Contents

7.1 Introduction

Nowadays sizing of safety valves is generally performed with the help of sizing software like VALVESTAR®, which make the sizing and selection process fast and relatively easy.

The purpose of this chapter of ENGINEERING is to:

- provide an overview about the most important sizing standards and the formulas which are used within sizing software
- based on LESER's long experience provide helpful advice how to deal with specific applications or sizing problems
- explain some of the physical background, which is helpful to understand specific problems.

This chapter is limited to the sizing of safety valves. The calculation of

- pressure loss in the inlet line
- back pressure
- reaction force
- noise emission

can be found in chapter 6 Installation and Plant Design

7.1.1 General Sizing Procedure

A safety valve must be sized to vent the required amount of fluid so that the pressure within the protected equipment does not exceed the maximum allowable accumulated pressure (MAAP). The fluid can be steam, a gas or vapor, a liquid or a two-phase mixture, e. g. oil and gas or an evaporating liquid.

The general sizing procedure foresees:

- The determination of the required mass flow
- The calculation of the minimum orifice area using the selected sizing standard
- The selection of a larger orifice area from the LESER catalog

Safety valves must be sized and selected by those who have a complete knowledge of the safety requirements of the pressurized unit to be protected. These requirements comprehend at least but not exclusively the

- Knowledge of the fluid state during venting (gaseous, liquid, frozen or flashing two-phase)
- Relieving pressure and temperature
- Mass or volume flow rate
- Back pressure
- Fluid properties at the relieving temperature
  For *liquids*: density, viscosity
  For *gases, vapors*: isentropic coefficient[1], compressibility factor, molar mass, density
  For *two-phase flows*: those of the liquid and gas phase. Furthermore, for flashing flows, saturation enthalpies and specific volumes.

If some data are missing, it is general rule to consider those occurring in the worst possible case scenario, which considers the simultaneous occurrence of all possible causes of overpressure.

Once the required data are collected, there are three alternative ways to determine the correct size of the safety valve:

- Using VALVESTAR® (www.valvestar.com)

  VALVESTAR® is LESER's sizing software and it delivers directly both the orifice size and the complete documentation for the safety valve according to the chosen sizing standard.

- Sizing formulas

  They permit the user to size the valve by himself. This presumes that the user is familiar with the sizing procedures and the formulas. It is one aim of this chapter of ENGINEERING to guide the users and to familiarize with the sizing procedures.

- Capacity charts

  They are tabulated capacities for steam, air and water in function of the relieving pressure, which are available in our catalogues for each valve type and orifice area. The user can immediately select the orifice area which meets or exceeds the required mass flow rate. Capacity charts were a common sizing tool, when no sizing software like VALVESTAR® was available

[1] In US technical literature, this quantity is often referred to as *ratio of specific heats*

7.1.2 Selection of the Sizing Standard

The information contained in chapter 7 Sizing is based on following edition of codes and standards:

Code / Standard	Edition
ASME Section XIII	2021
ASME Section VIII	2021
ASME Section I	2021
API RP 520	2020
API 521	2020
ISO 4126-1	2016
ISO 4126-7	2016
TRD 421	1998
TRD 721	1997
AD Merkblatt 2000-A2	2020

Table 7.1.1-1: Sizing standard edition

This chapter of ENGINEERING covers the sizing procedures and their application with several examples according to the most common standards.

The standards which are described here for the sizing of gas and vapor, steam and liquid flows are

- ASME Section I & XIII (VIII) and API RP 520, incl. two-phase flow sizing from Appendix C, fire case and thermal expansion of entrapped liquids from API 521
- ISO 4126-1 and -7
- AD Merkblatt 2000-A2 as well as older TRD 421 and TRD 721

The ASME Boiler and Pressure Vessel Code has been extended by the additional Section XIII with the title "Section XIII RULES FOR OVERPRESSURE PROTECTION".
Various of the previous 12 Sections such as Section IV or VIII defined the requirements for overpressure protection devices, their design, testing, materials and approvals.
In the ASME BPVC Sec. XIII, a large part of these requirements is now combined into one section and deleted in the respective other sections. This means that from now on, these requirements are no longer spread over several sections, but are combined in Section XIII.

If the customer does not give any indication, according to which standard the sizing should be done, LESER adopts:

Sizing standard selected by LESER	Customer based in	Section in this chapter
ISO 4126	Europe, incl. Russia and former CIS States	Section 5
AD 2000-A2		Section 6
ASME Section XIII (ASME Section VIII)	US or in an other country/region which usually adopts American standards, like North America, Middle East or Far East Asian countries.	Section 4
API RP 520	only if explicitly requested by customer	Section 4

Table 7.1.1-2: Selection of sizing standard

7.2 Engineering Support

In this section the norms are based on following edition:
ASME Section XIII (2021), ASME Section VIII (2021) and API RP 520 (2020), ISO 4126-1 (2016), ISO 4126-7 (2016)

The section Engineering Support is a quick and concise guide to the physics involved in the sizing of safety valves. It explains the most important physical properties used in sizing formulas.

7.2.1 List of Symbols

Symbol	Description	Units [SI]
c_p	Specific heat at constant pressure	[J/(kg K)]
c_v	Specific heat at constant volume	[J/(kg K)]
G	Specific gravity	[--]
h	Specific enthalpy	[J/kg]
h_G	Specific enthalpy (gas)	[J/kg]
h_L	Specific enthalpy (liquid)	[J/kg]
h_{mix}	Specific enthalpy (two-phase mixture)	[J/kg]
Δh_{GL}	Latent heat of evaporation	[J/kg]
M	Molecular weight	[kg/kmol]
k	Isentropic coefficient	[--]
p	Pressure	[bar]
p_b	Back pressure	[bar]
p_c	Critical Pressure	[bar]
p_r	Reduced Pressure	[--]
p_0	Relieving Pressure	[bar]
R	Gas constant divided by the molecular weight	[J/(kg K)]
T	Temperature	[K]
T_c	Critical temperature	[K]
T_r	Reduced temperature	[--]
v	Specific volume	[m³/kg]
Z	Compressibility factor	[--]
x	Gas mass portion in two-phase stream (quality)	[--]
ρ	Density	[kg/m³]
μ	Dynamic viscosity	[Pa s]

Table 7.2.1-1: List of symbols

7.2.2 Properties of Gases

Vapors and gases are gaseous media: a vapor is in a state of equilibrium with the liquid phase, like steam and water, while a gas is in a thermodynamic state, where no liquid or solid can form at that temperature, such as oxygen at typical ambient temperatures. It means that a vapor can condense or evaporate respectively by increasing or decreasing the pressure, while a gas can not.

The gas formulas in the sizing standards are based on the equation of state in equation *7.2.2-1*.

$$p\ v = Z\ R\ T \quad \textit{(Eq. 7.2.2-1)}$$

The density ρ is the inverse of the specific volume and identifies the mass of a medium contained in a volume.

The specific gravity G of a gas is the ratio of the density of the gas to that of air at the standard reference condition, see Eq. *7.2.2-2*.

$$G = \frac{\rho_G}{\rho_{air}} \ldots \textit{(Eq. 7.2.2-2)}$$

If the gas is pure (= no mixture of different gases), is at the same temperature and pressure of air and can be treated like an ideal gas (*Z=1*), the specific gravity G is the ratio of the molecular weights, see Eq. *7.2.2-3*. The molecular weight is the mass of one mole of a compound. A mole of any substance consists of an Avogadro's number (6.02214×10^{23}) of atoms or molecules.

$$G = \frac{M_G}{M_{air}} \quad (T_G = T_{air}\ ;\ p_G = p_{air}\ ;\ Z_G = Z_{air} = 1) \ldots \textit{(Eq. 7.2.2-3)}$$

The compressibility factor Z is determined from Fig. *7.2.2-1* in function of the reduced temperature and the reduced pressure, which are defined in Eq. *7.2.2-4* and *7.2.2-5* as the ratio between the actual (absolute) pressure or temperature and the ones at the critical point.

$$T_r = T/T_c \quad \textit{(Eq. 7.2.2-4)} \quad \text{and} \quad p_r = p/p_c \quad \textit{(Eq. 7.2.2-5)}$$

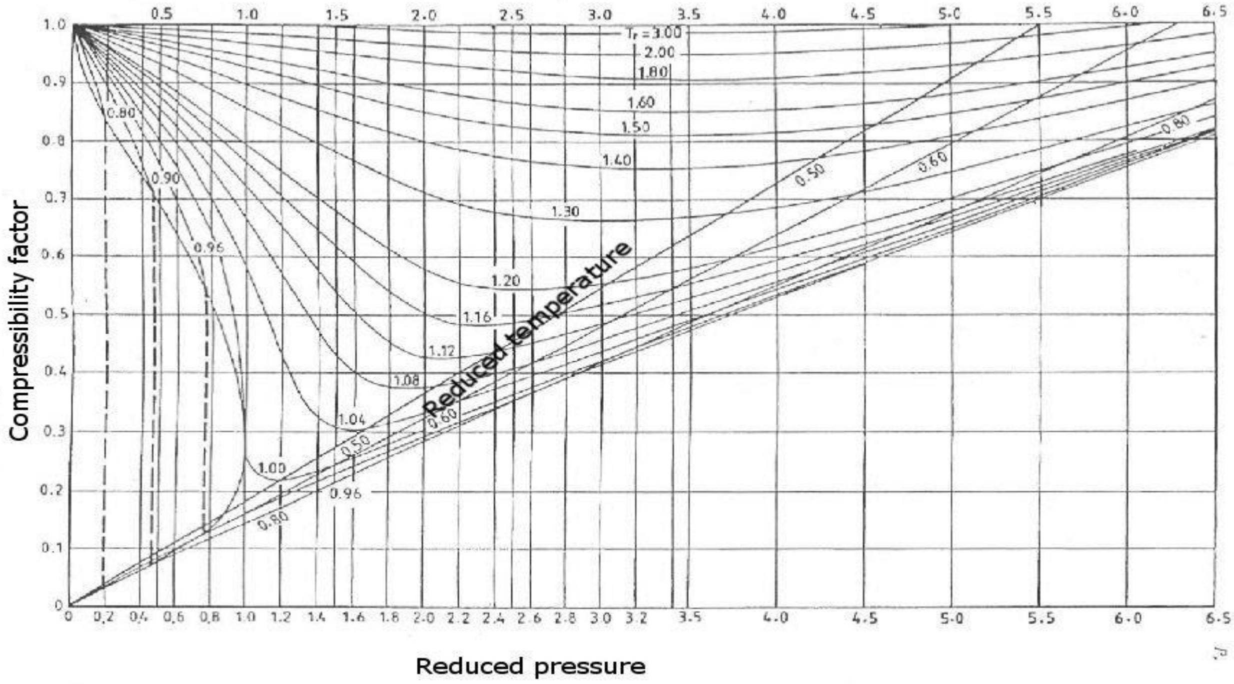


Figure 7.2.2-1: Compressibility factor Z in DIN EN ISO 4126-7, Page 26

The isentropic exponent or ratio of specific heats k is the ratio between the specific heat at constant pressure Cp and the one at constant volume Cv, Eq. *7.2.2-6*

$$k = c_p / c_v \geq 1 \quad \text{(Eq. 7.2.2-6)}$$

The sizing procedures require the knowledge of the isentropic exponent at the relieving condition. Since both specific heats are function of temperature and pressure, the isentropic coefficient at the relieving condition may differ significantly from the tabulated values at 1 atm and 15°C in ISO 4126-7 or 14.5 psi and 60°F in API RP 520. For instance, air at 100 bar and 20°C has an isentropic coefficient of 1.6 compared to 1.4 at atmospheric pressure. In general, at atmospheric pressure the isentropic coefficient is expected to decrease with the temperature.

The value of the compressibility and that of the isentropic coefficient may not be predicted a priori by a simple rule of thumb method. Dedicated commercial software for pure gases and gas mixtures, like NIST Standard Reference Database[2] or GERG-2004 and AGA8 for natural gas components may contain a detailed database for a specific application.

[2] NIST Chemistry WebBook

7.2.3 Critical and Subcritical Gas Flow

The distinction between critical and subcritical gas flows is present in all sizing standards and it generates two distinguished sizing formulas. In both cases the mass flow of gas in a safety valve is equal to that of an ideal nozzle multiplied by the discharge coefficient. On an engineering perspective, the gas flow in a nozzle is assumed to be adiabatic, that is without heat exchange with the ambience, and energy losses are usually neglected. Under these assumptions the relationship between the pressure and the specific volume follows Eq. *7.2.3-1*

$$p\, v^{k} = const \quad \text{(Eq. 7.2.3-1)}$$

If the back pressure p_b is below the critical value p_c, the mass flow in the nozzle is called critical and it depends only on the relieving condition, otherwise it is called subcritical and it is a function of the ratio of the back pressure p_b and the relieving pressure.

Critical gas flow	$p_b \leq p_c$
Subcritical gas flow	$p_b > p_c$

The critical pressure ratio in the nozzle depends only from the isentropic coefficient following Eq. *7.2.3-2.* In the calculation of the critical pressure ratio both the relieving and the back pressure are absolute pressures.

$$\frac{p_c}{p_0} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \quad \text{(Eq. 7.2.3-2)}$$

Table 7.2.3-1 lists the critical pressure ratios for some gases at 20°C and atmospheric pressure (source: ISO 4126-7, 2016).

Gas	k	p_c/p_0
Air	1.40	0.528
Ethylene	1.25	0.555
Methane	1.31	0.544
Nitrogen	1.40	0.528
Ammonia	1.31	0.544

Table7.2.3-1: Critical pressure ratios for selected gases at 20°C and atmospheric pressure

7.2.4 Liquid Properties and Viscous Flow

The density ρ of liquids changes with temperature but it is almost unchanged with pressure, unless the pressure is in the order of hundreds of bar.

The specific gravity G replaces liquid density in the sizing procedure of API RP 520. It is defined as the ratio of the density of the liquid to that of water at the same temperature. Therefore, substances with a specific gravity greater than 1 are denser than water and those with a specific gravity of less than 1 are less dense than water.

The dynamic viscosity μ is a measure of the resistance of a fluid to flow when it is deformed under stress. Viscous liquids need larger pressure differences to move the same mass flow than inviscid liquids. When sizing a safety valve, larger valves are necessary the more viscous the liquid is. The effect of the liquid viscosity in sizing a safety valve is accounted in the viscosity correction factor Kv, which is expressed in function of the Reynolds number *Re* at the orifice area.

The Reynolds number *Re*, see Eq. *7.2.4-1*, is the ratio of the inertial to the viscous force at the orifice area.

$$Re = \left(\frac{Q_m}{3{,}6\,\mu_o}\right)\sqrt{\frac{4}{\pi A}}$$

(Eq. 7.2.4-1)

The sizing standards consider the required mass flow rate in the definition of the Reynolds number, even if it is less than the actual discharged mass flow. VALVESTAR® optimizes the sizing procedure so that it determines the safety valve for the actual discharged mass flow at the relieving conditions. In Fig. *7.2.4-1* and *7.2.4-2* the viscosity correction factor in function of the Reynolds number is shown as it is respectively in ISO 4126-7 and in API RP 520.

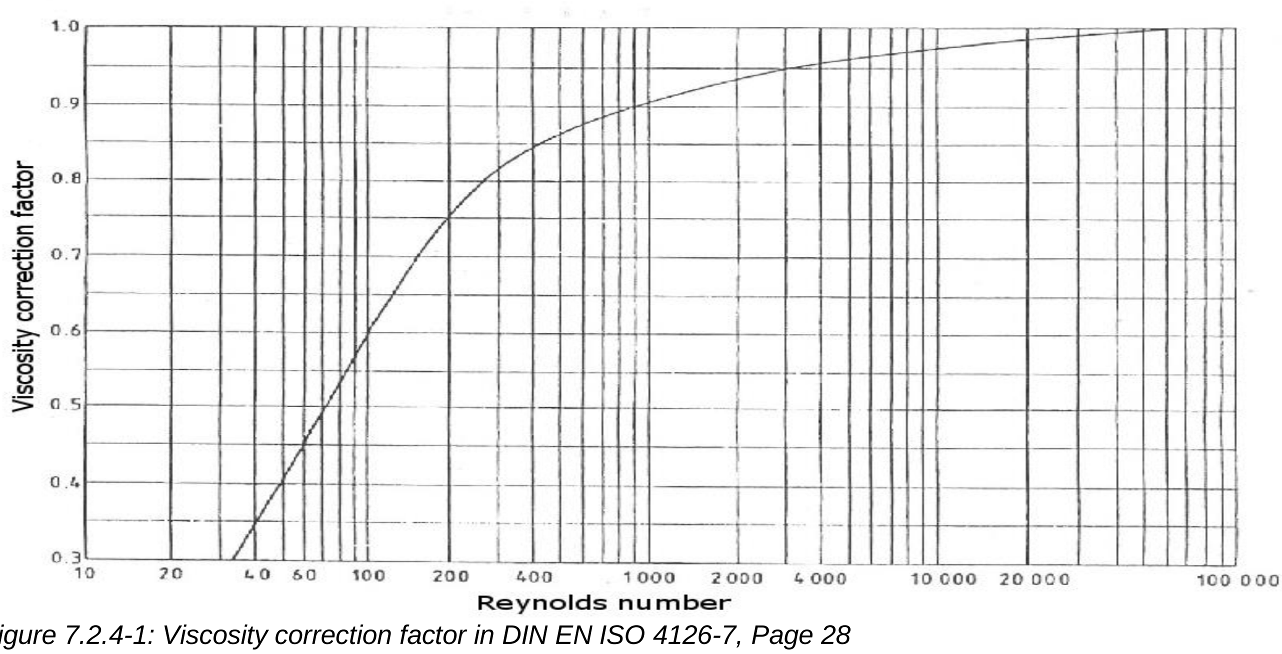


Figure 7.2.4-1: Viscosity correction factor in DIN EN ISO 4126-7, Page 28

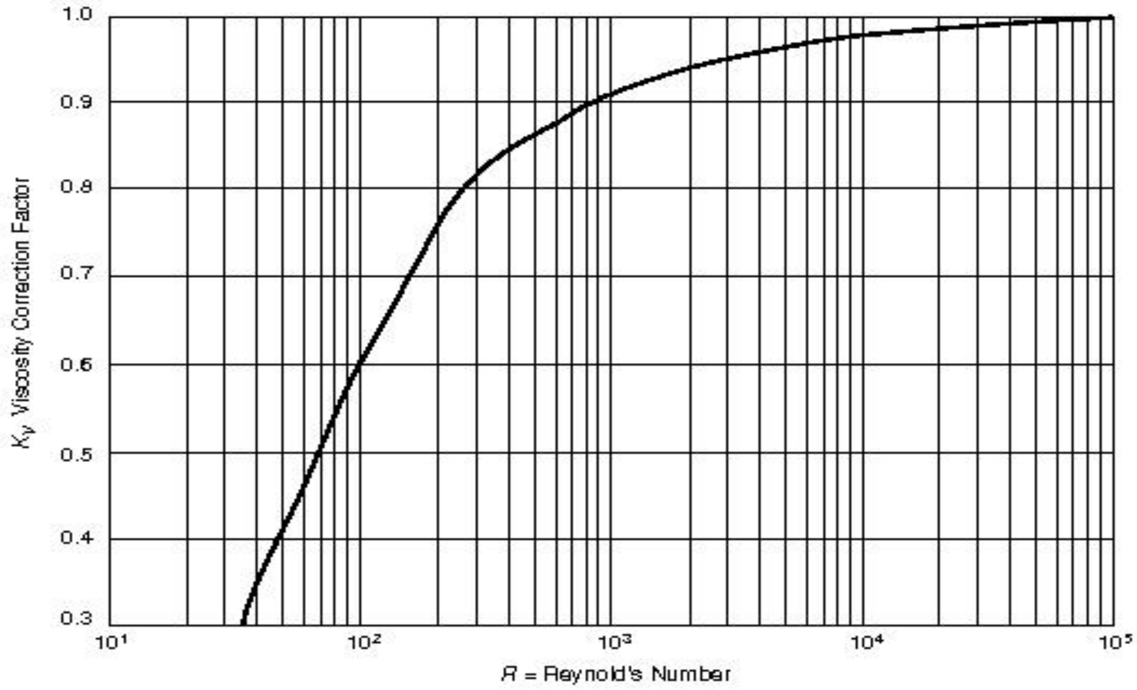


Figure 7.2.4-2: Viscosity correction factor in API RP 520, Page 93

Question: Is there a threshold in viscosity so that the proper safety valve can be selected without the calculation of the viscosity correction factor?

Answer: There is no general rule to define a threshold, since the Reynolds number depends not only on the viscosity of the liquid but also on the mass flow and on the orifice area.

Question: What should be done if the Reynolds number is below 34?

Answer: This occurrence is not yet regulated within the normative standards and there are some few publications in the scientific literature on the topic. In some cases it may be sufficient to heat up the liquid in order to reduce the viscosity and increase the Reynolds number.
In other cases performing flow tests with the viscous medium and a preliminary selected safety valve maybe the only option.

