximum quantity using thermophysical property tables for hydrogen. For this condition, the hydrogen is supercritical and has a relieving temperature T = 34,4 K.

The inlet temperature is found by evaluating the temperature Formula (29) from the inner vessel jacket to the relief valve inlet.

$T_e = T_a$ = 328 K; U_p = 78,5 W/(m²·K); Q_m = 172 kg/h; c_p = 13,12 kJ/(kg·K) (Table 3)

$A_j = \pi \cdot 0{,}0334 \cdot (0{,}9 + 6{,}7 + 0{,}1) = 0{,}808\ \text{m}^2$

$A_e = \pi \cdot 0{,}0\,334 \cdot (1{,}5 + 1{,}2 + 1{,}2 + 0{,}6 + 0{,}6 + 0{,}6) = 0{,}598\ \text{m}^2$

$T_x = T_i$ = 70,4 K

2) Determine average upstream specific volume, v_u.

$v\ (P = 13{,}25\ \text{bar}, T = 34{,}4\ \text{K}) = 5{,}954(10^{-2})\ \text{m}^3/\text{kg}$

$v\ (P = 13{,}25\ \text{bar}, T = 70{,}4\ \text{K}) = 2{,}124(10^{-1})\ \text{m}^3/\text{kg}$

$v_u = ([5{,}954(10^{-2}) + 2{,}124\ (10^{-1})]/2) = 1{,}360(10^{-1})\ \text{m}^3/\text{kg}$

3) Calculate inlet pressure, P_i, per Formula (36).

The total upstream pipe network flow resistance coefficient is found by evaluating the flow resistance of each element relative to the minimum cross-sectional area found in the upstream network and then summing all values. Since all upstream pipe elements in this example have the same flow area, $K_A = K_B$ (7.3.5.1). Additionally, for an inner diameter of 0,0266 m, the upstream system reference flow area is $A_{Fu} = A_B = 5{,}566\ (10^{-4})\ \text{m}^2$.

K_1 = 0,78 (Table 9; entrance, protruding pipe)

K_2 (Table 5; f_T for commercial steel pipe)

f_T = 0,022 4

l = (0,9 + 6,7 + 0,1 + 1,5 + 1,2 + 1,2 + 0,6 + 0,6 + 0,6) = 13,4 m

$$K_2 = \sqrt{\frac{\pi}{4 \cdot A_B}}\left(f_T \cdot l\right) = 11{,}28$$

K_3 (Table 6; six 90° elbows)

$K_3 = 6\ (30 \cdot f_T) = 4{,}03$

K_4 diverter valve flow coefficient C_V = 10

$$K_4 = 2{,}595 \cdot 10^9 \cdot \left(\frac{A_B}{0{,}865 \cdot C_V}\right)^2 = 10{,}74$$

$K_{Ru} = K_1 + K_2 + K_3 + K_4 = 26{,}83$

$$P_i = P - \frac{3{,}857 \cdot 10^{-13} \cdot {Q_m}^2 \cdot v_u \cdot K_{Ru}}{{A_{Fu}}^2} = 13{,}12\ \text{bar}$$

4) Verify that (P-P_i) is less than 3 % of (P_S-1,013).

$$\frac{P - P_i}{P_S - 1{,}013} = \frac{13{,}25 - 13{,}12}{12{,}05 - 1{,}013} = 0{,}0\,118 = 1{,}18\ \%$$

The inlet piping pressure drop is less than 3 %.

5) Determine the specific volume $v_i(P_i,T_i)$ and specific enthalpy h(P_i,T_i) at the inlet

v_i (P_i = 13,12 bar, T_i = 70,4 K) = 2,146(10^{-1}) m^3/kg

h_r (P_i = 13,12 bar, T_i = 70,4 K) = 948,0 kJ/kg

b) Determine relief valve outlet conditions.

1) Determine the maximum desirable relief valve outlet pressure, P_{b10}, per Formula (37).

$$P_{b10} = P_{exit} + 0{,}1\left(P_s - 1{,}013\right) = 1{,}013 + 0{,}1\left(12{,}05 - 1{,}013\right)$$

P_{b10} = 2,117 bar

2) Determine v_{b10} and T_{b10}.

v_{b10} (P_{b10} = 2,117 bar, h_r = 948,0 kJ/kg) = 1,305 m^3/kg

T_{b10} (P_{b10} = 2,117 bar, h_r = 948,0 kJ/kg) = 67,4 K

3) Determine the system exit temperature, T_{exit10}.