7.2.5 Phase Change and Two-Phase Flows

Depressurization of vessels partially filled with liquids may result in two-phase flows at the inlet of the safety valve. This paragraph presents a short introduction on the topic of phase change and two-phase flows and is helpful to understand the sizing algorithms presented e.g. by API RP 520 (see section 7.4.7).

For any combination of temperature and pressure a substance is present in one, two or even three states of agglomeration in equilibrium. Usually this information is reported in a phase diagram, where temperature and pressure are the coordinates and the result is the existing phase(s), see Fig. *7.2.5-1* for water. The triple point is individuated by that combination of temperature and pressure, where all three phases (solid, liquid, vapor) coexist in equilibrium. The critical point individuates the highest pressure and temperature where the gas and the liquid phase coexist. At any pressure between the triple point and the critical point there is a unique saturation temperature, when the liquid evaporates or the vapor condenses. A liquid at a temperature below that of saturation is said to be subcooled or *sub*-saturated , while a vapor, whose temperature is above that of saturation is superheated*.*

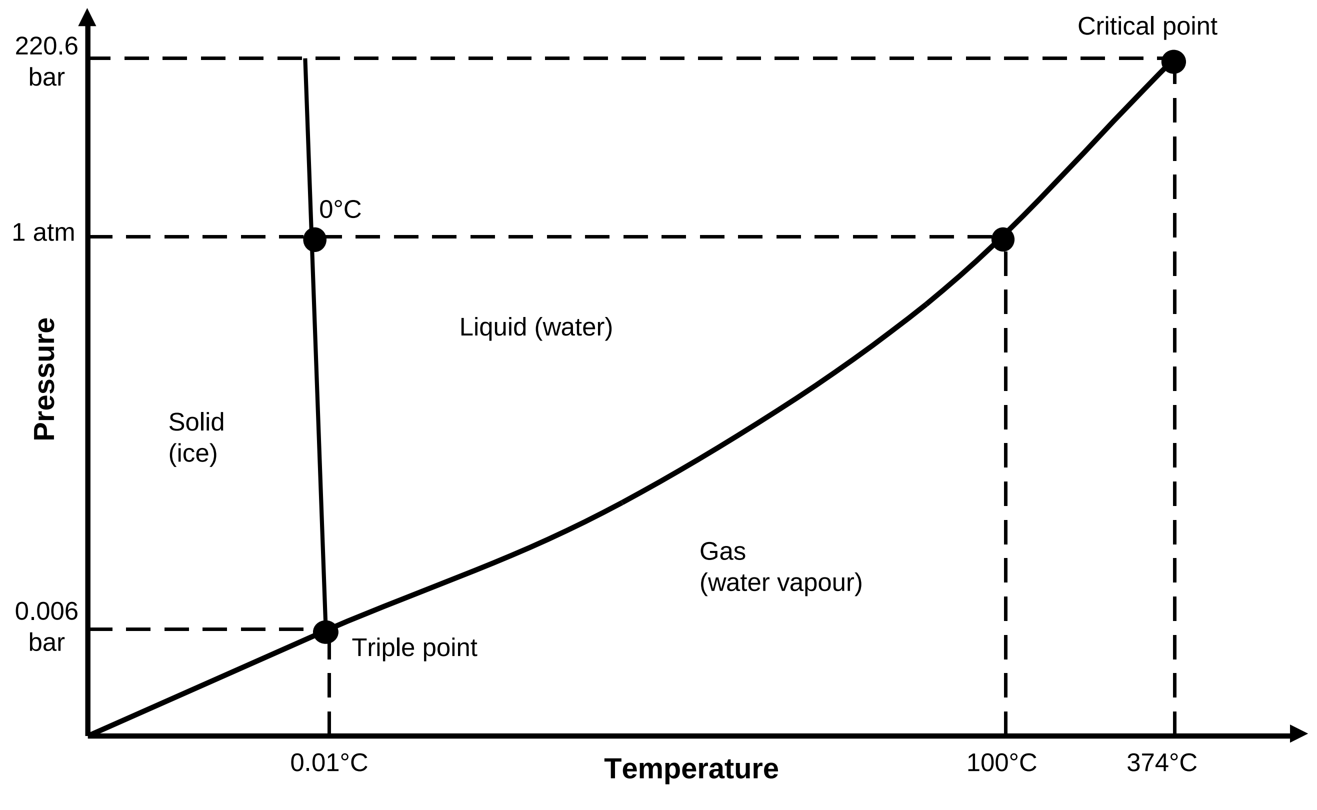


Figure 7.2.5-1: Phase diagram for water

Along the saturation curve the fluid is a two-phase mixture of liquid and vapor. From *7.2.5-1* it is however unclear how much of each phase is effectively present in the mixture. Therefore a second diagram, called *saturation diagram,* is necessary reporting the specific enthalpy of the vapor and the liquid at any saturation temperature or pressure, see Fig. *7.2.5-2* for water and steam.

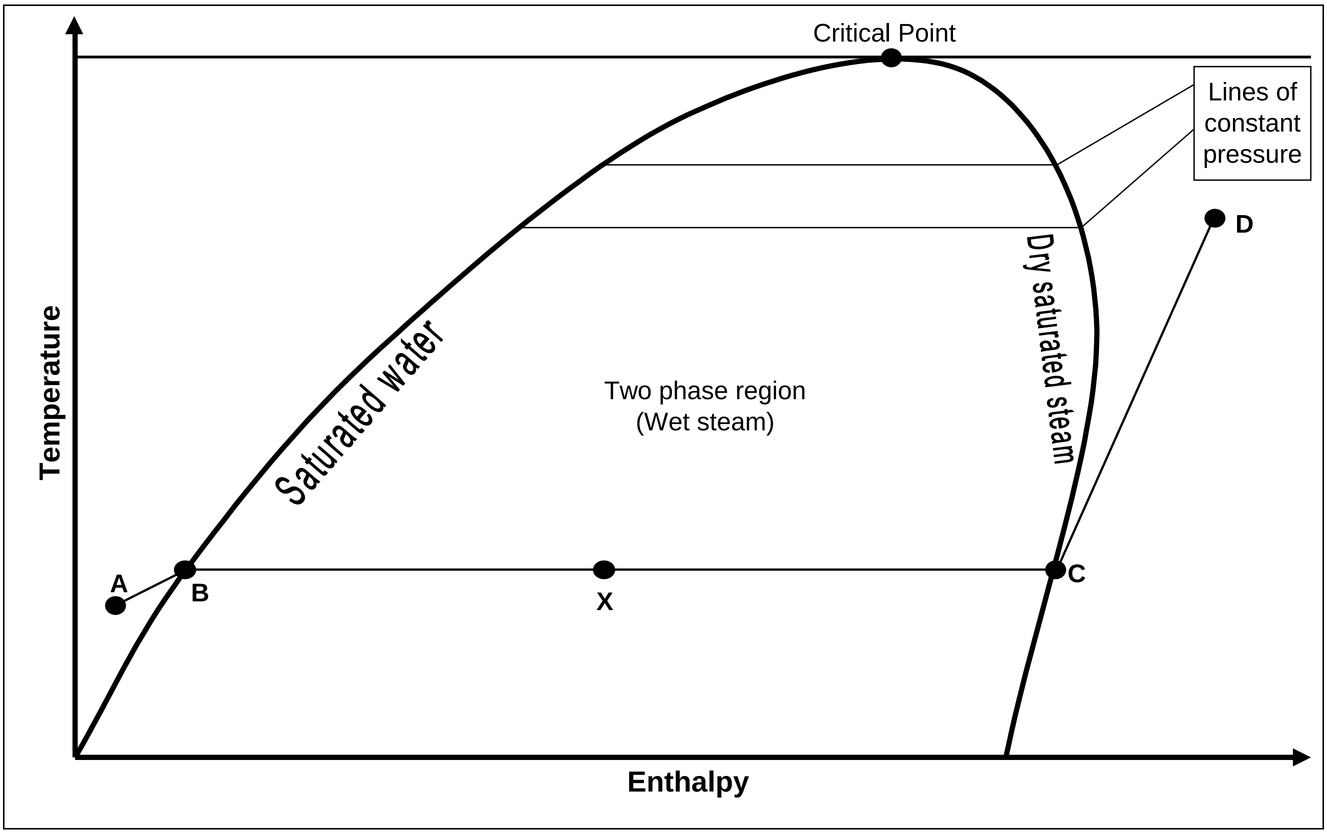


Figure 7.2.5-2: Saturation diagram for water and steam.

The diagram is made up of three sectors: the sub-cooled liquid region is on the left side, the region of superheated steam on the right and the two-phase region lies in the middle below the belt given by the saturation curves of vapor and liquid.

It shall be assumed that steam in a pressurized vessel at constant pressure is cooled from the initial state of superheated steam (Point D) to that of sub-cooled water (Point A). The first cooling reduces the temperature of steam until it reaches saturation. Any further cooling does not lead to a decrease in temperature but to condensation of some vapor: in any Point X the medium is present as a two-phase mixtures. The condensation goes on until the condition of saturated steam (Point C) is reached. Any further cooling of the now fully condensed water leads to a temperature reduction.

The difference between the enthalpy of the saturated liquid and that of the vapor is called latent heat of evaporation, Eq. *7.2.5-1*

$$\Delta h_{GL} = h_G - h_L \quad \textit{(Eq. 7.2.5-1)}$$

Fig. *7.2.5-2* shows that the latent heat of evaporation diminishes with the increase in the saturation pressure until it disappears at the critical point. From the knowledge of the enthalpy of the mixture and those of vapor and liquid the percental weight of steam in the mixture or quality can be calculated on the base of Eq. *7.2.5-2*

$$x = \frac{h_{mix} - h_L}{h_G - h_L} \quad \text{(Eq. 7.2.5-2)}$$

Graphically, the quality x is the ratio of the segment between Point B und Point X to that of the segment between Point B und Point C of Fig. *7.2.5-1*

The saturation diagram is not representative to estimate the quality of a two-phase mixture, which is vented in a safety valve in a very short time. The fast depressurization in the safety valve can cause some evaporation of the liquid, which is usually referred to as flashing. If the liquid is very subcooled or the medium is a two-phase mixture of a liquid with a non-condensable gas, it is more possible that no phase change occurs at all and that the quality of the mixture, here meaning the percental weight of the gas in the mixture, remains constant during the flow. This type of two-phase flows is called frozen.

7.2.6 Examples

7.2.6.1 Calculation of the Compressibility Factor of a Gas

Example 7.2.6.1. What is the compressibility factor of ethylene (C_2H_4) at the relieving condition of 55°C (328.15 K) and 62 bar a?

Solution. The first step is to find the critical temperature and pressure of ethylene. From Table *7.6.1-1* they are respectively 282.85 K and 51.57 bar. The reduced temperature and pressure at the relieving condition are then

$$T_r = \frac{T}{T_c} = \frac{328.15\ K}{282.85\ K} = 1.16 \qquad p_r = \frac{p}{p_c} = \frac{62\ bar\, a}{51.57\ bar\, a} = 1.20$$

implying a compressibility factor of around 0.712 according to Fig. 7.2.2-1.

7.2.6.2 Critical and Subcritical Gas Flow

Example 7.2.6.2. A buffer reservoir filled with air at 6 bar ($k = 1.4$) vents to the ambience. Determine if the flow is critical or not.

Solution. The critical pressure ratio Eq. 7.2.3-2 is equal to

$$\frac{p_c}{p_0} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} = \left(\frac{2}{1.4+1}\right)^{\frac{1.4}{1.4-1}} = 0.528$$

The back pressure to relief pressure ratio for this valve is equal to

$$\frac{p_b}{p_0} = \frac{1.01325\ bar}{6\ bar} = 0.169$$

which is below the critical pressure ratio and therefore the flow is critical.

7.3 Sizing Formulas - Summary

The following overview is a short summary of the main sizing formulas covered in the following sections.
The information contained in this section is based on following editions of codes and standards: ASME Section XIII (2021), ASME Section VIII (2021) and API RP 520 (2020), ISO 4126-7 (2016), AD Merkblatt 2000-A2 (2020).

Medium	Unit	ASME XIII (ASME VIII) / API RP 520	ISO 4126-7	AD 2000 Merkblatt A2
Gases and Vapors-critical flow	**US**	$A=\frac{W}{C\,K_bK_cK_dP_1}\sqrt{\frac{T\,Z}{M}}$	$A=\frac{Q_m}{p_0C\,K_{dr}}\sqrt{\frac{T_0Z}{M}}$	$A_0=0.1791\frac{q_m}{\psi\ \alpha_w p_0}\sqrt{\frac{T\,Z}{M}}$
	SI			
Gases and Vapors-subcritical flow -	**US**	$A=\frac{1}{735}\frac{W}{F_2K_cK_d}\sqrt{\frac{T\,Z}{M\ P_1}\frac{1}{P_1-P_2}}$		
	SI	$A=\frac{17.9\times W}{F_2K_dK_c}\sqrt{\frac{ZT}{M\times P_1(P_1-P_2)}}$	$A=\frac{Q_m}{p_0C\,K_bK_{dr}}\sqrt{\frac{T_0Z}{M}}$	
Steam	**US**	$A=\frac{1}{51.5}\cdot\frac{W}{P_1K_bK_cK_dK_NK_{SH}}$		
	SI	$A=\frac{190.5\times W}{P_1K_dK_bK_cK_NK_{SH}}$	$A=\frac{1}{0.2883}\frac{Q_m}{C\,K_{dr}}\sqrt{\frac{v}{p_0}}$	$A_0=\frac{x\,q_m}{\alpha_w p_0}$
Liquids	**US**	$A_{corr}=\frac{1}{38}\cdot\frac{Q}{K_cK_dK_vK_w}\sqrt{\frac{G}{P_1-P_2}}$		
	SI	$A=\frac{11.78\times Q}{K_dK_wK_cK_v}\sqrt{\frac{G1}{P_1-P_2}}$	$A=\frac{1}{1.61}\frac{Q_m}{K_{dr}K_v}\sqrt{\frac{v}{p_0-p_b}}$	$A_0=0.6211\frac{q_m}{\alpha_w\sqrt{\rho(p_0-p_a)}}$
Reference		**Section 7.4**	**Section 7.5**	**Section 7.6**

Table 7.3-1: Summary sizing formulas

General symbols:

A : Flow area, orifice area
G : Specific gravity (*process*)
Q : Volume flow (*process*)
W/Q_m : Mass flow (*process*)
Z/T_0 : Relieving temperature (*process*)
v : Specific volume (*process*)
Z : Compressibility factor (*process*)

Symbols in ASME XIII (ASME VIII) / API RP 520:

F_2 : Coefficient of subcritical flow see Eq. 7.4.4-1
K_b : Capacity correction factor due to back pressure (gas, vapors, steam) see Fig. 7.4.3-1
K_c = 1 (safety valve without rupture disk) and 0.9 (safety valve with rupture disk)
K_d : Discharge coefficient (*LESER catalog*)
K_N : Correction factor for Napier equation see Eq. 7.4.5-2 and Eq. 7.4.5-3
K_{SH} : Superheat steam correction factor see Table 7.4.5-1
K_v : Correction factor due to viscosity see Eq. 7.4.6-2
K_w : Correction factor due to the back pressure (liquids) see Fig. 7.4.3-2
P_1 : Relieving pressure (*process*)
P_2 : Back pressure (*process*)
C : Coefficient

The coefficient C is determined as follows.

In USC units:

$$C = 520\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{(k+1)}{(k-1)}}}$$

In SI units:

$$C = 0.03948\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{(k+1)}{(k-1)}}}$$

Symbols in ISO 4126-7:

C : Function of the isentropic coefficient see Eq. 7.5.3-2

$$C = 3.948\sqrt{k\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}}$$

K_b : Theoretical capacity correction factor for subcritical flow see Eq. 7.5.5.2-2
K_{dr} : Certified derated coefficient of discharge (*LESER catalog*)
K_v : Viscosity correction factor see Fig. 7.9.3-1
p_0 : Relieving pressure (*process*)
p_b : Back pressure (*process*)

Symbols in AD Merkblatt A2:

p_0 : Relieving pressure (*process*)
p_b : Back pressure (*process*)
α_w : Certified coefficient of discharge (*LESER catalog*)
ψ : Outflow function (gas flows) see Table 7.6.2-1
x : Pressure medium coefficient (gas flows) or vapour void fraction (two-phase flows), see Eq. 7.6.3-2

7.4 Sizing according to ASME Sect. XIII (ASME Sect. VIII), API RP 520 and API 521

The information contained in this section is based on following editions of codes and standards: ASME Section XIII (2021), ASME Section VIII (2021), API RP 520 (2020), API 521 (2020), API 526 (2017), API Standard 2000 (2014), API Standard 2510 (2001), ISO 23251(2020), prEN 14015-1 (2000)

7.4.1 Premise on ASME Section XIII and API RP 520

The ASME Code is a pressure vessel code that covers the certification of safety valves for the flows of saturated steam, water, air and natural gas (Section XIII chapter 7.8).

API RP 520 is a recommended practice to standardize the pre-selection of safety valves for gases, vapors, liquids and two-phase flow service already in the design phase of the plant. API RP 520 uses the same basic formulas as the ASME Code but extends them with correction factors, e.g. for back pressure and viscosity, to make them applicable to many practical applications.

Both the ASME Code and API RP 520 apply for relieving pressures above 15 psig.

In API RP 520 the pre-selection of a safety valve requires the determination of an *effective relief area* and an *effective coefficient of discharge*, which are nominal values and therefore independent from the selection of either the design or the manufacturer. The effective relief areas are those listed in API 526 in increasing order from letter D to T.

Once the safety valve orifice is selected it must be proven that the certified capacity meets or exceeds that of the preliminary sizing. For this calculation the engineer must use the *actual discharge coefficient* and the *actual discharge area* from the manufacturer's catalog. In many practical cases it is enough to verify that the product of the actual area and the actual discharge coefficient exceeds that of the effective area and the effective discharge coefficient, as shown in Eq. *7.4.1-1* Actual orifice areas and discharge coefficient of LESER safety valves are documented in the *ASME NB-18* (*Red Book)*[3].

$$K_{actual} \cdot A_{actual} \geq K_{d-effective} \cdot A_{effective} \quad \textit{(Eq. 7.4.1-1)}$$

LESER facilitates the selection of the safety valves by introducing LEO (LESER Effective Orifice). By using LEO the engineer can select the final size of the safety valve after the preliminary sizing by choosing a valve with a LEO larger than the effective orifice.

$$LEO = A_{actual} \cdot K_{actual} / K_{d-effective} \quad \textit{(Eq. 7.4.1-2)}$$

[3] ASME National Board Pressure Relief Device Certifications NB-18, Edition: 2021
NB-18, Pressure Relief Device Certification (nationalboard.org)

The actual discharge coefficients must be certified by ASME. The application of API RP 520 formulas with the ASME certified actual discharge coefficient and the actual relief areas from the manufacturers' catalog is commonly called "*Sizing acc. to ASME Section XIII (ASME Section VIII)*".

ASME Section XIII (ASME VIII) and API RP 520 are interconnected with each other and it is therefore common practice to present them together as a unique sizing procedure. All formulas are cited here in US units.

In VALVESTAR® a similar structure is present:

- The option "Sizing acc. to ASME XIII (ASME VIII)" is a one-step sizing procedure considering the sizing formulas in API RP 520 with their correction factors and using the actual discharge areas and actual discharge coefficients.
- The option "Sizing acc. to API RP 520" considers the two-step sizing procedure discussed before.

In both cases the same safety valve will be selected.

Table *7.4.1-1* lists the effective and the actual discharge coefficients as well as the effective and actual discharge areas for LESER API Series Type 526.