The system exit temperature, T_{exit10}, is found by evaluating the temperature Formula (29) from the relief valve outlet to the system exit.

T_e = T_a = 328 K; Q_m = 172 kg/h; c_p = 13,12 kJ/(kg·K) (Table 3)

T_n = T_{b10} = 67,4 K

A_j = 0 m^2

A_e = π·0,0 334·(0,6 + 0,3 + 3,0 + 3,0 + 1,0 + 3,0 + 8,0) = 1,983 m^2

From T_{b10} = 67,4 K to T_x = 75 K, U_p = 78,5 W/(m^2·K), which yields

A_e = 0,235 m^2 at T_x = 75 K

and from T_n = 75 K to T_x = T_{exit10}: U_p = 16,5 W/(m^2·K), A_e = 1,983-0,235 = 1,748 m^2, which yields

T_x = T_{exit10} = 86,4 K

4) Determine v_{exit10}.

v_{exit10} (P_{exit}, T_{exit10}) = 3,515 m^3/kg

5) Calculate the average downstream specific volume, v_{d10}, per Formula (38).

$$v_{d10} = \frac{v_{b10} + v_{exit10}}{2} = \frac{1{,}305 + 3{,}515}{2} = 2{,}410\,\text{m}^3 / kg$$

6) Calculate the maximum desirable average downstream specific volume, v_{dmax}, per Formula (39).

The total downstream pipe network flow resistance coefficient is found by evaluating the flow resistance of each element relative to the minimum cross-sectional area found in the downstream network and then summing all values. Since all downstream pipe elements in this example have the same flow area, K_A = K_B (7.3.5.1). Additionally, for an inner diameter of 0,0266 m, the downstream system flow area is A_{Fd} = A_B = 5,566 (10^{-4}) m^2.

K_5 = 1 (Table 9; exit, relief valve outlet)

K_6 (Table 5; f_T for commercial steel pipe)

f_T = 0,022 4

l = (0,6 + 0,3 + 3,0 + 3,0 + 1,0 + 3,0 + 8,0) = 18,9 m

$$K_6 = \sqrt{\frac{\pi}{4 \cdot A_B}}\left(f_T \cdot l\right) = 15{,}90$$

K_7 (Table 6; four 90° elbows)

$K_7 = 4 \cdot (30 \cdot f_T) = 2{,}69$

K_8 [Table 6; 90° mitre bend (approximation for single flow converging tee)]

$K_8 = 60 \cdot f_T = 1{,}34$

$K_{Rd} = K_5 + K_6 + K_7 + K_8 = 20{,}93$

$$v_{dmax} = \frac{A_{Fd}{}^2 \cdot \left[0{,}1\left(P_S - 1{,}013\right)\right]}{3{,}857 \cdot 10^{-13} \cdot Q_m{}^2 \cdot K_{Rd}} = 1{,}432 \text{m}^3 / \text{kg}$$

7) Compare v_{d10} and v_{dmax}.

Since v_{d10} (2,410 m^3/kg) is greater than v_{dmax} (1,432 m^3/kg), built-up back pressure in excess of 10 % of the set pressure will exist when relieving. As such, a reduction in built-up back pressure is desired through design iteration of the downstream system. For example, if the 7,0 m long drop portion of the downstream pipe network depicted in Figure 2 were eliminated and the remaining pipe diameter increased to the next available commercial size (0,0350 m I.D. × 0,0422 m O.D.), the proceeding recalculation of the governing parameters would result:

$A_{Fd} = 9{,}65(10^{-4})$ m^2; $A_e = 1{,}578$ m^2; $K_{Rd} = 12{,}27$; $T_{exit10} = 83{,}8$ K

v_{exit10} (P_{exit}, T_{exit10}) = 3,408 m^3/kg

$v_{d10} = 2{,}357$ m^3/kg

$v_{dmax} = 7{,}341$ m^3/kg

With v_{d10} now less than v_{dmax}, the built-up back pressure is less than 10 % of the set pressure and therefore, within the desired range.

8) Determine relief valve back pressure, P_b, per Formula (40).