Medium	**API RP 520**	**ASME Code Sect. XIII (ASME Code Sect. VIII) LESER API Series 526**
	$K_{d-effective}$ [-]	K_{actual} [-]
Gas, vapors, steam	0.975	0.455 (Orifice D) 0.801 (Orifice E-T)
Liquid	0.65	0.343 (Orifice D) 0.579 (Orifice E-T)
Two-phase flows	0.85	No certification procedure

Orifice letter	**API RP 520 Effective discharge area**		**ASME XIII (ASME VIII) Actual discharge area LESER API Series 526**	
	[in²]	[mm²]	[in²]	[mm²]
D	0.110	71	0.239	154
E	0.196	126	0.239	154
F	0.307	198	0.394	254
G	0.503	325	0.616	398
H	0.785	506	0.975	625
J	1.287	830	1.58	1018
K	1.838	1186	2.25	1452
L	2.853	1841	3.48	2248
M	3.600	2322	4.43	2846
N	4.340	2800	5.30	3421
P	6.380	4116	7.79	5026
Q	11.050	7129	13.55	8742
R	16.000	10322	19.48	12668
T	26.000	16774	31.75	20485

Table 7.4.1-1: Effective and actual discharge coefficients and discharge areas for LESER API Series Type 526

7.4.2 List of Symbols/Nomenclature According to API RP 520

Symbol	Description	Units [US]
A	Required discharge area of the safety valve	in^2
C	Coefficient determined from an expression of the ratio of specific heats of the gas or vapor at relieving conditions	$\frac{\sqrt{lb \cdot lb_{mol} \cdot °R}}{lb_f \cdot hr}$
F_2	Coefficient of subcritical flow	--
G	Specific gravity of the gas at standard conditions referred to air at standard conditions or Specific gravity of the liquid at flowing temperature referred to water at standard conditions	--
k	Ratio of the specific heats	--
K_b	Capacity correction factor due to back pressure (gas, vapors, steam). Applies to balanced bellows valves only	--
K_c	Combination correction factor for safety valves installed with a rupture disk upstream of the valve	--
K_d	Discharge coefficient	--
K_N	Correction factor for Napier equation	--
K_{SH}	Superheat steam correction factor	--
K_v	Correction factor due to viscosity	--
K_w	Correction factor due to the back pressure (liquids). Applies to balanced bellows valves only	--
M	Molecular weight of the gas or vapor at inlet relieving conditions	lb/lb_{mol}
P_1	Relieving pressure	psi
P_2	Back pressure	psi
Q	Flow rate	gpm
T	Relieving temperature	°R
U	Viscosity of the liquid at the flowing temperature	SSU
V	Required flow through the device	scfm at 14.7 psia and 60°F
W	Required flow	lb/hr
Z	Compressibility factor for the deviation of the actual gas from a perfect gas, evaluated at relieving conditions	--
μ	Absolute viscosity of the liquid at the flowing temperature	cP

Table 7.4.2-1: List of symbols

The relieving pressure P_1 is defined in Eq. 7.4.2-1 as the sum of the set pressure, the overpressure and the atmospheric value.

$$P_1 = P_{set} + \Delta P_{overpressure} + P_{atm} \quad \text{(Eq. 7.4.2-1)}$$

The correction factor for the back pressure, K_b, is obtainable from LESER's catalog. Pilot and conventional valves in critical flows do not necessitate such a correction. The combination correction factor K_c in the preliminary sizing must be taken equal to 0.9 if a rupture disk is inserted upstream of the valve. Otherwise $K_c = 1.0$.

7.4.3 Gases and Vapors - Critical Flow

$$A = \frac{W}{C\ K_b K_c K_d P_1}\sqrt{\frac{T\,Z}{M}} \quad \text{(Eq. 7.4.3-1)}$$

$$A = \frac{1}{6.32}\frac{V\sqrt{TZM}}{CK_b K_c K_d P_1} \quad \text{(Eq. 7.4.3-2)}$$

$$A = \frac{1}{1.175}\frac{V\sqrt{TZG}}{CK_b K_c K_d P_1} \quad \text{(Eq. 7.4.3-3)}$$

The correction factor due to the back pressure K_b for the preliminary sizing is given in Fig. 7.4.3-1

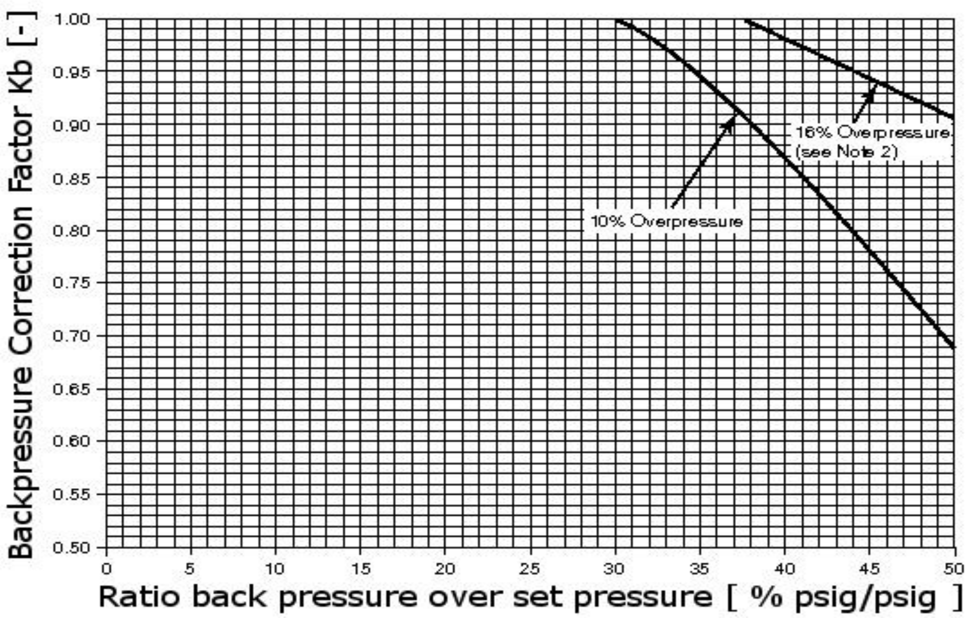


Figure 7.4.3-1: Back pressure correction factor for gases and vapors K_b from API RP 520, Page 59

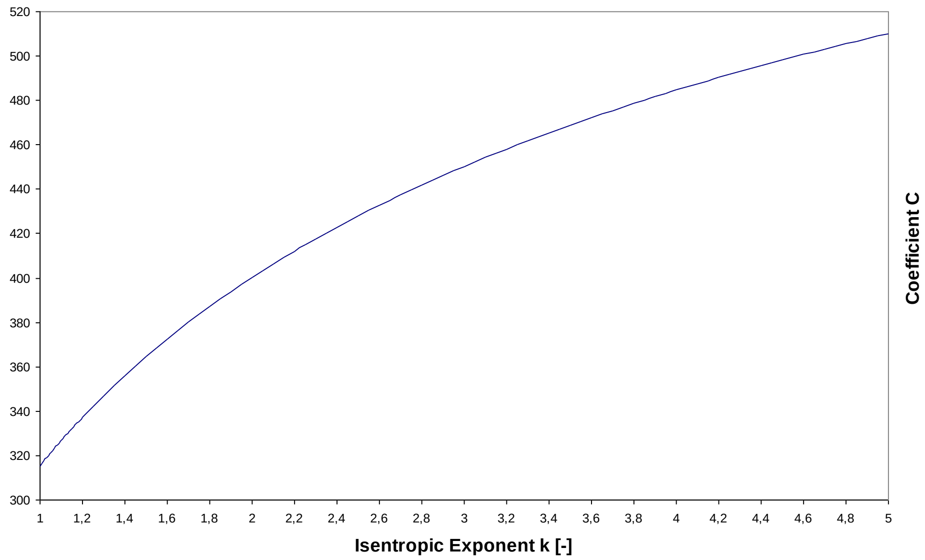


Figure 7.4.3-2: Coefficient C in function of the specific heat ratio from API RP 520, Page 74.

In alternative to Fig. *7.4.3-1* the coefficient C can be calculated from Eq. 7.4.3-4

$$C = 520\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \quad \text{Unit: } \frac{\sqrt{lb_m lb_{mol}\,{}^\circ R}}{lb_f\, hr} \qquad \textit{(Eq. 7.4.3-4)}$$

7.4.4 Gases and Vapors - Subcritical Flow

$$A = \frac{1}{735} \frac{W}{F_2 K_c K_d} \sqrt{\frac{T\,Z}{M\;P_1} \frac{1}{P_1 - P_2}} \qquad \textit{(Eq. 7.4.4-1)}$$

$$A = \frac{1}{4645} \frac{V}{F_2 K_c K_d} \sqrt{\frac{ZTM}{P_1 (P_1 - P_2)}} \qquad \textit{(Eq. 7.4.4-2)}$$

$$A = \frac{1}{864} \frac{V}{F_2 K_c K_d} \sqrt{\frac{ZTG}{P_1 (P_1 - P_2)}} \qquad \textit{(Eq. 7.4.4-3)}$$

or equivalently

$$A = \frac{1}{735} \frac{W}{F_2 K_c K_d P_1} \sqrt{\frac{T\,Z}{M} \frac{1}{1-r}} \quad \text{with} \quad r = \frac{P_1}{P_2} \qquad \textit{(Eq. 7.4.4-4)}$$

where F_2 is calculated from Eq. *7.4.4-5* or obtained from Fig. *7.4.4-1*

$$F_2 = \sqrt{\frac{k}{k-1} \cdot r^{\frac{2}{k}} \cdot \frac{1 - r^{\frac{k-1}{k}}}{1-r}} \qquad \textit{(Eq. 7.4.4-5)}$$

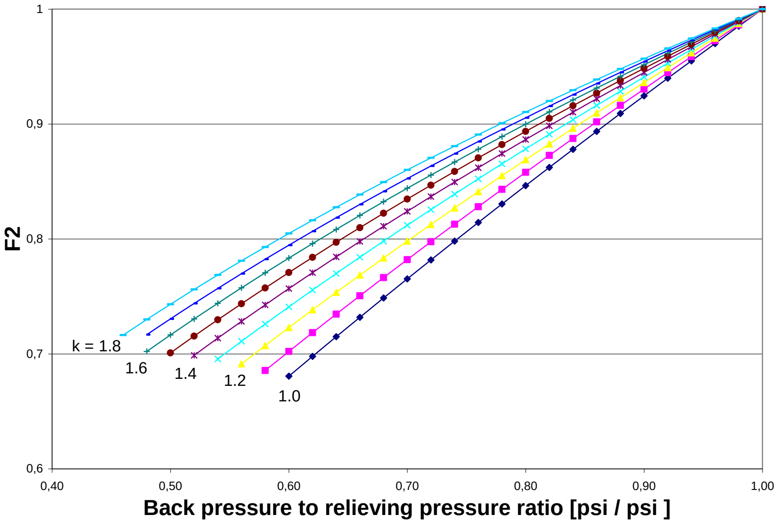


Figure 7.4.4-1: Coefficient F_2 in function of the ratio of absolute back pressure on absolute relieving pressure for various specific heat ratios.

7.4.5 Steam

$$A = \frac{1}{51.5} \cdot \frac{W}{P_1 K_b K_c K_d K_N K_{SH}} \quad \text{(Eq. 7.4.5-1)}$$

The correction factor for Napier equation K_N is expressed by Eq. *7.4.5-2* and *7.4.5-3*

$$K_N = \frac{0.1906 \cdot P_1 - 1000}{0.2292 \cdot P_1 - 1061} \quad \text{if} \quad P_1 > 1500 \quad psia \quad \text{(Eq. 7.4.5-2)}$$

$$K_N = 1 \quad \text{if} \quad P_1 \leq 1500 \quad psia \quad \text{(Eq. 7.4.5-3)}$$

The Superheat steam correction factor K_{SH} can be taken from Table 7.4.5-1, which is extracted from Table 9 on Page 51 of API RP 520.

Set pressure [psig]	Temperature [°F]									
	300	400	500	600	700	800	900	1000	1100	1200
15	1.00	0.98	0.93	0.88	0.84	0.80	0.77	0.74	0.72	0.70
20	1.00	0.98	0.93	0.88	0.84	0.80	0.77	0.74	0.72	0.70
40	1.00	0.99	0.93	0.88	0.84	0.81	0.77	0.74	0.72	0.70
60	1.00	0.99	0.93	0.88	0.84	0.81	0.77	0.75	0.72	0.70
80	1.00	0.99	0.93	0.88	0.84	0.81	0.77	0.75	0.72	0.70
100	1.00	0.99	0.94	0.89	0.84	0.81	0.77	0.75	0.72	0.70
120	1.00	0.99	0.94	0.89	0.84	0.81	0.78	0.75	0.72	0.70
140	1.00	0.99	0.94	0.89	0.85	0.81	0.78	0.75	0.72	0.70
160	1.00	0.99	0.94	0.89	0.85	0.81	0.78	0.75	0.72	0.70
180	1.00	0.99	0.94	0.89	0.85	0.81	0.78	0.75	0.72	0.70
200	1.00	0.99	0.95	0.89	0.85	0.81	0.78	0.75	0.72	0.70
220	1.00	0.99	0.95	0.89	0.85	0.81	0.78	0.75	0.72	0.70
240	1.00	1.00	0.95	0.90	0.85	0.81	0.78	0.75	0.72	0.70
260	1.00	1.00	0.95	0.90	0.85	0.81	0.78	0.75	0.72	0.70
280	1.00	1.00	0.96	0.90	0.85	0.81	0.78	0.75	0.72	0.70
300	1.00	1.00	0.96	0.90	0.85	0.82	0.78	0.75	0.72	0.70
350		1.00	0.96	0.90	0.86	0.82	0.78	0.75	0.72	0.70
400		1.00	0.96	0.91	0.86	0.82	0.78	0.75	0.72	0.70
500		1.00	0.96	0.92	0.86	0.82	0.78	0.75	0.73	0.70
600		1.00	0.97	0.92	0.87	0.82	0.79	0.75	0.73	0.70
800			1.00	0.95	0.88	0.83	0.79	0.76	0.73	0.70
1000			1.00	0.96	0.89	0.84	0.78	0.76	0.73	0.71
1250			1.00	0.97	0.91	0.85	0.80	0.77	0.74	0.71
1500				1.00	0.93	0.86	0.81	0.77	0.74	0.71
1750				1.00	0.94	0.86	0.81	0.77	0.73	0.70
2000				1.00	0.95	0.86	0.80	0.76	0.72	0.69
2500				1.00	0.95	0.85	0.78	0.73	0.69	0.66
3000					1.00	0.82	0.74	0.69	0.65	0.62

Table 7.4.5-1: Correction factors K_{SH} for superheat steam acc. to API RP 520 Page 86

7.4.6 Liquids

$$A = \frac{1}{38} \cdot \frac{Q}{K_c K_d K_v K_w} \sqrt{\frac{G}{P_1 - P_2}} \quad \textit{(Eq. 7.4.6-1)}$$

The correction factor due to the back pressure K_w for the preliminary sizing can be read from Fig. *7.4.6-1*. The correction factor due to viscosity K_v can be either calculated from Eq. *7.4.6-2.*

$$K_v = \left(\frac{170}{Re_L} + 1 \right)^{-0.5}$$

…(Eq. 7.4.6-2)

by using the definition of the Reynolds number in Eq. *7.4.6-3*

$$\mathrm{Re} = 2800 \frac{Q\,G}{\mu\,\sqrt{A}} \quad \text{or} \quad \mathrm{Re} = 12700 \frac{Q}{U\,\sqrt{A}} \quad \textit{(Eq. 7.4.6-3)}$$

or graphically estimated from Fig. 7.2.4-2. When a safety valve is to be sized for viscous liquids, it should first be sized as the fluid were in viscid ($K_v = 1$) to obtain a preliminary minimum discharge area using Eq. *7.4.6-1*. The next larger effective orifice area is then selected from Table 7.4.1-1 to calculate the Reynolds number in Eq. 7.4.6-3, which is used to determine the viscosity correction factor in Eq. 7.4.6-2. This correction factor K_v is introduced back into Eq. *7.4.6-1* to correct the preliminary discharge area. If the corrected area exceeds the chosen standard orifice, this procedure should be repeated using the next larger standard orifice area from Table 7.4.1-1.

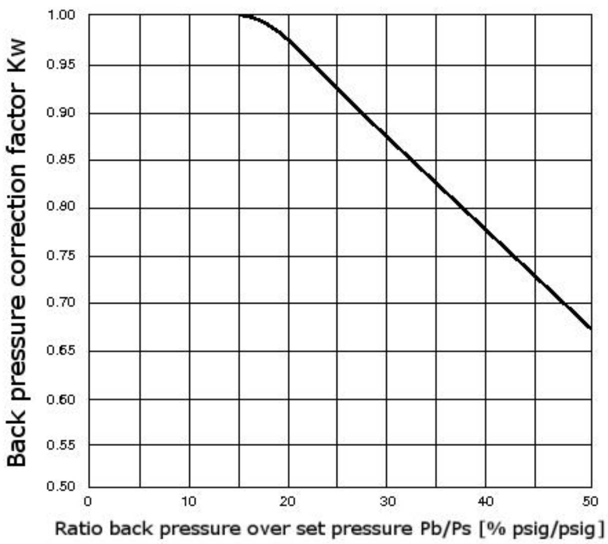


Figure 7.4.6-1: Back pressure correction factor for liquids K_w from API RP 520, Page 60

7.4.7 Two-Phase Flows according to API RP 520

This first subchapter incl. 7.4.7.3 represent an older edition of the API 520 , 7th Edition, 2000, Appendix D. It shall remain in order to continue to provide the calculation logic of superseded case definitions as a calculation archive. The subchapter 7.4.7.4 and 7.4.7.5 of API 520, 10th Edition 2020 contain current sizing methods.

In API RP 520 on page 69 there is a short preface intended for people approaching two-phase flow calculation routines. The reader is invited to read it carefully before using this sizing procedure.

The most relevant points are that

1. This sizing procedure is just <u>one of the several techniques</u> currently in use.
2. This sizing procedure has <u>not</u> been <u>yet validated by tests.</u>
3. There is <u>no recognized procedure</u> for the <u>certification</u> of safety valves in two-phase flows.

Two-phase flows occur in a variety of scenarios, where either

- a liquid vaporizes within the safety valve, or
- a two-phase mixture enters the safety valve or
- a vapor condenses in the safety valve
- a supercritical fluid enters the safety valve and condenses

In all cases a two-phase mixture is likely to be discharged from the safety valve.

The complete list of the two-phase flow scenarios for safety valves is presented in Table 7.4.7-1.

Saturated liquid and saturated vapor enter the valve and the liquid flashes. No non-condensable gas is present (*flashing flow*).	See section 7.4.7.1
Supercritical fluid condensing in the safety valve.	
Highly subcooled liquid and either non-condensable gas, condensable vapors or both enter the valve but the liquid does not flash (*frozen flow*).	See section 7.4.7.2
Subcooled liquid enters the valve and flashes. No vapor or gas is present at the inlet.	See section 7.4.7.3
Generic two-phase flow with a subcooled or saturated liquid and non-condensable gas with or without condensable vapor.	(not present in this chapter)

Table 7.4.7-1*: Two-phase flow scenarios*

The sizing procedure of API RP 520 Appendix D is based on the Omega method of Leung[4]. This sizing method uses the so-called Omega-parameter, which is a measure of the compressibility of the two-phase mixture.

The required steps of this method are:

- Calculation of the Omega-Parameter
- Determination if the flow is critical or subcritical
- Calculation of the mass flux, which is the mass flow per unit area
- Calculation of the required orifice area of the safety valve among those in API RP 526

[4] Leung, J.C. *On the application of the method of Landau and Lifshitz to sonic velocities in homogeneous two-phase mixtures*, **J. Fluids Engineering**, 1996, 118, 1,186–188.

Some additional nomenclature, which is necessary for two-phase flows, is given in Table 7.4.7-2.