With P_b known to be within the desired limits (greater than $P_{exit} = 1{,}013$ bar and less than $P_{b10} = 2{,}117$ bar), iteration of P_b between these limits can be performed until agreement is reached.

$$P_b = \frac{1{,}929 \cdot 10^{-13} \cdot Q_m{}^2 \cdot K_{Rd}\left(v_{b,Pb} + v_{exit,Pb}\right)}{A_{Fd}{}^2} + P_{exit} = 0{,}075\left(v_{b,Pb} + v_{exit,Pb}\right) + 1{,}013$$

Iteration of P_b leads to the following solution:

For $P_b = 1{,}415$ bar:

$v_{b,Pb}$ (P_b, h_r) = 1,951 m^3/kg

$T_{b,Pb}$ (P_b, h_r) = 67,2 K

$T_{exit,Pb} = 83{,}7$ K

$v_{exit,Pb}$(P_{exit}, $T_{exit,Pb}$) = 3,404 m^3/kg

$$P_b = 0{,}075\left(1{,}951 + 3{,}404\right) + 1{,}013 = 1{,}415 \text{bar}$$

The assumed and calculated values of P_b are equal, therefore the solution has converged.

c) Determine if the flow is critical or subcritical

Substituting $P_i = 13{,}12$ bar, $P_b = 1{,}415$ bar, and $\kappa = 1{,}77$ [evaluated at (P_i, T_i)] into Formula (30).

$$\frac{P_b}{P_i} \le \left(\frac{2}{\kappa+1}\right)^{\left(\frac{\kappa}{\kappa-1}\right)}$$

108 ≤ 0,473, therefore the flow is critical.

d) Determine orifice area and valve selection.

1) Calculate the minimum required valve orifice area A_{V1}.

Coefficient C is given by Formula (33).

$$C = 3{,}948\sqrt{\kappa\left(\frac{2}{\kappa+1}\right)^{\frac{(\kappa+1)}{(\kappa-1)}}} = 3{,}948\sqrt{1{,}77\left(\frac{2}{1{,}77+1}\right)^{\frac{(1{,}77+1)}{(1{,}77-1)}}} = 2{,}924$$

Thus, the minimum required valve flow area [Formula (32)] is given by

$$A_{V1} = \frac{Q_m}{0{,}2883 \cdot C \cdot K_{dr} \cdot \sqrt{\frac{P_i}{v_i}}} = \frac{172}{0{,}2883 \cdot 2{,}924 \cdot 0{,}82 \cdot \sqrt{\frac{13{,}12}{0{,}2146}}} = 31{,}82 \text{mm}^2$$

which is equivalent to an orifice diameter of 6,365 mm.

2) Evaluate valve selection.

A valve with a 6,5mm diameter orifice and derated coefficient of discharge of 0,85 is identified for evaluation. The flow capacity of this valve in the system is calculated per Formula (41).

$$Q_{ma} = Q_m\left(\frac{A_{Va} \cdot K_{dr,a}}{A_{V1} \cdot K_{dr,1}}\right) = 172\left(\frac{\pi\left(6{,}5^2/4\right) \cdot 0{,}85}{31{,}82 \cdot 0{,}82}\right) = 185{,}9 \text{kg/h}$$

3) Verify acceptable upstream and downstream pressure drops with the selected valve.

Substitution of Q_{ma} = 185,9 kg/h into the upstream procedure results in a valve inlet pressure of P_i = 13,10 bar, yielding an acceptable (≤3 %) upstream pressure drop of 1,36 %.

Evaluation of the downstream system for P_i = 13,10 bar, h_r = 919,4 kJ/kg, and Q_{ma} = 185,9 kg/h results in a valve outlet pressure of P_b = 1,349 bar, yielding an acceptable (≤10 %) downstream pressure drop of 3,04 %.

The selected 6,5 mm diameter orifice valve, therefore satisfies the mass flow rate, upstream pressure drop, and downstream pressure drop requirements.

7.3 Sizing of bursting discs

7.3.1 Discharge capacity

For pressure relief through bursting discs, the flow resistance of the complete pipe network (including bursting discs) is to be taken into account.

Bursting discs may not offer the full flow area after rupture. It is highly recommended that the user obtain certification from the manufacturer of the bursting disc guaranteeing the minimum flow area after rupture.

7.3.2 Determination of critical vs. subcritical flow for gases

The expression for K_{RC} is used to determine if the flow is to be considered critical or subcritical.

$$K_{RC} = (1{,}887 - 1{,}751 \cdot \varphi)^{-3{,}52} \tag{42}$$

where

$\varphi = \frac{P_{exit}}{P}$;

P_{exit} is the system exit pressure, in bar absolute;

P is the relieving pressure inside the vessel, in bar absolute;

$K_{RC} >$ K_R for critical flow;

$K_{RC} <$ K_R for subcritical flow.