Symbol	Description	Units [US]
C_p	Specific heat at constant pressure of the liquid at the safety valve inlet	Btu/(lb °R)
G	Mass flux	lb/(s ft²)
h_{vl0}	Latent heat of vaporization at the safety valve inlet. For multicomponent systems, it represents the difference between the vapor and the liquid specific enthalpies at the safety valve inlet	Btu/lb
h_{vls}	Latent heat of vaporization at P_s. For multi-component systems it is the difference between the vapor and liquid specific enthalpies at P_s	Btu/lb
P_1	Pressure at safety valve inlet	psi
P_a	Downstream back pressure	psi
P_c	Critical pressure	psi
P_r	Relative pressure	[--]
P_s	Saturation pressure (single-component flows) or bubble point pressure (multi-component flows) at the relieving temperature T_0	psi
Q	Volumetric flow rate	gal/min
T_0	Temperature at safety valve inlet	°R
T_r	Relative temperature	[--]
v_{v0}	Specific volume of the vapor at safety valve inlet	ft³/lb
v_0	Specific volume of the two-phase mixture at safety valve inlet	ft³/lb
v_{vg0}	Specific volume of the vapor, gas or combined vapor and gas at the safety valve inlet	ft³/lb
v_{vl0}	Difference between the vapor and the liquid specific volumes at the safety valve inlet	ft³/lb
v_{vls}	Difference between the vapor and the liquid specific volumes at P_s	ft³/lb
v_9	Specific volume evaluated at 90% of the safety valve inlet pressure (= relieving pressure), assuming isentropic flashing	ft³/lb
x_0	Vapor (or gas or combined vapor and gas) mass fraction (quality) at safety valve inlet	[--]
η_a	Ratio between ambient pressure and relieving pressure	[--]
η_c	Ratio between critical pressure and relieving pressure	[--]
η_s	Ratio between saturation pressure at relieving temperature and relieving pressure	[--]
ρ_{l0}	Density of the liquid at the inlet of the safety valve	lb/ft³
ρ_9	Density evaluated at 90% of the saturation pressure (single-component flows) or bubble point pressure (multi-component flows) P_s at T_0. The flash calculation should be carried out isentropically.	lb/ft³
ω	Omega Parameter	[--]
ω_s	Omega Parameter for subcooled liquid flows at safety valve inlet	[--]

Table 7.4.7-2: List of symbols for two-phase flows

7.4.7.1 Saturated Liquid and Saturated Vapor, Liquid Flashes

The definitions of the Omega-Parameter in Eq. *7.4.7.1-1*, *7.4.7.1-2* and *7.4.7.1-3* can be employed for multi-component systems, whose nominal boiling range, that is the difference in the atmospheric boiling points of the heaviest and the lightest components, is less than 150°F. For single-component systems with relative temperature $T_r \leq 0.9$ (see Eq. 7.2.2-4) and pressure (see Eq. 7.2.2-5) $p_r \leq 0.5$, either Eq. 7.4.7.1-1 or Eq. 7.4.7.1-2 can be used.

$$\omega = \frac{x_0 v_{v0}}{v_0} \cdot \left(1 - 0.37 \frac{P_1 \cdot v_{vl0}}{h_{vl0}}\right) + 0.185 \frac{C_p T_0 P_1}{v_0} \left(\frac{v_{vl0}}{h_{vl0}}\right)^2 \quad \text{(Eq. 7.4.7.1-1)}$$

$$\omega = \frac{x_0 v_{v0}}{v_0 k} + 0.185 \frac{C_p T_0 P_1}{v_0} \left(\frac{v_{vl0}}{h_{vl0}}\right)^2 \quad \text{(Eq. 7.4.7.1-2)}$$

For multi-component systems, whose nominal boiling range is greater than 150°F or for single-component systems close to the thermodynamic critical point or supercritical fluids in condensing two-phase flows Eq. 7.4.7.1-3 must be used.

$$\omega = 9\left(\frac{v_9}{v_0} - 1\right) \quad \text{(Eq. 7.4.7.1-3)}$$

The two-phase flow is critical if the critical pressure is larger than the back pressure

$P_c > P_b \Rightarrow$ the two-phase flow is *critical*

$P_c < P_b \Rightarrow$ the two-phase flow is *subcritical*

The critical pressure ratio, $\eta_c = P_c / P_1$, is the iterative solution of Eq. 7.4.7.1-4

$$\eta_c^2 + \left(\omega^2 - 2\omega\right)\left(1 - \eta_c\right)^2 + 2\omega^2 \ln\left(\eta_c\right) + 2\omega^2\left(1 - \eta_c\right) = 0 \quad \text{(Eq. 7.4.7.1-4)}$$

The mass flux is defined in Eq. 7.4.7.1-5 for critical flow and in Eq. 7.4.7.1-6 for subcritical flow

$G = 68.09 \cdot \eta_c \cdot \sqrt{\frac{1}{\omega} \frac{P_1}{v_0}}$	critical flow	*(Eq. 7.4.7.1-5)*
$G = 68.09 \sqrt{\frac{P_1}{v_0}} \frac{\sqrt{-2 \cdot \left[\omega \ln\left(P_a / P_1\right) + \left(\omega - 1\right)\left(1 - P_a / P_1\right)\right]}}{\omega\left(P_1 / P_a - 1\right) + 1}$	subcritical flow	*(Eq. 7.4.7.1-6)*

Finally, the required area of the safety valve can be computed from Eq. 7.4.7.1-7

$$A = 0.04 \cdot \frac{1}{K_b K_c K_d} \cdot \frac{W}{G} \quad \text{(Eq.7.4.7.1-7)}$$

For a preliminary sizing to calculate the effective orifice area the discharge coefficient K_d can be assumed equal to 0.85 and the correction factor for back pressure is that in Fig 7.4.3-1.

7.4.7.2 Highly Subcooled Liquid, Non-Condensable Gas/Condensable Vapors, Non-Flashing Liquid (Frozen Flow).

Same sizing procedure as in Section 7.4.7.1 but with the Omega Parameter in Eq. 7.4.7.2-1

$$\omega = \frac{x_0 v_{vg0}}{v_0 k} \quad \text{(Eq. 7.4.7.2.-1)}$$

7.4.7.3 Subcooled Liquid enters the Valve and Flashes, No Vapor or Gas at the Inlet

For subcooled liquid flows the Omega-Parameter is generally referred with ω_s. For multi-component systems with nominal boiling range less than 150°F ω_s can be calculated either from Eq. 7.4.7.3-1 or from Eq. 7.4.7.3-2. For single component systems with a relative temperature and pressure within the limits $T_r \le 0.9$ and $p_r \le 0.5$ ω_s is given by Eq. 7.4.7.3-1.

$$\omega_s = 0.185 \rho_{l0} C_p T_0 P_s \left(\frac{v_{vls}}{h_{vls}} \right)^2 \quad \text{(Eq. 7.4.7.3-1)}$$

For multi-component systems, whose nominal boiling range is greater than 150°F or for single-component systems close to the thermodynamic critical point ω_s is given by Eq. 7.4.7.3-2.

$$\omega_s = 9 \left(\frac{\rho_{l0}}{\rho_9} - 1 \right) \quad \text{(Eq. 7.4.7.3-2)}$$

When a liquid enters the safety valve in a subcooled state, it is necessary to determine where indicatively it saturates and the extension of the subcooling region on the base of the following table:

$P_s > P_0 \frac{2 \cdot \omega_s}{1 + 2 \cdot \omega_s}$	*low subcooling region* (flashing occurs before the valve throat)
$P_s < P_0 \frac{2 \cdot \omega_s}{1 + 2 \cdot \omega_s}$	*high subcooling region* (flashing occurs at the valve throat)

The condition for the existence of critical and subcritical flow are:

	Critical flow	Subcritical flow
in the low subcooling region	$P_c > P_a$	$P_c < P_a$
in the high subcooling region	$P_s > P_a$	$P_s < P_a$

The mass flux in case of low and high subcooling is:

<table>
<tr><td rowspan="2">Low subcooling region</td><td rowspan="2">$G = 68.09 \frac{\left\{ 2(1-\eta_s) + 2\left[\omega_s \eta_s \ln\left(/ \ \eta_s/\eta \right) - (\omega_s - 1)(\eta_s - \eta)\right] \right\}^{0.5}}{\omega_s(\eta_s/\eta - 1) + 1} \sqrt{P_1 \rho_{l0}}$</td><td rowspan="2">with</td><td>$\eta = \eta_c$</td><td>Crit. flow</td></tr>
<tr><td>$\eta = \eta_a$</td><td>Subcrit. flow</td></tr>
<tr><td rowspan="2">High subcooling region</td><td rowspan="2">$G = 96.3\left[\rho_{l0} \cdot (P_1 - P)\right]^{0.5}$</td><td rowspan="2">with</td><td>$P = P_s$</td><td>Crit. Flow</td></tr>
<tr><td>$P = P_a$</td><td>Subcrit. flow</td></tr>
</table>

The required area of the pressure relief valve is calculated from Eq. 7.4.7.3-3

$$A = 0.3208 \frac{1}{K_b K_c K_d} \frac{Q \cdot \rho_{l0}}{G} \quad \textit{(Eq.7.4.7.3-3)}$$

The correction factor for back pressure for balanced bellow valves is K_w in Fig. 7.4.6-1. The discharge coefficient K_d for a preliminary sizing is equal to 0.65 for subcooled liquids at the safety valve inlet or 0.85 for saturated liquids.

7.4.7.4 Omega Method API 520-1 (2020) Chapter C2.2 Sizing for Two-phase Flashing or Nonflashing Flow Through a pressure-relief valve using the Omega Method

$$\omega = 9\left(\frac{v_9}{v_0} - 1\right) \quad \textit{(Eq. 7.4.7.4-1)}$$

Note that here for determining v_9, it should be evaluated using isentropic flash calculation; but an isenthalpic (adiabatic) flash is sufficient for low quality mixtures far from the thermodynamic critical point.

The two-phase flow is critical if the critical pressure is larger than the back pressure

$P_c > P_b \Rightarrow$ the two-phase flow is *critical*

$P_c < P_b \Rightarrow$ the two-phase flow is *subcritical*

The critical pressure ratio, $\eta_c = P_c / P_1$, is the iterative solution of Eq. 7.4.7.4-2

$$\eta_c^2 + \left(\omega^2 - 2\omega\right)\left(1 - \eta_c\right)^2 + 2\omega^2 \ln\left(\eta_c\right) + 2\omega^2\left(1 - \eta_c\right) = 0 \quad \textit{(Eq. 7.4.7.4-2)}$$

The mass flux is defined in Eq. 7.4.7.4-3 for critical flow and in Eq. 7.4.7.4-4 for subcritical flow

$G = 68.09 \cdot \eta_c \cdot \sqrt{\frac{1}{\omega}\frac{P_1}{v_0}}$	critical flow	*(Eq. 7.4.7.4-3)*
$G = 68.09\sqrt{\frac{P_1}{v_0}}\,\frac{\sqrt{-2\cdot\left[\omega \ln\left(P_a/P_1\right) + \left(\omega - 1\right)\left(1 - P_a/P_1\right)\right]}}{\omega\left(P_1/P_a - 1\right) + 1}$	subcritical flow	*(Eq. 7.4.7.4-4)*

Finally, the required area of the safety valve can be computed from Eq. 7.4.7.4-5

$$A = \frac{0{,}04\ W}{K_b K_d K_c K_v G}$$

$$A = \frac{277.8\ W}{K_b K_d K_c K_v G} \quad \textit{(Eq.7.4.7.4-5)}$$

For a preliminary sizing to calculate the effective orifice area the discharge coefficient K_d can be assumed equal to 0.85 and the correction factor for back pressure is that in Fig 7.4.3-1.

7.4.7.5 Omega Method API 520-1 (2020) Chapter C2.3 Sizing for Subcooled Liquid at the Pressure-relief Valve Inlet Using the Omega Method considering SI-Units

Calculation for saturated omega parameter can be performed using two pressure specific volume data points (ρ_{10} & ρ_9), using following equation

$\omega_s = 9\left(\frac{\rho_{10}}{\rho_9} - 1\right)$	*(Eq. 7.4.7.5-1)*

Note that for Multicomponent system, the bubble point pressure corresponding to To for Ps should be used.

For determining Density (ρ_9) evaluated at 90% of PRV inlet pressure, it should be evaluated using isentropic flash calculation; but an isenthalpic (adiabatic) flash is sufficient for low quality mixtures far from the thermodynamic critical point.

1. Determine the subcooling region:
   a. Calculation of Transition saturation pressure ratio (η_{st}):

$\eta_{st} = \frac{2\omega_s}{1 + 2\omega_s}$	*(Eq. 7.4.7.5-2)*

   b. Determine the type (high or low) of subcooling region with following comparison:

   If saturation pressure (Ps) is less than product of transition saturation pressure ratio (η_{st}) and relieving pressure (P_0) then the region will be high subcooling region.

$$If \quad P_s < \eta_{st} P_0 \text{ then high subcooling region (flashing occurs at throat)}$$

   If saturation pressure (Ps) is greater than or equal to the product of transition saturation pressure ratio (η_{st}) and relieving pressure (P_0) then the region will be low subcooling region.

$$If \quad P_s \geq \eta_{st} P_0 \text{ then low subcooling region (flashing occurs upstream of throat)}$$

2. Check for critical or subcritical flow depending on subcooling region (high or low):
   1. Determination of critical or subcritical flow for high subcooling region:

   If saturation pressure (Ps) is greater than or equal to total back pressure (Pa) then flow will be critical flow.

$$If \quad P_s \geq P_a \text{ then flow is critical flow}$$

If saturation Pressure (Ps) is less than the total back pressure (Pa) then flow will be subcritical flow.

$If \quad P_s < P_a$ then flow is subcritical flow (all liquid flow)

2. Determination of critical or subcritical flow for low subcooling region:
   A. Calculation of Critical Flow Pressure:

$P_c = \eta_c P_0$	*(Eq. 7.4.7.5-3)*

i. Considerations for calculation of critical pressure ratio (η_c):

The critical pressure ratio (η_c) is dependent on saturation pressure ratio (η_s) and transition saturation pressure ratio (η_{st}). The critical pressure is evaluated using following given steps.

a. Calculation for Saturation pressure ratio (η_s):

$\eta_s = \frac{P_s}{P_0}$	*(Eq. 7.4.7.5-4)*

b. Calculation of critical pressure ratio where saturation pressure ratio is less than or equal to transition saturation pressure ratio, i.e.
if ($\eta_s \leq \eta_{st}$), use following equation:

$\eta_c = \eta_s$	*(Eq. 7.4.7.5-5)*

c. Calculation of critical pressure ratio where saturation pressure ratio is greater than transition saturation pressure ratio, i.e. if ($\eta_s > \eta_{st}$), use following equation:

The critical pressure ratio (η_c) is calculated using following approximated equation

$\eta_c = \eta_s \times \left(\frac{2 \times \omega_s}{2 \times \omega_s - 1}\right) \times \left[1 - \sqrt{1 - \frac{1}{\eta_s} \times \left(\frac{2 \times \omega_s - 1}{2 \times \omega_s}\right)}\right]$	*(Eq. 7.4.7.5-6)*

User can also calculate critical pressure ratio (η_c) using following equation

$\frac{\left(\omega_s + \frac{1}{\omega_s} - 2\right)}{2 \times \eta_s} \times \eta_c^2 - 2 \times (\omega_s - 1) \times \eta_c + \omega_s \times \eta_s \times \ln\left(\frac{\eta_c}{\eta_s}\right) + \frac{3}{2} \times \omega_s \times \eta_s - 1 = 0$	*(Eq. 7.4.7.5-7)*

Note that the critical pressure ratio (η_c) can also be calculated using figure C.2 given on page 123 in API 520-1 Ninth Edition 2014 Annex C.2.3.1. Refer screenshot given

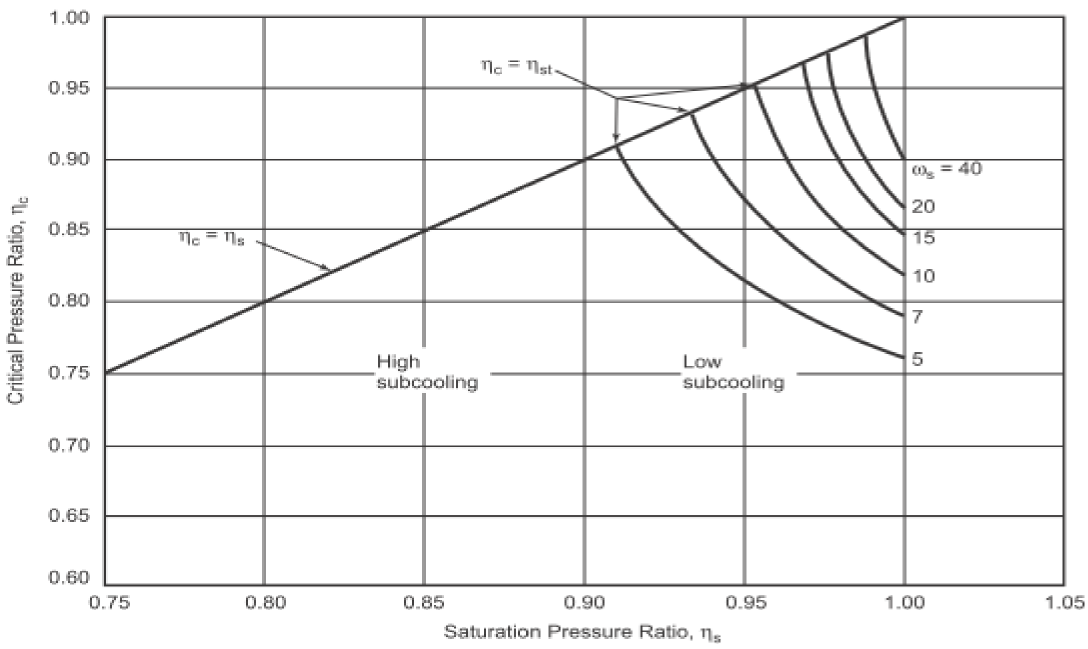


Figure C.2—Correlation for Nozzle Critical Flow of Inlet Subcooled Liquid

B. Determination of critical or subcritical flow for low subcooling region:

If Critical Pressure (Pc) is greater than or equal to downstream back pressure (Pa) then flow will be critical flow.

$If \quad P_c \geq P_a$ then flow is critical flow

If Critical Pressure (Pc) is less than downstream back pressure (Pa) then flow will be subcritical flow.

$If \quad P_c < P_a$ then flow is subcritical flow

3. Calculation of the mass flux (G) depending on subcooling region:
   1. Calculation of the mass flux (G) depending on type of flow (critical or subcritical) in low subcooling region:

      Standardized equation for mass flux (G):

$G = \dfrac{\left\{2(1-\eta_s) + 2\left[\omega_s \eta_s \ln\frac{\eta_s}{\eta} - (\omega_s - 1)(\eta_s - \eta)\right]\right\}^{1/2}}{\omega_s\left(\frac{\eta_s}{\eta} - 1\right) + 1}\sqrt{P_0 \rho_{l0}}$	*(Eq. 7.4.7.5-8)*

a. For critical flow use following equation to calculate mass flux (G) for critical flow in low subcooling region (This equation is obtained by substituting η_c for η in above standardized equation).

$G = \dfrac{\left\{2(1-\eta_s) + 2\left[\omega_s \eta_s \ln\dfrac{\eta_s}{\eta_c} - (\omega_s - 1)(\eta_s - \eta_c)\right]\right\}^{1/2}}{\omega_s\left(\dfrac{\eta_s}{\eta_c} - 1\right) + 1}\sqrt{P_0\,\rho_{10}}$	*(Eq. 7.4.7.5-9)*

b. For subcritical flow (all liquid flow) using following equation to calculate mass flux (G) for subcritical flow in low subcooling region (This equation is obtained by substituting η_a for η in above standardized equation).

$G = \dfrac{\left\{2(1-\eta_s) + 2\left[\omega_s \eta_s \ln\dfrac{\eta_s}{\eta_a} - (\omega_s - 1)(\eta_s - \eta_a)\right]\right\}^{1/2}}{\omega_s\left(\dfrac{\eta_s}{\eta_a} - 1\right) + 1}\sqrt{P_0\,\rho_{10}}$	*(Eq. 7.4.7.5-10)*

i. Considerations for calculation of subcritical pressure ratio in above equation:

The subcritical pressure ratio (η_a) can be calculated using following equation

$\eta_a = \dfrac{P_a}{P_0}$	*(Eq. 7.4.7.5-11)*

2. Calculation of the mass flux (G) depending on type of flow (critical or subcritical) in high subcooling region:

Standardized equation for mass flux (G):

$G = 1.414\,[\rho_{10}(P_0 - P)]^{\frac{1}{2}}$	*(Eq. 7.4.7.5-12)*

a. For critical flow use following equation to calculate mass flux (G) for critical flow in high subcooling region (This equation is obtained by substituting P_s for P in above standardized equation).

$G = 1.414\,[\rho_{10}(P_0 - P_s)]^{\frac{1}{2}}$	*(Eq. 7.4.7.5-13)*

b. For subcritical flow (all liquid flow) using following equation to calculate mass flux (G) for subcritical flow in high subcooling region (This equation is obtained by substituting P_a for P in above standardized equation).

$G = 1.414\,[\rho_{10}(P_0 - P_a)]^{\frac{1}{2}}$	*(Eq. 7.4.7.5-14)*

4. Calculation of required effective discharge area (A):

a. Calculation for required flow area can be performed based on various combinations of user inputs. Considering required volumetric flow rate (Q) is known and Mass Flux (G) calculated above, use following equation

$\mathrm{A} = 16.67\,\dfrac{\mathrm{Q} \times \rho_{10}}{K_b K_d K_c K_v G}$	*(Eq. 7.4.7.5-15)*

7.4.8 Fire Case and Hydraulic (Thermal) Expansion acc. to API 521 and ISO 23251

This standard deals with the planning of safety requirements for pressure-relieving and depressurizing systems. It analyses the major causes for overpressure and gives some indicative values for the determination of the individual relieving rates in a variety of practical cases. It was fully introduced in the new standard[5] ISO 23251. This ISO 23251 document supplements API Std 521, the requirements of which are applicable with the exceptions specified in this document. Formulas in both standards are identical, except for the units. For the application of API 521 formulas the user must use the US units, which are reported on the third column of Table 7.4.8.1-1, while for the formulas in ISO 23251 the SI units, defined of the fourth column of the same table.

This section of ENGINEERING shows the equations for the sizing in case of

- ✓ Hydraulic Expansion (API 521, ISO 23251)
- ✓ External Fire Case (API 521, ISO 23251)

Hydraulic expansion or Thermal expansion is the increase in the liquid volume due to an increment in temperature. Typically it occurs for liquids, which are trapped in vessels, pipes, heat exchangers and exposed to heat, for instance from electrical coils, ambient heat, fire, etc.

In the external fire case sizing API 521 distinguishes between *wetted* and *unwetted vessels* according to the following definitions and presents for each of them a sizing procedure.

A wetted vessel contains a liquid in equilibrium with its vapor or a gas. Wetted vessels contain temperated systems. In consequence of the heat transfer from the external fire a partial evaporation of the liquid occurs. In the calculation of the portion of vessel exposed to fire only that portion in contact with the liquid within a distance of 25 feet (7.6 m) above the fire source must be considered for sizing, see Table 7.4.8.3-1. If the exposure to fire leads to vapor generation from thermal cracking, alternate sizing methods may be appropriate.

An unwetted vessel is a vessel, which is either thermally insulated on the internal walls or filled with gases, vapors or a supercritical fluid. Unwetted vessels contain gassy systems. Vessels with separated liquid and vapor under normal conditions which become single-phase at relieving conditions belong here as well. However, vessels, whose walls become thermally insulated due to the deposition of coke or material from the contained fluids, are still considered wetted for fire sizing case however additional protection is required. In comparison to wetted vessels the thermal flow from the walls to the interior is low in unwetted vessels due to the large thermal resistance. In case of prolonged exposure of the outside surface to the fire source the temperature within the walls may be so high to cause thermal rupture of the vessel.

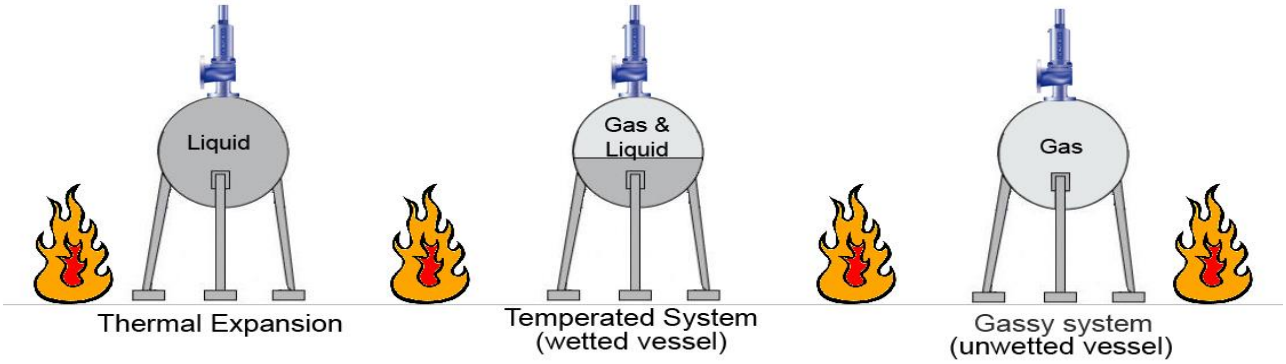


Figure: 7.4.8-1: Hydraulic (thermal) expansion and fire case

[5] ISO 23251 Petroleum and natural gas industries – Pressure relieving and depressuring systems, 2020

7.4.8.1 List of Symbols/Nomenclature

Symbol	Description	Units [US]	Units [SI]
A	Effective discharge area of the valve	[in²]	*
A'	Exposed surface area of the vessel	[ft²]	*
A_{ws}	Total wetted surface	[ft²]	[m²]
α_v	Cubical expansion coefficient of the liquid at the expected temperature	[1/°F]	[1/°C]
c	Specific heat capacity of the trapped liquid	[Btu/(lb °F)]	[J/(kg K)]
F	Environment factor	--	--
d	Relative density referred to water at 60°F (15.6°C)	--	--
h_{vl0}	Latent heat of vaporization	[Btu/lb]	[J/kg]
K_D	Coefficient of discharge	--	--
ϕ	Total heat transfer rate	[Btu/hr]	[W]
M	Molecular mass of the gas	[lb/lb_{mol}]	[kg/k_{mol}]
P_1	Upstream relieving absolute pressure	[psi]	*
Q	Total absorbed (input) heat to the wetted surface	[Btu/hr]	[W]
q	Volume flow rate at the flowing temperature	[gpm]	[m³/s]
q_m	Relief load / mass flow rate	[lb/hr]	*
T_1	Gas temperature at upstream relieving pressure	[°R]	*
T_w	Recommended max. vessel wall temperature	[°R]	*

Table 7.4.8.1-1 List of symbols for sizing acc. to API 521

* For-application of the formula using US units is recommended.

7.4.8.2 Hydraulic Expansion (Thermal Expansion)

The mass flow rate for the sizing of the safety valve for a liquid vessel exposed to a heat source can be approximated by Eq. 7.4.8.2-1 (Eq. 7.4.8.2-2) for the case that the trapped liquid does not evaporate. However, the mass flow rates are usually so small that a safety valve sized NPS ¾ x NPS 1 (DN 20 x DN 25) should be sufficient acc. to API 521 Par. 4.14.12.2.

$$q = \frac{1}{500}\frac{\alpha_v \cdot \phi}{d \cdot c}$$ (USC Units) *(Eq. 7.4.8.2-1)*

$$q = \frac{1}{1000}\frac{\alpha_v \cdot \phi}{d \cdot c}$$ (SI Units) *(Eq. 7.4.8.2-2)*

The cubical expansion coefficient of the liquid should be obtained from the process data; however, for water and hydrocarbon liquids at 60°F (15.6°C) some reference values are given in Table 7.4.8.2-1. However, more precise values should be obtained from process design data.

Gravity of liquid (°API)	α_v [1/°F]	α_v [1/°C]
3 – 34.9	0.0004	0.00072
35 – 50.9	0.0005	0.0009
51 – 63.9	0.0006	0.00108
64 – 78.9	0.0007	0.00126
79 – 88.9	0.0008	0.00144
89 – 93.9	0.00085	0.00153
94 – 100 and lighter	0.0009	0.00162
Water	0.0001	0.00018

Table 7.4.8.2-1 Value of cubical expansion coefficient for hydrocarbon liquids at 60°F in API 521

If the liquid is supposed to flash or form solids during the flow in the safety valve, the sizing procedure for two-phase flows in API RP 520 is recommended.

7.4.8.3 External Fire - Wetted Vessels

Class of vessels	Portion of liquid inventory	Remarks
Liquid-full, e.g. treaters	All up to the height of 25 ft (7.6 m)	
Surge or knockout drums, process vessels	Normal operating level up to the height of 25 ft (7.6 m)	
Fractionating columns	Normal level in bottom plus liquid hold-up from all trays dumped to the normal level in the column bottom; total wetted surface up to the height of 25 ft (7.6 m)	Level in reboiler is to be included if the reboiler is an integral part of the column
Working storage	Max. inventory level up to 25 ft (7.6 m), normally excluding the portions of the wetted area in contact with the foundations or the ground	For storage and process tanks, see API Standard 2000[6] or prEN 14015[7]
Spheres and spheroids	Up to the height of 25 ft or up to the max. horizontal diameter, whichever is greater	

Table 7.4.8.3-1 Portions of wetted surfaces to be considered

The amount of heat absorbed from a non-insulated vessel filled with a liquid depends at least on

- The type of fuel feeding the fire
- The degree of envelopment of the vessel with fire, which is a function of its size and shape
- The immediateness of firefighting measures and the possibility of drainage of flammable materials from the vessel

The total heat absorption Q for the wetted surface can be estimated by Eq. 7.4.8.3-1 in case of adequate drainage and prompt firefighting measures and by Eq. 7.4.8.3-2 in case of absent adequate drainage and/or firefighting measures.

	US units	SI units	
Drainage and firefighting measures	$Q=21000\ FA_{ws}^{0.82}$	$Q=43200\ FA_{ws}^{0.82}$	(Eq. 7.4.8.3-1)
Absent drainage and/or firefighting measures	$Q=34500\ FA_{ws}^{0.82}$	$Q=70900\ FA_{ws}^{0.82}$	(Eq. 7.4.8.3-2)

Adequate drainage of flammable fuels might be implemented with a strategic use of sewers and trenches as well as of the natural slope of the land. The values of the environment factor F for some types of installations are collected in Table 7.4.8.3-2. In case the conditions for Eq. 7.4.8.3-1 and 7.4.8.3-2 are not present, either higher values of the environment factor are assigned on the base of engineering judgment or some protection measures against fire exposure must be introduced to the plant. For water application facilities on bare vessels and depressurizing or emptying facilities insulation should withstand dislodgement by fire hose streams. Some example drainage criteria are given in API Standard 2510[8]

[6] API Standard 2000 Venting atmospheric and low pressure storage tanks : nonrefrigerated and refrigerated, 2014.

[7] prEN 14015: Specification for the design and manufacture of site built, vertical, cylindrical, flat-bottomed, above ground, welded, metallic tanks for the storage of liquids at ambient temperature and above – Part 1: Steel tanks, 2017.

[8] API Standard 2510 Design and construction of liquefied petroleum gas installations (LPG), 2001

Type of Equipment		F
Bare vessel		1.0
Insulated vessel , with insulation conductance values for fire exposure conditions		
4 [Btu/(hr ft² °F)]	22.71 [W/ (m² K)]	0.3
2	11.36	0.15
1	5.68	0.075
0.67	3.80	0.05
0.5	2.84	0.0376
0.4	2.27	0.03
0.33	1.87	0.026
Water-application facilities, on bare vessel		1.0
Depressurizing and emptying facilities		1.0
Earth-covered storage		0.03
Below-grade storage		0.00

Table 7.4.8.3-2 Values of the environment factor F for various types of installations

Heat absorption equations in Eq. 7.4.8.3-1 and 7.4.8.3-2 are for process vessels and pressurized storage of liquefied gases. For other storage, whether on pressure vessels or vessels and tanks with a design pressure of 15 psig or less the recommended heat absorption rates in case of external fire exposure can be extracted from API Standard 2000. The wetted areas for pressurized vessels of different forms in respect of Table 7.4.8.3-1 are collected in Table 7.4.8.3-3. Some examples are described also graphically in Fig. 7.4.3.3-1. The symbols are conform to those in VALVESTAR®.

Class of vessels	Portion of liquid inventory and remarks
Sphere	$A_{wet} = \pi \cdot D \cdot F_{eff}$
Horizontal cylindrical vessel with flat ends	$A_{wet} = \beta \cdot D \cdot \left[L + \frac{D}{2} \right] - D \cdot \sin\beta \cdot \left[\frac{D}{2} - F_{eff} \right]$
Horizontal cylindrical vessel with spherical ends	$A_{wet} = \pi \cdot D \cdot \left[(L - D)\frac{\beta}{\pi} + F_{eff} \right]$
Vertical cylinder with flat ends ✓ Partially filled ($F < L$)	$A_{wet} = \pi \cdot D \cdot \left[\frac{D}{4} + F_{eff} \right]$
✓ Totally filled ($F = L$)	$A_{wet} = \pi \cdot D \cdot \left[\frac{D}{2} + F_{eff} \right]$
Vertical cylinder with spherical ends	$A_{wet} = \pi \cdot D \cdot F_{eff}$

Table 7.4.8.3-3 Calculation of the total wetted surface for some vessels.

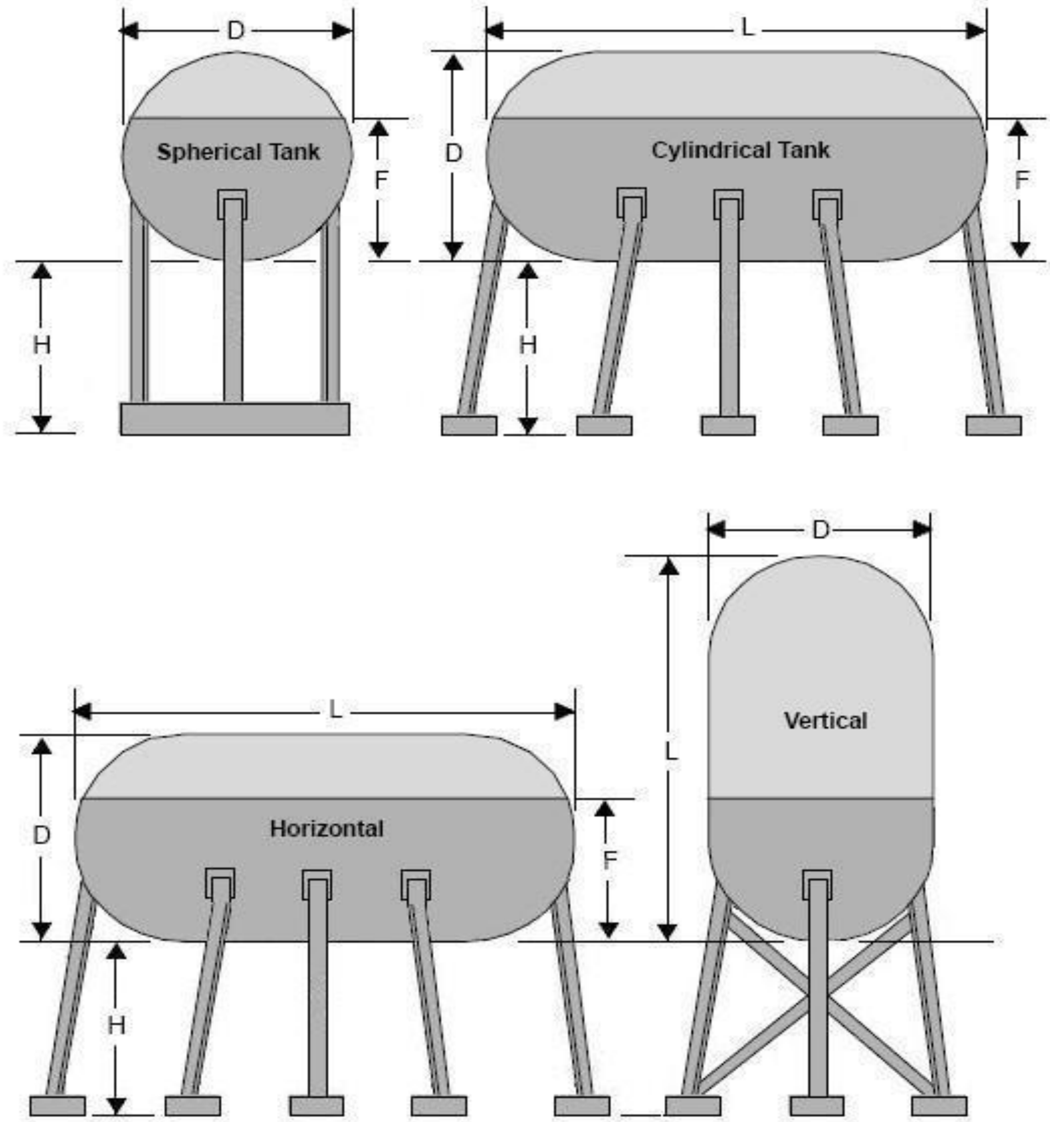


Figure 7.4.8.3-1 : Possible positions of wetted vessels, partially filled with liquids

The angle β in Table 7.4.8.3-3 is defined in Eq. 7.4.8.3-3

$$\beta = \cos^{-1}(1-2F/D) \quad \textit{(Eq. 7.4.8.3-3)}$$

and the height F_{eff} is the effective liquid level up to a max. distance of 25 feet away from the flame source, Eq. 7.4.8.3-4 (Eq. 7.4.8.3-5)

$$F_{eff} = \min(25\ \ ft; F) - H \quad \text{(USC Units)} \quad \textit{(Eq. 7.4.8.3-4)}$$

$$F_{eff} = \min(7.6\ \ m; F) - H \quad \text{(SI Units)} \quad \textit{(Eq. 7.4.8.3-5)}$$

The mass flow rate to the safety valve is determined by Eq. 7.4.8.3-6, considering that all absorbed heat vaporizes the liquid

$$W = Q / h_{vl0} \quad \textit{(Eq. 7.4.8.3-6)}$$

7.4.8.4 External Fire - unwetted vessels

If the vessel is filled with a gas, a vapor or a supercritical medium, Eq. 7.4.8.4-1 may be used to find the safety valve discharge area

$$A = \frac{F'A'}{\sqrt{P_1}} \quad \textit{(Eq. 7.4.8.4-1)}$$

F' may be determined from Eq. 7.4.8.4-2 if the calculated value is less than 0.01, then a recommended minimum value equal to 0.01 must be taken. When the available information is not enough to use Eq. 7.4.8.3-8, then the environment factor can be assumed equal to 0.045. The recommended maximum vessel wall temperature T_w for the usual carbon steel plate materials is 1100°F (593°C). For plates made of alloys the wall temperature must be changed to a more adequate recommended max. value.

The constant C is given from Eq. 7.4.3-4.

$$F' = \frac{0.1406}{C \cdot K_d}\left[\frac{(T_w - T_1)^{1.25}}{T_1^{0.6506}}\right] \quad \textit{(Eq. 7.4.8.4-2)}$$

The relieving temperature T_1 is determined from Eq. 7.4.8.4-3 in function of the normal operating temperature and pressure, respectively T_n and p_n, and of the relieving pressure

$$T_1 = T_n \frac{P_1}{P_n} \quad \textit{(Eq. 7.4.8.4-3)}$$

For plates made of alloys the gas mass flow rate can be calculated from Eq. 7.4.8.4-4

$$W = 0.1406\sqrt{M\ P_1}\left(A'\frac{(T_w - T_1)^{1.25}}{T_1^{1.1506}}\right) \quad \textit{(Eq. 7.4.8.4-4)}$$

The derivation of the formulas for unwetted vessels is based on the physical properties of air and ideal gas laws. Furthermore, they assume that the vessel is non-insulated and without its own mass, that the vessel wall temperature will not reach rupture under stress and that the fluid temperature does not change. All these assumptions should be checked if they are appropriate for the particular situation.

7.4.8.5 Consideration of Accumulated Pressure in Fire and Non-Fire Contingencies

The requirements on the accumulated pressure in API RP 520, propose different treatments for the cases of fire and non-fire contingencies.

In non-fire contingencies the accumulated pressure shall be limited to 110% of the maximum allowable working pressure (MAWP) in vessels that are protected by only one safety valve. If the MAWP lies between 15 and 30 psig, the allowable accumulation is fixed to 3 psi.
In vessels which are protected by more valves in non-fire contingencies, the accumulated pressure shall be limited to 116% of the maximum allowable working pressure (MAWP) or to 4 psi, if the MAWP lies between 15 and 30 psig. Typically the first safety valve is set at 100% of the MAWP and it is smaller than all other ones so to minimize the product loss. The additional valve is larger and it is sized in order to ensure the protection against the maximum required mass flow.

In fire contingencies the accumulated pressure shall be below 121% (= 10% above 110%) of the maximum allowable working pressure (MAWP), independently if the vessels are protected by one or more safety valves. Safety valves sized for the fire case may be also used in non-fire situations, provided that they satisfy the constrain on the accumulated pressure of 110% (one valve) and 116% (= 10% above 105%) (more valves) respectively.

Following the strategy of Table 7.4.8.5-1, which is extracted from the table in API RP 520, a safe sizing with a minimum product loss is possible. The supplemental valves are installed in case of an additional hazard, like fire case or other sources of external heat. Supplemental valves are in addition to devices for non-fire contingency.

	Single valve installation		Multiple valve installation	
Contingency	**Max. set pressure [%]**	**Max. accumulated pressure [%]**	**Max. set pressure [%]**	**Max. accumulated pressure [%]**
Non-fire contingency				
First valve	100	110	100	116
Additional valves	-	-	105	116
Fire contingency				
First valve	100	121	100	121
Additional valves	-	-	105	121
Supplemental valve	-	-	110	121

Table 7.4.8.5-1 Set pressure and accumulated pressure limits for safety valves

7.4.9 Lift Restriction according to ASME Section XIII

ASME Section XIII of the ASME Boiler and Pressure Vessel Code provides the guidelines for restricting the lift of a safety valve to achieve a reduced relieving capacity. Safety valves of NPS ¾" or larger can be lift restricted to not less than 30% of the full rated lift, nor less than 0.08 inch / 2.0 mm.

A lift restriction according ASME Section XIII requires a certification by an ASME designated organization, which LESER currently does not have.

As LESER safety valves have double certification by ASME XIII (ASME VIII) and PED / ISO 4126 , LESER can supply LESER products with a lift restriction according to PED / ISO 4126. In this case the safety valve will not carry an UV-stamp. For details please refer to section 7.5.8 and 7.6.5.

Examples

7.4.9.1 Gases and Vapors - Critical Flow (1)

Example 7.4.9.1. It is required to size a conventional valve without rupture disc for a vessel filled with ethylene (C_2H_4) at the relieving temperature of 55°C (590.7 °R) and a set pressure of 55 bar g (797.7 psig). The mass flow rate and the back pressure are respectively 4200 kg/h (9259 lb_m/hr) and 10 bar g (145 psig). The safety valve shall be from the LESER API Series 526.