7.3.3 Critical flow

The net expansion factors associated with critical flow are used to relate the minimum required net flow area to the system parameters. For critical flow, the minimum required net flow area is given by Formula (43).

$$A_F = \frac{Q_m}{8{,}642 \cdot 10^7 \cdot P} \sqrt{\frac{T_x}{M}} K_R^{\ 0{,}4} \tag{43}$$

where

A_F is the minimum cross-sectional area (reference area) in the pipe network, in m^2;

Q_m is the mass flow to be relieved by the device, in kg/h;

T_x is the adjusted flow temperature at the system exit, in Kelvin;

M is the molar mass of the gas, in kg/mol;

K_R is the flow resistance coefficient of the complete pipe network (including bursting disc), in terms of a system pipe size of area, A_F. Applicable for values of K_R greater than 1,2 and less than 100.

7.3.4 Subcritical flow

For subcritical flow, the minimum required net flow area is given by Formula (44).

$$A_F = \frac{Q_m}{1{,}865 \cdot 10^8 \cdot P} \sqrt{\frac{T_x}{M}} \left[\frac{1}{\lambda_1 \cdot (\varphi)^{3/2} + \lambda_2 \cdot (\varphi)^{1/2}} \right] \tag{44}$$

where

$$\lambda_1 = \frac{(-0{,}3 \cdot K_R) - 1{,}264}{(-3{,}769 \cdot 10^{-5} \cdot K_R^{\ 3}) + (K_R^{\ 2}) + (K_R)} \tag{45}$$

$$\lambda_2 = \sqrt{\frac{1}{K_R}} \tag{46}$$

7.3.5 Recommended analysis method

7.3.5.1 Determination of K_R for the complete pipe network

Each pipe element requires its resistance to be expressed in terms of the minimum flow area, A_F, found within the pipe network. For bursting discs, enlargements and contractions, and pipe entrances and exits, flow resistance is considered to be independent of size and therefore, does not require adjustment relative to the reference area, A_F. For valves, fittings, and pipes, reference flow resistances are determined by proportioning to the ratio of the square of the areas.

$$K_A = K_B\left(\frac{A_F}{A_B}\right)^2 \quad (47)$$

where

A_B is the actual flow area of a pipe element, in m^2;

K_B is the flow resistance coefficient of a pipe element in terms of its actual flow area, A_B (see Tables 5 to 7);

K_A is the flow resistance coefficient of a pipe element in terms of area, A_F (see Tables 8 to 9),

To determine the flow resistance coefficient, K_B, for pipes and pipe elements, the friction coefficient, f_T, is determined using Table 5.

Table 5 — Pipe flow friction coefficients

	f_T		
A_B	Drawn tubing	Commercial steel	Cast
7,30 $(10)^{-4}$	0,011 0	0,022 0	0,036 0
2,92 $(10)^{-3}$	0,009 5	0,018 5	0,030 0
6,57 $(10)^{-3}$	0,009 0	0,016 8	0,026 5
1,17 $(10)^{-2}$	0,008 5	0,015 8	0,024 0
1,82 $(10)^{-2}$	0,008 3	0,015 0	0,022 5
2,63 $(10)^{-2}$	0,008 0	0,014 5	0,021 5
3,58 $(10)^{-2}$	0,007 8	0,014 0	0,020 8
4,67 $(10)^{-2}$	0,007 6	0,013 6	0,020 0
5,91 $(10)^{-2}$	0,007 4	0,013 3	0,019 3
7,30 $(10)^{-2}$	0,007 3	0,013 0	0,018 8

For straight sections of pipe of length, l (meters), K_B is given by Formula (48).

$$K_B = \sqrt{\frac{\pi}{4 \cdot A_B}}\left(f_T \cdot l\right) \quad (48)$$

For pipe elements containing discrete directional transitions, K_B is determined using Table 6.

Table 6 — Normalized flow resistance coefficients for discrete transitions

	K_B/f_T	
Angle (degrees)	**Tight radius elbows**	**Mitre bends**
15	—	4
30	—	8
45	16	15
60	—	25
75	—	40
90	30	60
180	50	—

For 90° elbows with an average transition radius, r, and flow area, A_B, K_B is determined using Table 7.

Table 7 — Normalized flow resistance coefficients for 90° curved transitions

r^2/A_B	K_B/f_T
1,3	20
3	14
5	12
11	12
20	14
46	17
81	24
127	30
183	34
250	38
325	42
500	50

For valves, K_B is determined from the manufacturer's flow factor, K_V, where K_V is the flow rate through the valve in cubic metres per hour of water at a temperature of 289 K with a pressure drop across the valve of 1 bar.

$$K_B = 2{,}595 \cdot 10^9 \cdot \left(\frac{A_B}{K_V}\right)^2 \tag{49}$$

Similarly, a manufacturer's flow coefficient, C_V, is determined in imperial units as the flow rate through a valve in US gallons per minute of water at a temperature of 289 K with a pressure drop across the valve of one pound per square inch. The relationship between K_V and C_V is given by Formula (50).

$$K_V = 0{,}865 \cdot C_V \tag{50}$$

For Tees and Wyes with equally balanced converging or diverging flow rates, K_B is determined using Table 8.

Table 8 — Flow resistance coefficients for converging and diverging flow

	K_B, Converging flow		K_B, Diverging flow	
Type	Branch	Straight-through	Branch	Straight-through
90° Tee	0,40	0,55	1,15	0
60° Wye	0,30	0,50	0,55	0
45° Wye	0,20	0,40	0,40	0
30° Wye	0,15	0,30	0,30	0

For pipe elements with changes in flow area, K_A is determined directly using Table 9.

Table 9 — Flow resistance coefficients for size transitions

Type	K_A
Enlargement, sudden, or gradual	$(1-A_R)^2/A_R^2$
Contraction, sudden	$(1-A_R)/(2 \cdot A_R^2)$
Contraction, gradual	$(1-A_R)/(3 \cdot A_R^2)$
Entrance, with protruding pipe	0,78
Entrance, no protruding pipe	0,50
Exit	1,00

where

A_R is the ratio of the smaller area, A_S, of the pipe element divided by the larger area, A_L, of the pipe element.

For a contraction to be considered gradual, the length of the contraction must satisfy Formula (51).

$$l \geq 1{,}36\left(A_L - A_S\right) \tag{51}$$

For bursting discs, manufacturer supplied values for the resistance coefficients are to be used. These values shall not be reduced when computing the overall flow resistance in terms of the minimum area A_F.

To determine the overall flow resistance coefficient, K_R, of the complete pipe network, the individual element resistances, K_A, are summed using the series and parallel relationships for flow resistance.

$$K_{SUM} = K_{A,1} + K_{A,2} + K_{A,3} + \ldots + K_{A,n} \quad \text{(series)} \tag{52}$$

$$\frac{1}{\sqrt{K_{SUM}}} = \frac{1}{\sqrt{K_{A,1}}} + \frac{1}{\sqrt{K_{A,2}}} + \frac{1}{\sqrt{K_{A,3}}} + \ldots + \frac{1}{\sqrt{K_{A,n}}} \quad \text{(parallel)} \tag{53}$$

For a system comprised completely of elements in series, K_R will equal the sum of the individual K_A values. For more complex systems, the values of K_{SUM} found in the above series and parallel relationships are to be appropriately combined to determine K_R.

7.3.5.2 Determination of adjusted flow temperature T_x

Calculate the adjusted flow temperature, T_x at the system exit as per 6.3. The flow start location (inner vessel) temperature $T_n = T$ is determined in accordance with 5.2.

7.3.5.3 Determination of critical vs. subcritical flow for gases

Calculate the value of K_{RC} and compare it to the system flow resistance coefficient, K_R, as per 7.3.2.