Solution. The relieving pressure is calculated from Eq. 7.4.2-1 and it values

$$P_1 = P_{set} + \Delta P_{overpressure} + P_{atm} = 797.7\ \ psig + 79.8\ \ psig + 14.7\ \ psi = 892.2\ \ psi$$

From the Example 7.2.6.1 the calculated compressibility factor Z is 0.712. The isentropic exponent k and the molecular weight M are given from the customer as 1.19 and 28.03 lb/lb_{mol} respectively. The back pressure coefficient can be calculated from Fig. 7.4.3-1, by expressing the set pressure and the back pressure in psig

$$\frac{p_b}{p_s} = \frac{10\ bar\ g}{55\ bar\ g} = \frac{145\ \ psig}{797.7\ \ psig} = 0.182$$

and it results that no correction for the back pressure is necessary ($K_b = 1.0$).
The value of the coefficient C is obtained from Eq. 7.4.3-3

$$C = 520\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} = 520\sqrt{1.19\left(\frac{2}{1.19+1}\right)^{\frac{1.19+1}{1.19-1}}} = 336.22\frac{\sqrt{lb \cdot lb_{mol} \cdot {}^\circ R}}{lb_f \cdot hr}$$

The critical pressure ratio can be calculated from Eq. 7.2.3-2

$$\left.\frac{p}{P_1}\right]_{critical-flow} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} = \left(\frac{2}{1.19+1}\right)^{\frac{1.19}{1.19-1}} = 0.5664$$

The absolute pressure ratio for this sizing problem is

$$\frac{p_b}{P_1} = \frac{145\ psig + 14.7\ psi}{892.2\ psi} = 0.178$$

which is much lower than the critical pressure ratio and therefore the flow is critical. The minimum required <u>effective discharge area</u> can be calculated from Eq. 7.4.4-1 with $K_d = 0.975$

$$A = \frac{W}{C\ K_b K_c K_d P_1}\sqrt{\frac{T\,Z}{M}} = \frac{9259}{336.22 \cdot 1 \cdot 1 \cdot \underline{0.975} \cdot 892.2}\sqrt{\frac{590.7 \cdot 0.712}{28.03}}in^2 = 0.122\ \ in^2$$

From Table 7.2.1-2 the discharge area of the effective orifice E ($A = 0.196\ \ in^2 > 0.122\ \ in^2$) exceeds the minimum requirement. It must be now proven that the <u>actual discharge area</u> of the E orifice ($K_d = 0.801$; $A = 0.239\ \ in^2$) meets or exceeds the minimum required actual relief area.

$$A = \frac{W}{C\ K_b K_c K_d P_1}\sqrt{\frac{T\,Z}{M}} = \frac{9259}{336.22 \cdot 1 \cdot 1 \cdot 0.801 \cdot 892.2}\sqrt{\frac{590.7 \cdot 0.712}{28.03}}in^2 = 0.149\ \ in^2$$

The discharge area of the actual Orifice E is larger than that the required minimum relief area and therefore it suffices the sizing. From the Selection Chart on Page 01/20 of the Catalog LESER Series API the required flange ratings are 600 for the inlet and 150 for the outlet. The safety valve size would be then **<u>LESER Type 526</u> <u>1E2 (5262.0172)</u>**.

7.4.9.2 Gases and Vapors - Critical Flow (2)

Example 7.4.9.2. A safety valve is required for a vessel containing natural gas (= methane, $M = 16.04 \ lb/lb_{mol}$) venting to the ambience. The required mass flow is 22600 lb/hr. The relieving temperature is 650°R and the design pressure (= set pressure) of the vessel is 80 psig.

Solution. The relieving pressure for an overpressure of 10 % values

$$P_1 = P_{set} + \Delta P_{overpressure} + P_{atm} = 80 \ psig + 8 \ psig + 14.7 \ psi = 102.7 \ psi$$

The critical temperature and pressure of methane are extracted from Table 7 on Page 43 of API RP 520. They are 673 psi and -116°F (= 343°R). The relative temperature and pressure are therefore

$$T_R = \frac{T}{T_c} = \frac{650\,°R}{343\,°R} = 1.895 \qquad p_R = \frac{P_1}{p_c} = \frac{102.7 \ psi}{673 \ psi} = 0.152$$

The compressibility factor Z from Fig. 7.9.1-1 for the calculated relative temperature and pressure is about 0.98 (NIST WebBook : 0.993). The isentropic exponent k from the NIST Chemistry WebBook is almost 1.286.

The back pressure coefficient can be extracted from Fig. 7.4.3-1 in terms of ratio between the set pressure and the back pressure, both in psig

$$\frac{p_b}{p_s} = \frac{14.7 \ psig}{80 \ psig} = 0.1837$$

and here as well no correction for the back pressure is necessary ($K_b = 1.0$).

The value of the coefficient C is obtained from Eq. 7.4.3-3

$$C = 520\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} = 520\sqrt{1.286\left(\frac{2}{1.286+1}\right)^{\frac{1.286+1}{1.286-1}}} = 345.65 \ \frac{\sqrt{lb \cdot lb_{mol} \cdot °R}}{lb_f \cdot hr}$$

The critical pressure ratio can be calculated from Eq. 7.3.2-2

$$\left.\frac{p}{P_1}\right]_{critical-flow} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} = \left(\frac{2}{1.286+1}\right)^{\frac{1.286}{1.286-1}} = 0.548$$

The absolute pressure ratio is much lower than the critical pressure ratio and therefore the flow is critical. The minimum required <u>effective discharge area</u> from Eq. 7.4.4-1 is

$$A = \frac{W}{C\,K_b K_c K_d P_1}\sqrt{\frac{T\,Z}{M}} = \frac{22600}{345.65 \cdot 1 \cdot 1 \cdot \underline{0.975} \cdot 102.7}\sqrt{\frac{650 \cdot 0.993}{16.04}} in^2 = 4.14 \ in^2$$

From Table 7.4.1-2 the effective discharge area of the orifice N exceeds the minimum requirement. It remains to prove that the <u>actual discharge area</u> of the N orifice ($K_d = 0.801$; $A = 5.30 \ in^2$) exceeds the minimum requirement.

$$A = \frac{W}{C\,K_b K_c K_d P_1}\sqrt{\frac{T\,Z}{M}} = \frac{22600}{345.65 \cdot 1 \cdot 1 \cdot \underline{0.801} \cdot 102.7}\sqrt{\frac{650 \cdot 0.993}{16.04}} in^2 = 5.06 \ in^2 \rightarrow \text{OK}$$

and therefore the actual orifice N will be selected. From the Selection Chart on Page 01/20 of the LESER Catalog API Series the required flange levels are 150 for both the inlet and the outlet and therefore the safety valve **<u>LESER Type 526 4N6 (5262.5902)</u>** suits the requirements**.**

7.4.9.3 Gases and Vapors - Subcritical Flow

Example 7.4.9.3. Same case as Example 7.4.9.2. but with a set pressure of 20 psig (20+3+14.7 =37.7 psi), back pressure 10 psig (24.7 psi) and $Z=1$.

Solution. The critical pressure ratio is again that of the Example 7.4.9.2.

$$\left.\frac{p}{P_1}\right]_{critical-flow} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} = \left(\frac{2}{1.286+1}\right)^{\frac{1.286}{1.286-1}} = 0.548$$

However, this time the ratio of the absolute back pressure on the relieving pressure, which is

$$r = \frac{P_2}{P_1} = \frac{24.7 \ \ psi}{37.7 \ \ psi} = 0.6552$$

is larger than the critical pressure ratio and therefore the flow is subcritical. The parameter F_2 from Eq. 7.4.4-3 is equal to

$$F_2 = \sqrt{\frac{k}{k-1}\cdot r^{2/k}\cdot\frac{1-r^{1-1/k}}{1-r}} = \sqrt{\frac{1.286}{1.286-1}\cdot 0.6552^{2/1.286}\cdot\frac{1-0.6552^{1-1/1.286}}{1-0.6552}} = 0.779$$

The minimum required <u>effective </u>discharge area from Eq. 7.4.4-2 is

$$A = \frac{1}{735}\frac{W}{F_2K_cK_dP_1}\sqrt{\frac{TZ}{M}\frac{1}{1-r}} = \frac{1}{735}\frac{22600}{0.779\cdot 1\cdot 0.975\cdot 37.7}\sqrt{\frac{650\cdot 1}{16.04}\cdot\frac{1}{1-0.6552}} = 11.73 \ in^2$$

The effective discharge area is then an R orifice. It must now be verified that the <u>actual </u>discharge area of a R orifice of LESER Type 526 ($K_d = 0.801$; $A = 19.48 \ \ in^2$) is large enough, which is when it exceeds the minimum actual required area of

$$A = \frac{1}{735}\frac{W}{F_2K_cK_dP_1}\sqrt{\frac{TZ}{M}\frac{1}{1-r}} = \frac{1}{735}\frac{22600}{0.779\cdot 1\cdot 0.801\cdot 37.7}\sqrt{\frac{650\cdot 1}{16.04}\cdot\frac{1}{1-0.673}} = 14.28 \ in^2 \rightarrow \text{OK}$$

The final choice of the safety valve is therefore <u>**LESER Type 526 6R8 (5262.6652)**</u>.

7.4.9.4 Steam

Example 7.4.9.4. A safety valve must be sized for a large vessel containing saturated steam ($K_{SH}=1$) at a set pressure of 1600 psig (10% accumulation). The expected mass flow rate is of 154000 lb/hr.

Solution: A conventional safety valve ($K_b=1$) without additional rupture disk ($K_c=1$) is chosen.

The relieving pressure is

$$P_1 = P_{set} + \Delta P_{overpressure} + P_{atm} = 1600 \ \ psig + 160 \ \ psig + 14.7 \ \ psi = 1774.7 \ \ psi$$

The correction factor for Napier equation K_N is calculated from Eq. 7.4.5-2

$$K_N = \frac{0.1906\cdot P_1 - 1000}{0.2292\cdot P_1 - 1061} = \frac{0.1906\cdot 1774.7 - 1000}{0.2292\cdot 1774.7 - 1061} = 1.0115$$

The minimum required <u>effective</u> discharge area is calculated from Eq. 7.4.5-1

$$A = \frac{1}{51.5}\cdot\frac{W}{P_1K_bK_cK_dK_NK_{SH}} = \frac{1}{51.5}\cdot\frac{154000}{1774.4\cdot 1\cdot 1\cdot 0.975\cdot 1.0115\cdot 1} = 1.709 \ \ in^2$$

which is exceeded by selecting an orifice K.

The orifice K of LESER Type 526 ($K_d = 0.801$; $A = 2.25 \ \ in^2$) is selected for the actual discharge area since it exceeds the minimum requirement of

$$A = \frac{1}{51.5}\cdot\frac{W}{P_1K_bK_cK_dK_NK_{SH}} = \frac{1}{51.5}\cdot\frac{154000}{1774.4\cdot 1\cdot 1\cdot 0.801\cdot 1.0115\cdot 1} = 2.08 \ \ in^2$$

The required flanges are 900 (inlet) and 150 (outlet) according to Page 01/40 of LESER Catalog for the API Series and therefore the safety valve to be purchased is <u>**LESER Type 526 3K6 (5262.2053).**</u>

7.4.9.5 Liquids

Example 7.4.9.5. A safety valve must be sized for a flow rate of 5 l/s (79.25 gpm) of glycerin ($G = 1.26; \mu = 1410 \;\; cP$). The set pressure is 10 bar-g (145 psig) with 10% accumulation and atmospheric backpressure.

Solution The relieving pressure is

$$P_1 = P_{set} + \Delta P_{overpressure} + P_{atm} = 145 \;\; psig + 14.5 \;\; psig + 14.7 \;\; psi = 174.2 \;\; psi$$

The procedure in API RP 520 foresees a preliminary relief area for inviscid service by using Eq. 7.4.6-1 assuming $K_v = 1$. The minimum preliminary effective discharge area is

$$A_{prel} = \frac{1}{38} \cdot \frac{Q}{K_c K_d K_w} \sqrt{\frac{G}{P_1 - P_2}} = \frac{1}{38} \cdot \frac{79.25}{1 \cdot 0.65 \cdot 1} \sqrt{\frac{1.26}{159.5}} = 0.285 \;\; in^2$$

which would lead to an F orifice ($A = 0.307 \;\; in^2$) as effective discharge area for the inviscid fluid.

Now the viscosity of the fluid has to be considered. The assumption of the API RP 520 is that the effective relief area for the inviscid flow may also suit the sizing of the viscous flow. Therefore the user must calculate the Reynolds number on the base of Eq. 7.4.6-3 on that orifice area.

$$\mathrm{Re} = 2800 \frac{Q \; G}{\mu \; \sqrt{A}} = 2800 \frac{79.25 \cdot 1.26}{1410 \;\; \sqrt{0.307}} = 357.9$$

and on the base of this Reynolds number the viscosity correction factor from Eq. 7.4.6-2

$$Kv = \left(\frac{170}{ReL} + 1\right)^{-0,5} = \quad Kv = \left(\frac{170}{357,9} + 1\right)^{-0,5} = 0,8234$$

The corrected (effective minimum) discharge area for the viscous liquid is then

$$\mathrm{A} = \frac{\mathrm{Q}}{38 * \mathrm{K_w K_d K_c K_v}} \left(\frac{G}{\mathrm{P_1} - \mathrm{P_2}}\right)^{0,5} = \frac{79.25}{38 * 1 * 1 * 0.65 * 0.8234} \left(\frac{1.26}{159.5}\right)^{0,5} = 0.3465 \; in^2$$

Since the effective minimum corrected discharge area exceeds the foreseen orifice, the above procedure for viscous flows must be repeated with the larger orifice G ($A = 0.503 \;\; in^2$). For sake of brevity the Reynolds number, viscosity correction factor and corrected minimum discharge area are given here below.

Re = 279.6 $\quad K_v = 0.789 \quad A_{corr} = 0.362 \; in^2$

Since the corrected minimum discharge area is smaller than the G orifice, the selected orifice size is sufficient. A quick verification that the actual G orifice of LESER Type 441 ($K_d = 0.579$; $A = 0.616 \;\; in^2$) suffices is given as following.

$A_{prel} = 0.320 \; in^2 \quad$ Re = 252.65 $\quad K_v = 0.773 \quad A_{corr} = 0.414 \; in^2$

The required valve, incl. the flanges, is **LESER Type 526 1½G3 (5262.0452)**.

7.4.9.6 Two Phase Flow – Flashing C2.2 (API 520-1 Rev. 2020)

Input	Value	Unit
Set pressure, P_s	413.7	kPag
Total Back pressure, P_2	103.421 204746	kPag Pa
Allowable Overpressure (10%) for single valves	41.37	kPa
Viscosity correction factor, K_v	1	-
Mass flow rate, W	216560	kg / h
Specific volume evaluated at 90% of PRV inlet pressure, v_9	0.02265	m^3/kg
Specific volume of two phase system, v_1	0.01945	m^3/kg
Relieving Temperature, T	200 366.5	˚F K
Combination capacity factor (if Safety valve is in combination of Rupture disk), K_c	0.9	-
Combination capacity factor (if Safety valve with no Rupture disk), K_c	1.0	-
Certified derated coefficient of discharge (Considered average of vapor (0.699) and liquid (0.521) coefficient discharge), K_d	0.61	-
Type	441 XXL	-

Note: For this example Combination capacity factor (K_c) value of 1.0 is considered.

1. Calculation of Relief Pressure:

   Relief pressure (P1) = Ps + allowable overpressure + environmental pressure absolute

   P1 = 413.7 + (0.10 * 413.7) + 101.325

   = 556.395 kPa

   = 556395 Pa (conversion from kilopascal to pascal)

   Here, a single valve is considered to be in operation, hence an allowable overpressure of 0.1 times the PRV Set pressure is considered.

2. Calculation of Back pressure correction factor, Kb:

   Percentage gauge pressure = (Pa/Ps) × 100

   = (103.421/413.7)

= 24.99 %

Note this calculated % gauge backpressure needs to be checked in Figure 31 from API 520-1 Tenth Edition 2020 (page 59) to get the value of Back pressure correction factor (Kb).

For the case under consideration, Kb = 1 (Taken from figure 31) considering valve is of Balanced Bellows type valve.

Note: For LESER products the generated p20/p0 curves shall be used for sizing if balanced bellows is used for gas/steam only. As for two-phase flow no values are available, the figure 31 data shall be used.

3. Calculation of omega parameter (ω):

$$\omega = 9\left(\frac{v_9}{v_1} - 1\right)$$

$$\omega = 9\left(\frac{0.02265}{0.01945} - 1\right)$$

= 1.481

Where, v_9 = Specific volume evaluated at 90% of PRV inlet pressure

v_1 = Specific volume of two phase system

4. Calculation of critical pressure ratio (η_c) using above equations specified in step 5.1.2.a.i

$$\eta_c = [1 + (1.0446 - 0.0093431 \times \omega^{0.5}) \times \omega^{-0.56261}]^{(-0.70356 + 0.014685 \times \ln \omega)}$$

$$\eta_c = [1 + (1.0446 - 0.0093431 \times 1.481^{0.5}) \times 1.481^{-0.56261}]^{(-0.70356 + 0.014685 \times \ln 1.481)}$$

= 0.66

5. Calculation of Critical Pressure (Pcf):

$$P_{cf} = \eta_c P_0$$

$$P_{cf} = 0.66 * 556395$$

= 365170.78 Pa

Where, η_c = Critical pressure ratio (η_c)

P_1 = Relieving Pressure (P_1)

6. Check for critical and subcritical flow using above equations specified in step 5.1.2.b

   $P_2\ (204746) < P_{cf}\ (365170.78)$, hence flow is considered as critical flow.

7. Calculation of mass flux (G) based on critical flow:

$$G = \eta_c \sqrt{\frac{P_1}{v_1 \omega}}$$

$$G = 0.66 \sqrt{\frac{556395}{0.01945 * 1.481}}$$

= 2884.7 kg/s·m2

8. Calculation of required orifice area, A

$$\mathrm{A} = \frac{277.8 * \mathrm{W}}{K_b * K_d * K_c * K_v * G}$$

$$\mathrm{A} = \frac{277.8 * 216560}{0.981 * 0.61 * 1 * 1 * 2884.7}$$

= 34850.1 mm2

9. Select valve (Type 441 XXL, do =235 mm, As = 43373.6 mm2)

   Certified mass flow (qm, zu) is evaluated by substituting A=43373.6 mm2 in the above equation:

$$\mathrm{qm, zu} = \frac{A_s\ \mathrm{K_b}\ \mathrm{K_d}\ \mathrm{K_c}\ \mathrm{K_v}\ \mathrm{G}}{277.8}$$

$$qm, zu = \frac{43373.6 *\ 0.981 * 0.61 * 1 * 1 * 2884.7}{277.8}$$

= 269526 kg/h

The required valve, incl. the flanges, is **LESER Type 441 XXL DN300 (4412.4772)**.

7.4.9.7 Two Phase Flow – Subcooled C2.3 (API 520-1 Rev. 2020)

Input	Value	Unit
Set pressure, P	1792.6 1893925	kPag Pa
Total Back pressure, P_a	68.95 170272.57	kPag Pa
Allowable Overpressure (10%)	179.2	kPa

Viscosity correction factor, K_v	1	-
Mass flow rate, Q	378.5	L/min
Density evaluated at 90% of PRV inlet pressure, ρ_9	262.727	kg/m³
Liquid density at PRV inlet, ρ_{10}	511.3	kg/m³
Relieving Temperature, T	60 288.7	F K
Saturation Pressure, P_s	741.875 741875	KPa Pa
Combination capacity factor (if Safety valve is in combination of Rupture disk), K_c	0.9	-
Combination capacity factor (if Safety valve with no Rupture disk), K_c	1.0	-
Certified derated coefficient of discharge (Considered average of vapor (0.801) and liquid (0.579) coefficient discharge), K_d	0.69	-
Type	526	-

Note: For this example Combination capacity factor (K_c) value of 1.0 is considered.

1. Calculation of Relief Pressure:

   Relief pressure (P0) = P + allowable overpressure + environmental pressure absolute

   P0 = 1792.6 + (0.10 * 1792.6) + 101.325

   = 2073.185 kPa

   = 2073185 Pa (conversion from kilopascal to pascal)

   Here, a single valve is considered to be in operation, hence an allowable overpressure of 0.1 times the PRV Set pressure is considered.

2. Calculation of Back pressure correction factor, Kb:

   Percentage gauge backpressure = (Pa/P) × 100 (in gauge)

   = (68947.57/1792600)

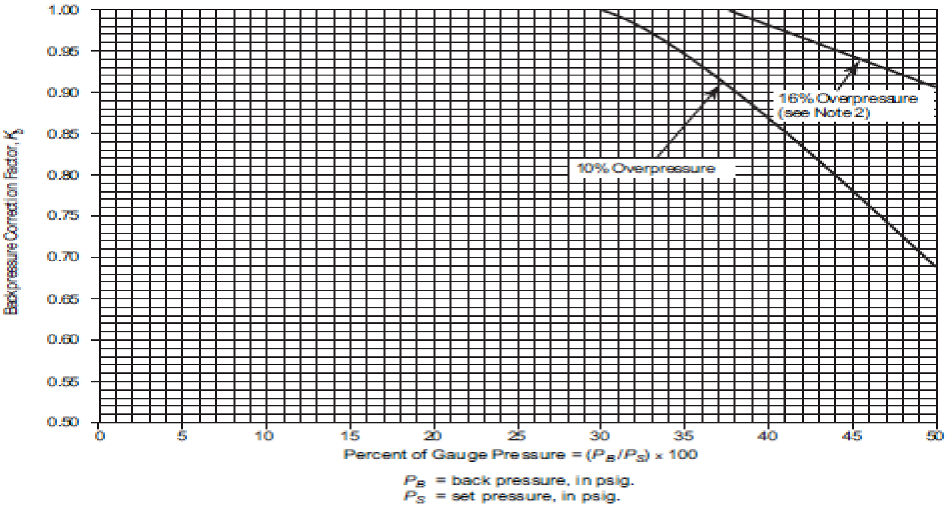
   = 3.84 %

   Note this calculated % gauge pressure needs to be checked in Figure 30 from API 520-1 Ninth Edition 2014 (page 48) to get the value of Back pressure correction factor (Kb).

   For the case under consideration, Kb = 1 (Taken from figure 30) considering valve is of Balanced Bellows type valve.

Note: For LESER products the generated pa0/p0 curves shall be used for sizing if balanced bellows is used.

Refer Screenshot provided below for Figure 30:



NOTES

1. The curves above represent a compromise of the values recommended by a number of relief valve manufacturers and may be used when the make of the valve or the critical flow pressure point for the vapor or gas is unknown. When the make of the valve is known, the manufacturer should be consulted for the correction factor. These curves are for set pressures of 50 psig and above. They are limited to back pressure below critical flow pressure for a given set pressure. For set pressures below 50 psig or for subcritical flow, the manufacturer must be consulted for values of K_b.
2. See 5.3.3.
3. For 21 % overpressure, K_b equals 1.0 up to P_B/P_S = 50 %.

Figure 30—Backpressure Correction Factor, K_b, for Balanced-bellows PRV (Vapors and Gases)

3. Calculation of saturated omega parameter (ω_s):

$$\omega_s = 9\left(\frac{\rho_{10}}{\rho_9} - 1\right)$$

$$\omega_s = 9\left(\frac{511.3}{262.727} - 1\right)$$

ω_s = 8.515

Where, ρ_9 = Specific volume evaluated at 90% of PRV inlet pressure from Table 6.1

ρ_{10} = Specific volume of two phase system from Table 6.1

4. Calculation of Transition saturation pressure ratio (η_{st}):

$$\eta_{st} = \frac{2\omega_s}{1 + 2\omega_s}$$

$$\eta_{st} = \frac{2 * 8.515}{1 + 2 * 8.515}$$

η_{st} = 0.9445

5. Determine the type (high or low) subcooling region with following comparison:

Need to compare saturation pressure (Ps) with the product of transition saturation pressure ratio (η_{st}) and relieving pressure (P_0)

Here, $P_s(741875) < \eta_{st} P_0(1958201.5)$, Hence flow is considered in high subcooling region.

6. Determination of critical or subcritical flow for high subcooling region:

   Need to compare saturation pressure (Ps) with the total backpressure;

Here, $P_s(741875) \geq P_a(68947.57)$, hence flow is considered as critical flow.

7. Calculation of the mass flux (G) depending on type of flow (critical or subcritical) in high subcooling region:

   Here, flow type is observed as critical flow in high subcooling region. Therefore used formula mentioned in above step 5.1.4.2.a for calculating mass flux (G);

   $G = 1.414\,[\rho_{10}(P_0 - P_s)]^{\frac{1}{2}}$

   $G = 1.414\,[511.3 * (2073185 - 741875)]^{\frac{1}{2}}$

   G = 36891.6 kg/s.m²

8. Calculation of required orifice area, A:

   $\mathrm{A} = 16.67 \frac{\mathrm{Q} \times \rho_{10}}{K_b K_d K_c K_v G}$

   $$\mathrm{A} = 16.67 \frac{378.5 * 511.3}{0.65 * 1.0 * 0.69 * 1.0 * 36891.6}$$

   A = 126.7 mm²

9. Select valve (Type 526, do = 14 mm, As = 153.938 mm²)

   Certified volume flow (qvb, zu) is evaluated by substituting A = 153.938 mm² in the above equation:

   $$qvb, zu = \frac{A_s\, K_b\, K_d\, K_c\, K_v\, G}{16.67\, \rho_{10}}$$

   $$qvb, zu = \frac{153.938 * 1.0 * 0.69 * 1.0 * 1.0 * 36891.6}{16.67 * 511.3}$$

   qvb, zu = 460 L/min

The required valve, incl. the flanges, is **LESER Type 526 1E2 (5262.0015)**.

7.4.9.8 Hydraulic (Thermal) Expansion acc. to API 521

Example 7.4.9.8. The vessel containing ~~the~~ heating oil ~~of the previous example~~ is exposed to sun light. Calculate the mass flow rate that would occur in case of thermal radiation and size the safety valve for the same relieving and back pressure, assuming a maximum heat transfer rate of 55.2 kJ/hr (58.24 BTU/hr).

Solution: The specific gravity of the heating oil at relieving conditions is $G = 687/999.1 = 0.6876$.
The gravity of the liquid in API for oils is calculated on the base of the well known formula

$$°API = \frac{141.5}{G} - 131.5 = \frac{141.5}{0.6876} - 131.5 = 74.28$$

which corresponds to a value of the cubical expansion coefficient B of approx. 0.0007.
The mass flow rate to be released according to Eq. 7.4.8.2-1 is

$$Q_{gpm} = \frac{1}{500}\frac{B \cdot H}{G \cdot C} = \frac{1}{500} \cdot \frac{0.0007 \cdot 58.24}{0.6876 \cdot 0.633} = 0.000187 \ \ gpm \text{ (0.56 kg/hr)}$$

The minimum effective safety valve flow area can be calculated. However, for such a small flow rate the smallest safety valve, orifice **1D2 (5262.0012)**, is by far enough.

7.4.9.9 External Fire acc. to API 521 - Unwetted Walls

Example 7.4.9.9. A carbon steel vessel ($T_w = 1560\ °R$) is filled with air at a set pressure of 100 psig. The exposed surface area A' is 250 ft². The normal temperature and pressure are 125°F (584.7°R) and 80 psig (94.7 psi).

Solution:The relieving pressure according to Paragraph 7.4.8.4 is

$$P_1 = P_{set} + \Delta P_{overpressure} + P_{atm} = 100 \ \ psig + 21 \ \ psig + 14.7 \ \ psi = 135.7 \ \ psi$$

On the base of Eq. 7.4.8.4-3 the relieving temperature is

$$T_1 = T_n \frac{P_1}{P_n} = 584.7°R \cdot \frac{135.7\,psi}{94.7\,psi} = 837.84°R$$

The specific heat ratio at relieving conditions according to the NIST WebBook Database is almost $k \cong 1.4$ ($k = 1.392$). With this isentropic coefficient the value of the parameter C is calculated with Eq. 7.4.3-3

$$C = 520\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} = 520\sqrt{1.4\left(\frac{2}{1.4+1}\right)^{\frac{1.4+1}{1.4-1}}} = 356.06\frac{\sqrt{lb_m lb_{mol}°R}}{lb_f hr}$$

The parameter F' is determined from Eq. 7.4.8.4-2

$$F' = \frac{0.1406}{C \cdot K_d}\left[\frac{(T_w - T_1)^{1.25}}{T_1^{0.6506}}\right] = \frac{0.1406}{356.06 \cdot 0.975}\left[\frac{(1560 - 837.84)^{1.25}}{837.84^{0.6506}}\right] = 0.019$$

Finally, the minimum effective relief area for the safety valve acc. to Eq. 7.2.8.4-1 is

$$A = \frac{F'A'}{\sqrt{P_1}} = \frac{0.019 \cdot 250}{\sqrt{135.7}} = 0.40 \ \ in^2$$

which is satisfied by an effective orifice **1$^1_2$G3 (5262.0452)**.

7.4.9.10 External Fire acc. to API 521 - Wetted Walls

Example 7.4.9.10. A vertical vessel with spherical ends at a set pressure of 200 psig contains benzene at 100°F (559.7°R). The vessel has a diameter of 15 ft, a length of 40 ft and an elevation of 15 ft. The maximum fluid level is 12 ft. Assume that the fire-fighting measures intervene promptly in the eventuality of fire and that adequate drainage is present.

Solution The amplitude of the wetted walls, heated by the flames, must be estimated to calculate the input thermal flow to the liquid. The free surface of benzene is 32 ft over the ground. Assuming that the fire level is at the ground, the height of the wetted walls, heated by the flames, is acc. to Eq. 7.4.8.3-5 equal to

$F_{eff} = \min(32\ ;\ 25) - 15 = 10\ \ ft$.

And the size of the wetted area from Table 7.4.8.3-3 is

$A_{wet} = \pi \cdot D \cdot F_{eff} = \pi \cdot 15 \cdot 10\ \ ft^2 = 471.23\ \ ft^2$

The thermal heat flow is calculated from Eq. 7.4.8.3-1, assuming the worst case of bare vessel (with *F=1* from Table 7.4.8.3-2)

$Q = 21000\ F\ A_{wet}^{0.82} = 21000 \cdot 1 \cdot 471.23^{0.82}$ Btu/hr = 3 267 911 Btu/hr

The relieving pressure P_1 in the vessel is equal to 256.7 psi (= 200*1.21+14.7 psi). From NIST WebBook Database the latent heat of vaporization of benzene at 256 psi ($T_{vap} = T_1 = 875.5°R$) is about 114.9 Btu/lb_m. The discharged mass flow of vapor is calculated from Eq. 7.4.8.3-6

$W = Q / h_{vl0} = 3\ 267\ 911 / 114.9 \cong 28441.4$ Btu/lb_m.

The parameter C at relieving conditions is calculated from Eq. 7.4.3-3 with the specific heat ratio at relieving conditions of $k \cong 1.23$ taken from the NIST WebBook Database.

$$C = 520 \sqrt{k \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}}} = 520 \sqrt{1.23 \left(\frac{2}{1.23+1} \right)^{\frac{1.23+1}{1.23-1}}} = 340.23 \frac{\sqrt{lb_m lb_{mol} °R}}{lb_f hr}$$

The required effective flow area is given by Eq. 7.4.3-1 for critical vapor flow assuming ideal gas behavior.

$$A = \frac{W}{C\ K_b K_c K_d P_1} \sqrt{\frac{T\ Z}{M}} = \frac{28\ 441.4}{340.23 \cdot 1 \cdot 1 \cdot 0.975 \cdot 256.7} \sqrt{\frac{875.5 \cdot 1}{78.11}} = 1.118\ \ in^2$$

For this requirement the orifice **3J4 (5262.1622)** would be large enough.

7.5 Sizing according to ISO 4126-7

The information contained in this section is based on following editions of codes and standards:
ISO 4126-1 (2016), ISO 4126-7 (2016), ISO 23251 (2020).

7.5.1 Introduction

ISO 4126- is a Standard for the certification of safety valves, ISO 4126-7 for the sizing .The flow area, which is extracted from LESER's catalog, must be in excess of the minimum required flow area, which is calculated with the formulae in Paragraph 5.2 to 5.6 of this Chapter.
In comparison to API RP 520 there are no predefined effective orifices to select in a preliminary sizing procedure and the sizing for fire case and thermal expansion is described in the separate norm[9] ISO 23251, which is based on the API 521 (2020). ISO 4126-1 is applicable to safety valves with a flow diameter of at least 6 mm and at set pressures equal or above 0.1 bar gauge.
The sizing formulas in this section are solved explicitly in terms of the required flow area A, which permit the immediate selection of an actual flow area from LESER catalog. The sizing formulas in ISO 4126-7 are identical to those presented here except that they are written in terms of the mass flow rate Q_m.

7.5.2 List of Symbols/Nomenclature

Symbol	Description	Units [SI]
A	Flow area of the safety valve	[mm²]
C	Function of the isentropic coefficient	--
K_b	Theoretical capacity correction factor for subcritical flow	--
K_{dr}	Certified derated coefficient of discharge	--
K_v	Viscosity correction factor	--
k	Isentropic coefficient (see Par. 3.1)	--
M	Molar mass	[kg/k_{mol}]
p_0	Relieving pressure	[bar]
p_b	Back pressure	[bar]
Q_m	Mass flow rate	[kg/hr]
T_0	Relieving temperature	[K]
μ	Dynamic viscosity	[Pa s]
v	Specific volume at actual relieving pressure and temperature	[m³/kg]
x	Dryness fraction of wet steam at the safety valve inlet at actual relieving pressure and temperature	--
Z	Compressibility factor at actual relieving pressure and temperature (see Par. 3.21)	--

Table 7.5.2-1: List of symbols for sizing according to ISO 4126-7

The relieving pressure p_0 is defined in Eq. 7.5.2-1 as the sum of the set pressure, the overpressure and the atmospheric pressure. In Eq. 7.5.2-1 the overpressure is generally 10% of the set pressure also for safety valves, which are fully open at set pressure plus an overpressure below 10%.

$$p_0 = p_{set} + \Delta\ p_{over} + p_{amb} \quad \text{(Eq. 7.5.2-1)}$$

[9] ISO 23251 Petroleum, petrochemical and natural gas industries – pressure-relieving and depressurising systems, 2020

7.5.3 Saturated or Superheated Steam - Critical Flow (ISO 426-1 2004)

$$A = \frac{1}{0.2883}\,\frac{Q_m}{C\,K_{dr}}\sqrt{\frac{v}{p_0}} \quad \textit{(Eq. 7.5.3-1)}$$

with

$$C = 3.948\sqrt{k\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}} \quad \textit{(Eq. 7.5.3-2)}$$

Values for the isentropic coefficient *k* at ambient temperature and pressure of many common pure gases, which are cited in ISO 4126-7 [10].

7.5.4 Wet Steam (ISO 426-1 2004)

$$A = \frac{\sqrt{x}}{0.2883}\,\frac{Q_m}{C\,K_{dr}}\sqrt{\frac{v}{p_0}} \quad \textit{(Eq. 7.5.4-1)}$$

The formula applies only to homogeneous wet steam with a minimum dryness fraction of 90 %. The dryness fraction of 90% is an indicative value to distinguish between a wet steam flow and a more complex two phase flow.

7.5.5 Gaseous Media - Critical Flow occurring-lower dryness fraction (ISO 4126-1 2004)

$$A = \frac{Q_m}{p_0 C\,K_{dr}}\sqrt{\frac{ZT_0}{M}} \quad \textit{(Eq. 7.5.5-1)}$$

7.5.6 Gaseous Media - Subcritical Flow (ISO 4126-1 2004)

$$A = \frac{Q_m}{p_0 C\,K_b K_{dr}}\sqrt{\frac{ZT_0}{M}} \quad \text{(}\textit{Eq.}\text{ 7.5.6-1)}$$

with

$$K_b = \sqrt{\frac{\frac{2k}{k-1}\left[\left(\frac{p_b}{p_0}\right)^{2/k} - \left(\frac{p_b}{p_0}\right)^{(k+1)/k}\right]}{k\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}}} \quad \text{(}\textit{Eq.}\text{ 7.5.6-2)}$$

7.5.7 Liquids (ISO 4126-1 2004)

$$A = \frac{1}{1.61}\,\frac{Q_m}{K_{dr}K_v}\sqrt{\frac{v}{p_0 - p_b}} \quad \text{(}\textit{Eq.}\text{ 7.5.7-1)}$$

The viscosity correction factor K_v in function of the Reynolds number *Re* follows Fig. 7.9.3-1. The Reynolds number is defined as

$$\mathrm{Re} = \frac{1}{3.6}\,\frac{Q_m}{\mu}\sqrt{\frac{4}{\pi\,A}} \quad \text{(}\textit{Eq.}\text{ 7.5.7-2)}$$

Two phase flow is covered by ISO 4126-10

[10] ISO 4126-7 Safety devices for protection against excessive pressure – Part 7: common data, 2016.

7.5.8 Discharge Coefficient of Valves with Restricted Lift

A restricted lift allows the user to limit the discharged flow capacity from the safety valve to a value equal or closer to the required capacity. The restriction of the valve lift makes sense, when:

Gas or Two-phase flows

- the safety valve is oversized AND
- the inlet pressure loss is larger than 3% (→ possibility of valve chattering) or the built-up back pressure is too large due to excessive flow.

Liquid flows

- the inlet pressure loss is larger than 3% (→ possibility of valve chattering) or the built-up back pressure is too large due to excessive flow. Thermal expansion alone is not a reason.

In any case, oversizing alone is not the reason to install a lift restriction and there is no rule of thumb determination of an indicative percentage of allowable oversizing. It rather depends on the installation conditions of the safety valve, for instance on the inlet and outlet line configuration.
A lift restriction should be installed to reduce problems with excessive inlet pressure loss or built-up back pressure caused by the excessive flow in an oversized safety valve. The lift restriction limits the flow of the safety valve to the required one and therefore reduces the pressure loss at the inlet and the built-up back pressure at the outlet.

ISO 4126-1 allows the manufacturer to restrict the lift to a value larger than either 30 % of the unrestricted lift or 1 mm, whichever is greater.
For safety valves with a restricted lift the manufacturers are required to generate a curve showing the change of the discharge coefficient with the lift, like that in Fig. 7.5.8-1 for LESER Type 441/442. VdTÜV[11] guidance requires that this curve must be obtained with a ratio of the absolute back pressure on the relieving pressure, $p_{a0}/p_{0,}$ above the critical pressure ratio. An example how to calculate the restricted lift is proposed at the end of this chapter.

In VALVESTAR® the user can select the option of restricted lift with just a mouse click and the software sizes the safety valve with the minimum lift required to deliver the required mass flow.

[11] VdTÜV-Merkblatt Sicherheitsventil 100, *Richtlinie für die Baumusterprüfung von Sicherheitsventilen im Geltungsbereich der Richtlinie 2014/68/EU (Drückgeräte-Richtlinie)*

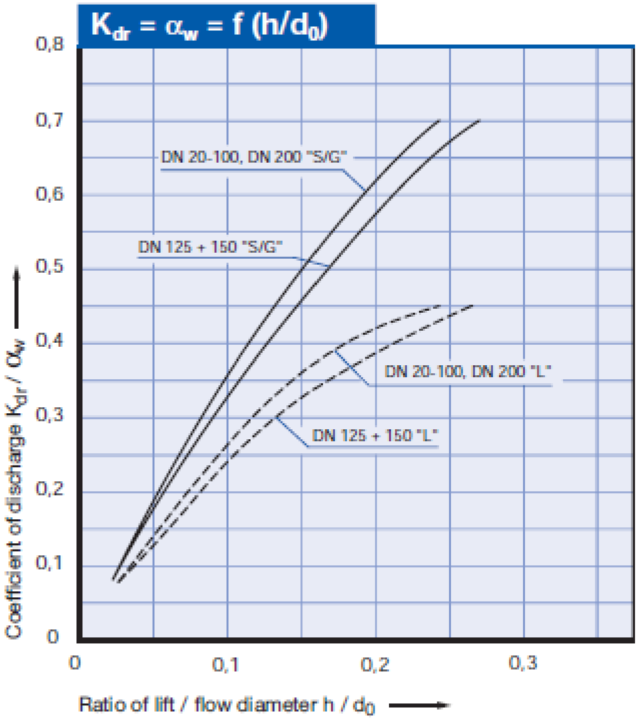


Figure 7.5.8-1 Discharge coefficient K_{dr} for gases in function of the lift h over flow diameter d_o for LESER Type 441

7.5.9 Discharge Coefficient of Valves at High Back Pressures

ISO 4126-7 also considers the possibility that the discharge coefficient for gases and vapors in subcritical flows is less than that in critical conditions. Concretely, if the ratio of the absolute back pressure P_{a0} to the relieving pressure P_0 exceeds the value of 0.25, the coefficient of discharge can depend upon this ratio. The manufacturer is required to certify the flow capacity of the valve for ratios of the absolute back pressure on the relieving pressure between 0.25 and the maximum pressure ratio. This curve may be extended to cover the tests with pressure ratios less than 0.25, if necessary. VdTÜV states explicitly that this curve must be obtained with a constant lift ratio, h/d_0. Fig. 7.5.9-1 represents such an example of a back pressure dependence for the safety valve LESER Type 441.

From its internal databases VALVESTAR® selects the discharge coefficients of the safety valve which occur for the given ratio of absolute back pressure to relieving pressure.

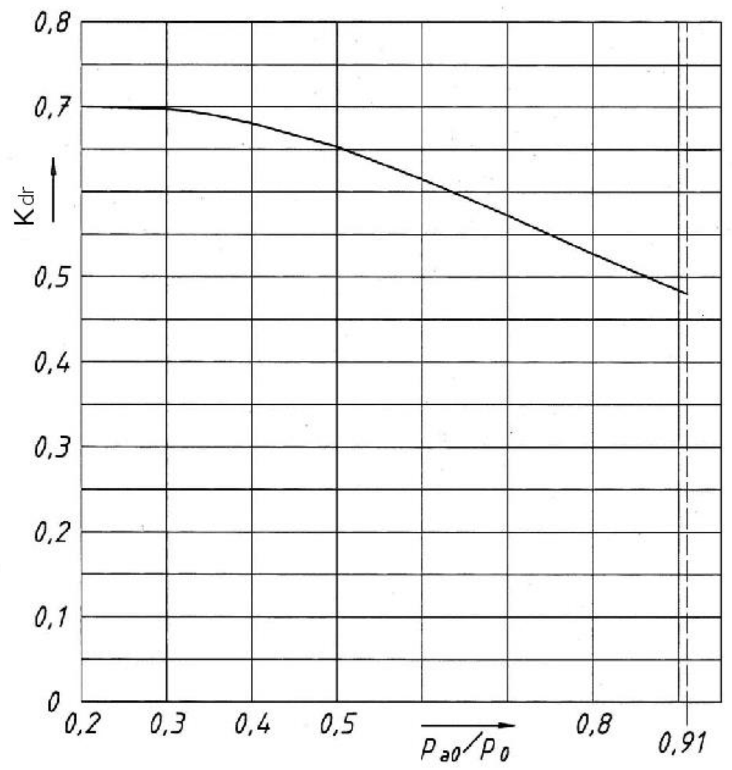


Figure 7.5.9-1 Discharge coefficient K_{dr} for gases in function of the ratio of the absolute back pressure P_{a0} on the relieving P_0 pressure for LESER Type 441

7.5.10 Examples

7.5.10.1 Gases - Critical Flow

Example 7.5.10.1. A safety valve for ethylene (C_2H_4) at the relieving temperature of 55°C (328.15 K) and a set pressure of 55 bar g for a relieving mass flow rate of 4200 kg/h and back pressure of 10 bar g is required. For the type assume LESER Type 459 with a K_{dr} equal to 0.81.