7.3.5.4 Calculation of reference flow area, A_F

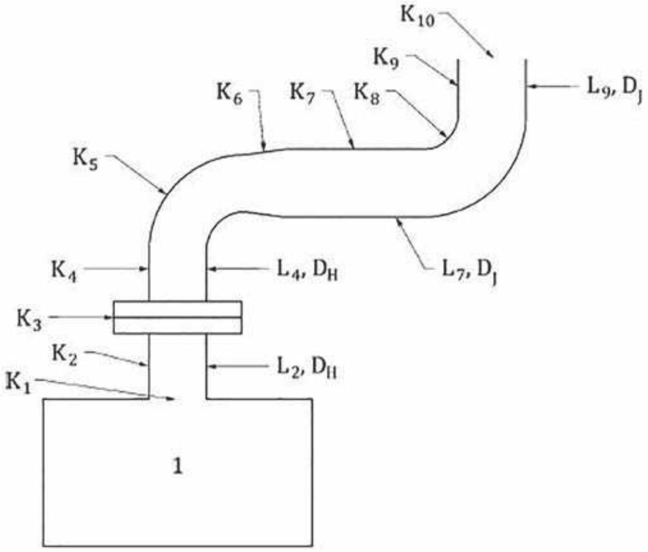
Evaluate A_F by substituting Q_m, P, T_x, M, and K_R into the appropriate area formula for critical or subcritical flow. If the solution is less than or equal to the actual minimum cross-sectional area, A_F, then the pipe network will be adequately sized to meet or exceed the requisite flow demand. If the solution is greater than the actual minimum cross-sectional area, A_F, then the pipe network will not adequately handle the flow demand and an iterative design solution will be required.

7.3.5.5 Iteration of design

For inadequate flow capacity results, modify the pipe network design for increased flow capacity and repeat analysis until the calculated value of A_F is less than the design value of A_F.

7.3.6 Example

Assume that hydrogen relieves at P = 13,8 bar through the pipe network and discharges to atmosphere as shown in Figure 3. The system is equipped with a bursting disc that has a manufacturer-rated flow resistance coefficient of K = 3,5 and minimum net flow area (MNFA) of 0,002 m^2. Assume an inner vessel fluid temperature T = 34,8 K as determined in 5.2.1 and a mass flow rate Q_m = 5000 kg/h. Assume that pipe L_2 resides in the interspace between the inner and outer jackets, while the remaining pipe network is external. For pipe element geometry, assume D_H = 0,05 m, D_J = 0,06 m, $L_2 = L_4$ = 0,10 m, $L_7 = L_9$ = 5 m. Determine if the pipe network is adequately sized to accommodate the requisite flow.



Key

1 vessel

Figure 3 — Example pipe network with bursting disc

a) Determine K_R for the complete pipe network.

K_R is determined by evaluating the flow resistance of each element in the pipe network in terms of the smallest pipe cross-sectional area within the network. For a minimum inner diameter of D_H = 0,05 m, the system reference flow area is A_F = 1,963(10^{-3}) m^2.

K_1 = 0,5 (Table 9; entrance, no protruding pipe)

K_2 (Table 5; interpolation of f_T for commercial steel pipe)

$A_B = A_F$; $l = L_2$

f_T = 0,020 0

$$K_B = \sqrt{\frac{\pi}{4 \cdot A_B}}(f_T \cdot l) = 0{,}040$$

$$K_2 = K_A = K_B \left(\frac{A_F}{A_B} \right)^2$$

K_2 = 0,040

K_3 = 3,5 (bursting disc manufacturer flow resistance value)

$K_4 = K_2$ = 0,040

K_5 (Table 6; 90° tight radius elbow)

$K_B = 30 \cdot f_T$ = 0,600; $A_B = A_F$

$$K_5 = K_A = K_B \left(\frac{A_F}{A_B} \right)^2$$

K_5 = 0,600

K_6 (Table 9; enlargement, sudden, or gradual)

$$A_R = \frac{A_S}{A_L} = \frac{A_F}{A_B} = \frac{A_F}{\pi \left(D_J^{\,2} \right) / 4} = 0{,}694$$

$$K_B = \frac{\left(1 - A_R\right)^2}{A_R^{\,2}} = 0{,}1936$$

$$K_6 = K_A = K_B \left(\frac{A_F}{A_B} \right)^2$$

K_6 = 0,094

K_7 (Table 5; interpolation of f_T for commercial steel pipe)

$$A_B = \pi \left(D_J^{\,2} \right) / 4 \quad ; l = L_7$$

f_T = 0,018 6

$$K_B = \sqrt{\frac{\pi}{4 \cdot A_B}}(f_T \cdot l) = 1{,}55$$

$$K_7 = K_A = K_B \left(\frac{A_F}{A_B} \right)^2$$

K_7 = 0,747

K_8 (Table 6; 90° tight radius elbow)

$$K_B = 30 \cdot f_T = 0{,}558; A_B = \pi \left(D_J^{\,2} \right) / 4$$

$$K_8 = K_A = K_B \left(\frac{A_F}{A_B} \right)^2$$

K_8 = 0,269

$K_9 = K_7 = 0{,}747$

$K_{10} = 1$ (Table 9; exit)

$K_R = K_{SUM} = K_1 + K_2 + K_3 + \ldots + K_{10}$

$K_R = 7{,}54$

b) Determine the system exit temperature (adjusted flow temperature), T_x.

Values for T_n, Q_m, c_p, A_j, and A_e are required in order to determine T_x as per 6.3.

— $T = T_n = 34{,}8$ K as per 5.2.1.

— $Q_m = 5\,000$ kg/h as given in this example description. Q_m is determined as per Clause 4 and 5.

— $c_p = 14{,}51$ kJ/(kg·K) as per Table 3.

— $A_j = 0{,}0157$ m² as determined by evaluating the surface area of pipe L_2.

— $A_e = 2{,}06$ m² as determined by evaluating the surface area of the external pipe network elements.

Substituting values into Formula (29) yields:

$T_x = 41{,}9$ K

c) Determine if the flow is critical or subcritical.

The flow is evaluated using the critical vs. subcritical flow Formula (42).

$$K_{RC} = \left(1{,}887 - 1{,}751 \cdot \varphi\right)^{-3{,}52}$$

where

$$K_{RC} = 1 - \frac{P_{exit}}{P} = 1 - \frac{1{,}013}{13{,}8} = 0{,}926$$

Which gives $K_{RC} = 106{,}4$. Since $K_{RC} = 106{,}4$ is greater than $K_R = 7{,}54$, the flow is critical and the flow area Formula (43) applies.

d) Calculate the minimum required flow area, A_F.

$$A_F = \frac{Q_m}{8{,}642 \cdot 10^7 \cdot P}\sqrt{\frac{T_x}{M}}K_R{}^{0{,}4} = \frac{5\,000}{8{,}642 \cdot 10^7 \cdot 13{,}8}\sqrt{\frac{41{,}9}{0{,}002}}7{,}54^{0{,}4}$$

$A_F = 1{,}36 \cdot 10^{-3}$ m²

Since the value calculated for A_F ($1{,}36 \cdot 10^{-3}$ m²) is less than the actual minimum flow area ($1{,}96 \cdot 10^{-3}$ m²), the pipe network is adequately sized to accommodate the requisite flow.

If the calculated value for A_F had been greater than the actual minimum flow area, then the pipe network would have required an increase in minimum flow area, A_F, or a decrease in the overall flow resistance coefficient, K_R, or both.

Annex A
(informative)

Cryostats

A.1 General

Cryostats discussed in this part of ISO 21013 are the containment pressure vessels and piping for cryogenic fluids used for maintaining low temperatures required for the specified process conditions.

A.2 Design of pressure relief devices for cryostats

In addition to the sources of heat transfer specified in 4.2.1 through 4.5.7, any heat generated from the applicable upset process conditions shall be included in the heat transfer quantities used in 5.1 through 5.2 to calculate the respective minimum mass flow requirements for pressure relief devices.

For instance, a loss of vacuum with either air or process cryogenic fluid or fire with loss of vacuum with either air or process cryogenic fluid of a cryostat used for a superconducting device should include the heat generated due to quench of the superconducting device resulting from the additional heat transfer entering the cryostat from the loss of vacuum or fire with loss of vacuum process upset conditions, as this will raise the operating temperature of the cryostat which will result in the quench. Depending on the set pressure of the pressure relief devices, there could be temperature inversions in the pressure relief piping resulting in mixed flow of gas and liquid. It is recommended that an appropriate software be used to analyse the mixed flow. Temperature distributions in the pressure relief piping can be calculated using Formula (29) and temperatures and pressures calculated using Clause 7.

A.3 Recommendations for cryostat system design

a) Provide a minimum gas space volume of 2 % of the cryostat volume above the liquid level of the cryostat and the inlet of the lowest set pressure relief device at the set pressure of that pressure relief device.

b) Keep the set pressure of the lowest set pressure relief device at or above 2 bar for liquid helium cryostats if the superconducting devices can tolerate this pressure.

c) Keep the exit pressure of pressure relief piping as low as possible.

d) Keep the set pressure of the lowest set pressure relief device as high as possible to keep the pressure relief piping as small as possible.

e) Get certified flow area after rupture for bursting discs from the manufacturer for use in calculations required by this part of ISO 21013.

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