Solution. The relieving pressure values

$$P_1 = P_{set} + \Delta P_{overpressure} + P_{atm} = 55 \ bar + 5.5 \ bar + 1 \ atm = 61.51 \ bar$$

From the Example 7.2.6.1 the compressibility factor Z is 0.712, the isentropic exponent k and the molecular weight M are respectively 1.19 and 28.03 kg/k_{mol}.
The flow function C is calculated from Eq. 7.5.3-2

$$C = 3.948\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} = 3.948\sqrt{1.19\left(\frac{2}{1.19+1}\right)^{\frac{1.19+1}{1.19-1}}} = 2.553$$

The critical back pressure is calculated from Fig. 7.5.2-2 and it is equal to

$$p_c = p_0\left(\frac{2}{k+1}\right)^{k/(k-1)} = 61.51 \ bar \cdot \left(\frac{2}{1.19+1}\right)^{1.19/(1.19-1)} = 34.84 \ bar$$

and the flow is critical since the back pressure of 11.01 bar is lower than the critical pressure. Therefore the coefficient K_b is in this case not necessary.
The required necessary relief area comes from Eq. 7.5.5.1-1

$$A = \frac{Q_m}{p_0 C \ K_{dr}}\sqrt{\frac{Z \ T_0}{M}} = \frac{4200}{61.51 \cdot 2.553 \cdot 0.81}\sqrt{\frac{0.712 \cdot 328.15}{28.03}} \ mm^2 = 95.4 \ mm^2$$

which is satisfied by the valve with a relief area of 133 mm² (diameter: 13 mm) **(4593.2512)**.

7.5.10.2 Gases - Subcritical Flow

Example 7.5.10.2. Same as Example 7.4.7.1 but with a back pressure of 35 bar g (36.01 bar).

Solution. The flow in the safety valve is in this case subcritical and therefore the correction factor must be calculated acc. to Eq. 7.5.5.2-2

$$K_b = \sqrt{\frac{\frac{2k}{k-1}\left[\left(\frac{p_b}{p_0}\right)^{2/k} - \left(\frac{p_b}{p_0}\right)^{(k+1)/k}\right]}{k\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}}} = \sqrt{\frac{\frac{2 \cdot 1.19}{1.19-1}\left[\left(\frac{36.01}{61.51}\right)^{2/1.19} - \left(\frac{36.01}{61.51}\right)^{(1.19+1)/1.19}\right]}{1.19\left(\frac{2}{1.19+1}\right)^{(1.19+1)/(1.19-1)}}} = 0.9991$$

The minimum required relief area, calculated from Eq. 7.5.4.2-1 is

$$A = \frac{Q_m}{p_0 C \ K_{dr} K_b}\sqrt{\frac{Z \ T_0}{M}} = \frac{4200}{61.51 \cdot 2.553 \cdot 0.721 \cdot 0.9991}\sqrt{\frac{0.712 \cdot 328.15}{28.03}} \ mm^2 = 107.2 \ mm^2$$

which is satisfied again by the LESER Type 459 with a relief area of 133 mm² (**4593.2512**).

Note: Observe that the derated discharge coefficient is less than that of the previous example due to the higher back pressure ratio. See Example 7.5.10.8 for a detailed example.

7.5.10.3 Dry Steam (ISO 4126-1 2004)

Example 7.5.10.3. A safety valve must be sized for (saturated) steam in a large vessel at a set pressure of 110.4 bar gauge for a mass flow rate of 69800 kg/hr , assuming 10% overpressure.

Solution. The relieving pressure is

$$P_1 = P_{set} + \Delta P_{overpressure} + P_{atm} = 110.4\ bar + 11.04\ bar + 1.01\ bar = 122.45\ bar$$

The specific volume and the isentropic exponent of saturated steam at relieving conditions acc. to IAPWS – IF 97 tables[12] is equal to 0.013885 m³/kg and 0.966, which is in good agreement with the value, obtained by interpolating the data from ISO 4126-7. With this isentropic coefficient the required parameter C from Eq. 7.5.3-2 is

$$C = 3.948\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} = 3.948\sqrt{0.966\left(\frac{2}{0.966+1}\right)^{\frac{0.966+1}{0.966-1}}} = 2.3636$$

In view of the high pressure and capacity requirements, a safety valve **LESER Type 458** is selected. At first we size using the derated discharge coefficient of 0.84 , which suits for most of the sizes of this safety valve type. With that value of the discharge coefficient the required flow area from Eq. 7.4.3-1 is

$$A = \frac{1}{0.2883}\frac{Q_m}{C\ K_{dr}}\sqrt{\frac{v}{p_0}} = \frac{1}{0.2883}\frac{69800}{2.3636 \cdot 0.84}\sqrt{\frac{0.013885}{122.45}}\ mm^2 = 1298\ mm^2$$

Consequently, a relief area of 1964 mm² (**DN 80/100**) (**4582.6142**) would suffice. However, the derated discharge coefficient for that size is 0.83; nevertheless, introducing of the true value of the discharge coefficient the valve size is confirmed.

$$A = \frac{1}{0.2883}\frac{Q_m}{C\ K_{dr}}\sqrt{\frac{v}{p_0}} = \frac{1}{0.2883}\frac{69800}{2.3636 \cdot 0.83}\sqrt{\frac{0.013885}{122.45}}\ mm^2 = 1314\ mm^2$$

Note. The isentropic coefficient of steam at the relieving conditions is different in ISO 4126-7 and IAPWS Database.

7.5.10.4 Wet Steam (ISO 4126-1 2004)

Example 7.5.10.4. Same problem as in Example 7.5.10.3. but assuming a wet fraction of 3 %

Solution Wet Steam. The fraction of dry steam on the wet steam is equal to 97 % or 0.97 . For wet steam a smaller minimum flow area is required than that if the steam were dry.
From Eq. 7.5.4-1 it is equal to

$$A = \frac{1}{0.2883}\frac{Q_m\sqrt{x}}{C\ K_{dr}}\sqrt{\frac{v}{p_0}} = \frac{1}{0.2883}\frac{69800\cdot\sqrt{0.97}}{2.3636 \cdot 0.83}\sqrt{\frac{0.013885}{122.45}}\ mm^2 = 1294.3\ mm^2$$

The relief area of the safety valve is nevertheless again equal to 1964 mm² (**4582.6142**).

[12] W. Wagner , H. Kretzschmar Ed., *International steam tables: Properties of water and steam based on the industrial formulation IAPWS-IF97,* Springer, Berlin, 2008

7.5.10.5 Superheated Steam (ISO 4126-1 2004)

Example 7.5.10.5. Same problem as in Example 7.5.10.3 but assuming superheated steam at a set pressure of 110.4 bar and 420°C

Solution Superheated Steam. Also in case of superheated heat values of the isentropic coefficient and of the specific volume at relieving conditions are needed. From IAPWS tables they are respectively 1.279 for the isentropic coefficient and 0.0214 m³/kg for the specific volume and they are close to the values from the interpolation of data in ISO 4126-7. On their behalf the parameter C from Eq. 7.5.3-2 is equal to

$$C = 3.948\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} = 3.948\sqrt{1.279\left(\frac{2}{1.279+1}\right)^{\frac{1.279+1}{1.279-1}}} = 2.6192$$

Assuming the derated discharge coefficient of 0.84, the required area using Eq. 7.5.3-1 must exceed

$$A = \frac{1}{0.2883}\frac{Q_m}{C\ K_{dr}}\sqrt{\frac{v}{p_0}} = \frac{1}{0.2883}\frac{69800\cdot}{2.6192\cdot 0.84}\sqrt{\frac{0.0214}{122.45}}\ mm^2 = 1454.7\ mm^2$$

which suggests that again a relief area of 1964 mm² is enough (**4582.6142**). Indeed, considering the corresponding derated discharge coefficient for that valve size, which is 0.83, the minimum required area is equal to

$$A = \frac{1}{0.2883}\frac{Q_m}{C\ K_{dr}}\sqrt{\frac{v}{p_0}} = \frac{1}{0.2883}\frac{69800\cdot}{2.6192\cdot 0.83}\sqrt{\frac{0.0214}{122.45}}\ mm^2 = 1472.2\ mm^2$$

7.5.10.6 Liquid - Viscous Flow

Example 7.5.10.6. A safety valve must be sized for a flow rate of 5 l/s of glycerin (density :1260 kg/m³ and viscosity: 1410 mPa s) at a set pressure is 10 bar-g and atmospheric backpressure with 10 % accumulation.

Solution The (mass) flow capacity must be expressed with the units of ISO 4126-7.

$$Q_m = 5l/s \cdot 1260\ kg/m^3 \cdot 3600\ s/hr = 22680\ kg/hr$$

For this high discharge application **LESER Type 441** can be selected. The relieving pressure is

$$P_1 = P_{set} + \Delta P_{overpressure} + P_{atm} = 10\ bar + 1\ bar + 1.01\ bar = 12.01\ bar$$

The required minimum flow area is calculated with a two-step procedure. At first the relief area is calculated as the liquid were inviscid. According to Eq. 7.5.6-1 this preliminary minimum flow area is

$$A = \frac{1}{1.61}\frac{Q_m}{K_{dr}}\sqrt{\frac{v}{p_0 - p_b}} = \frac{1}{0.2883}\frac{22680}{0.45}\sqrt{\frac{0.00079}{122.45}}\ mm^2 = 265.9\ mm^2$$

Then the next larger relief area A' must be selected from the manufacturer's catalog, which equals in this case 416 mm² (**DN 25/40**) and is assumed as the preliminary flow area. The ratio of the calculated A to A' gives the minimum value of the viscosity correction factor that the real factor is required to exceed. In this case the minimum viscosity correction factor is

$$K_{v-\min} = A/A' = 265.9/416 = 0.639$$

Using the selected relief area the Reynolds number is calculated from Eq. 7.4.6-2

$$\mathrm{Re} = \frac{1}{3.6}\frac{Q_m}{\mu}\sqrt{\frac{4}{\pi\ A'}} = \frac{1}{3.6}\frac{22680}{1.41}\sqrt{\frac{4}{\pi\ 416}} = 247.2$$

On behalf of this Reynolds number the viscosity correction factor from Fig. 7.9.3-1 is about 0.79. Since this viscosity correction factor coefficient exceeds the minimum required value, the safety valve **LESER Type 441 DN 25/40** **(4411.4382)** is the final flow area acc. to ISO 4126. In case it were not, the next larger A' must be extracted from the manufacturer's catalog and the previously illustrated procedure routines until the minimum viscosity correction factor is exceed.

7.5.10.7 Determination of a Required Lift Restriction

Example 7.5.10.7. Which lift restriction would be necessary in Example 7.5.10.1 to minimize the flow from the safety valve in excess of the required one?

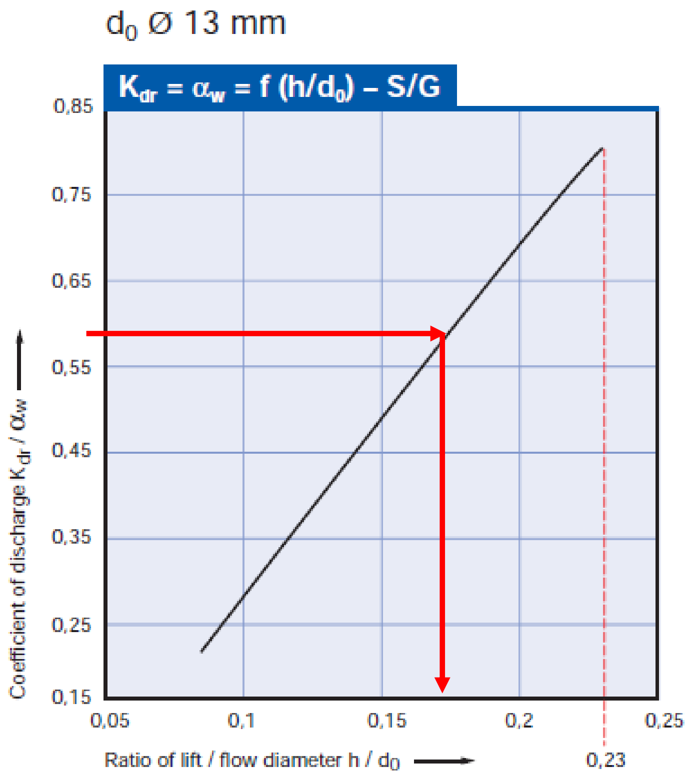
Solution. As a result from Example 7.5.10.1 a flow area of 133 mm² (d_0 = 13 mm) is chosen. However, from the process data the actual discharged mass flow acc. to Eq. 7.5.5.1-1 is much larger than the required one and exactly it is

$$Q_{m\ real} = p_0 C\ A\ K_{dr}\sqrt{\frac{M}{ZT_0}} = 61.51 \cdot 2.553 \cdot 133 \cdot 0.81\sqrt{\frac{28.03}{0.712 \cdot 328.15}} = 5859.6\ \frac{kg}{h}$$

In order to have a discharged mass flow closer to the required one, the disk lift must be reduced. The ratio between the reduced and the full lift derated discharge coefficient is given by the ratio of the required to the effectively discharged mass flow

$$\frac{K_{dr\ red}}{K_{dr\ full}} = \frac{Q_{m\ required}}{Q_{m\ effective}} \ \rightarrow\ K_{dr\ red} = K_{dr\ full} \cdot \frac{Q_{m\ required}}{Q_{m\ effective}} = 0.81 \cdot \frac{4200}{5859.6} = 0.58$$

which corresponds to the lift ratio h/d_0 of 0.1714 or 2.23 mm, acc. to the LESER Catalog Compact Performance, reported here below.



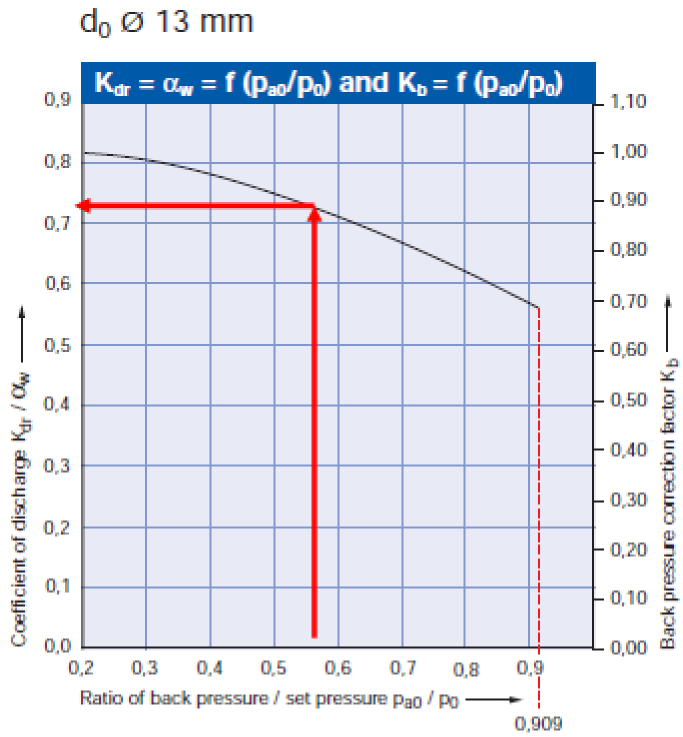
7.5.10.8 Determination of the Discharge Coefficient for Higher Back Pressures

Example 7.5.10.8. Find the discharge coefficient for the ratio of back pressure on the relieving pressure in Example 7.5.10.2

Solution. In Example 7.5.10.2 the back pressure is 35 bar gauge (36.01 bar) and the relieving pressure 61.51 bar, which corresponds to a p_{a0}/p_0 ratio

$$\frac{p_{a0}}{p_0} = \frac{36.01}{61.51} = 0.5854$$

Acc. to the LESER Catalog Compact Performance, reported here below, it corresponds to the derated discharge coefficient of 0.721.



7.6 Sizing according to AD 2000-Merkblatt A2

The information contained in this section is based on **AD 2000-Merkblatt A2 edition 2020.**

AD 2000 Merkblätter are guidelines satisfying the requirements for the construction of pressurized vessels contained in the PED directives. Among all other information, AD 2000 A2 contains indications for the installation and the sizing of safety valves and may be used alternatively to ISO 4126. Sizing acc. to AD 2000 A2 is applied by LESER upon explicit request from customers.

The minimal flow cross section of the safety valve must exceed the minimum one, which results from the following formulas. AD 2000 A2 prescribes a minimal flow diameter of at least 6 mm for the general case or 20 mm for pressure vessels with greasy or powdery media or for media, which are inclined to coalesce. The minimum values of the derated discharge coefficient that the safety valves are required to have are:

0.5	for full-lift valves, except for those with a lift restriction
0.08 (Gas/Vapor) 0.05 (Liquid)	respectively for normal and proportional safety valves

7.6.1 List of Symbols / Nomenclature

Symbol	Description	Units [SI]
A_0	Minimal cross section of flow	[mm²]
k	Isentropic exponent (see isentropic coefficient in ISO 4126) (see Par. 3.1)	--
M	Molar mass	[kg/k$_{mol}$]
p_a	Dynamic back pressure behind the valve	[bar]
p_s	Pressure of the medium at saturation temperature	[bar]
p_0	Absolute pressure in the pressure chamber	[bar]
q_m	Mass flow to be discharged	[kg/h]
T	Temperature of the medium in the protected system	[K]
v	Specific volume of the medium in the pressure chamber	[m³/kg]
x	Pressure medium coefficient (gas flows) Vapour void fraction (two-phase flows)	[h mm² bar/kg] --
Z	Compressibility factor of the medium in the pressure chamber (see Par. 3.21)	--
α_w	Certified discharge coefficient	--
ψ	Outflow function (gas flows)	--
ρ	Density	Kg/m³

Table 7.6.1-1: List of symbols for sizing according to AD 2000 A2

The relieving pressure p_0 is defined in Eq. *7.6.1-1* as the sum of the set pressure, the overpressure and the atmospheric value. For the overpressure in Eq. *7.6.1-1* generally 10% of the set pressure is used, also for safety valves that are fully open at set pressure plus an overpressure below 10%, e.g. for full lift safety valves with 5% overpressure..

$$p_0 = p_{set} + \Delta \; p_{over} + p_{amb} \quad \textit{(Eq. 7.6.1-1)}$$

7.6.2 Gases and Vapors

$$A_0 = 0.1791 \frac{q_m}{\psi\ \alpha_w p_0} \sqrt{\frac{T\ Z}{M}} \quad \text{(Eq. 7.6.2-1)}$$

with the outflow function defined in Table 7.6.2-1

Subritical flow	$\frac{p_a}{p_0} > \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$	$\psi = \sqrt{\frac{k}{k-1}} \sqrt{\left(\frac{p_a}{p_0}\right)^{\frac{2}{k}} - \left(\frac{p_a}{p_0}\right)^{\frac{k+1}{k}}}$
Critical flow	$\frac{p_a}{p_0} \le \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$	$\psi = \sqrt{\frac{k}{k+1}} \left(\frac{2}{k+1}\right)^{\frac{1}{k-1}}$

Tab. 7.6.2-1 Outflow function for critical and subcritical gas flows

7.6.3 Steam

$$A_0 = \frac{x\ q_m}{\alpha_w p_0} \quad \textit{(Eq. 7.6.3-1)}$$

The pressure medium coefficient x is defined in Eq. 7.6.3-2

$$x = 0.6211 \frac{\sqrt{p_0 v}}{\psi} \quad \textit{(Eq. 7.6.3-2)}$$

The values of the specific volume and the isentropic exponent for the calculation of ψ are extracted from *State Variables of Water and Steam*, Springer, Berlin, 1969. AD 2000 A2 does not state, if more actual versions of this database, like the IAPWS tables, shall be consulted. In replacement of Eq. 7.6.3-2 the pressure medium coefficient for critical flows can be taken from Fig. 7.6.3-1. For subcritical flows as well as for set pressures below 2 bar this graph can not be used and the pressure medium coefficient must be calculated.

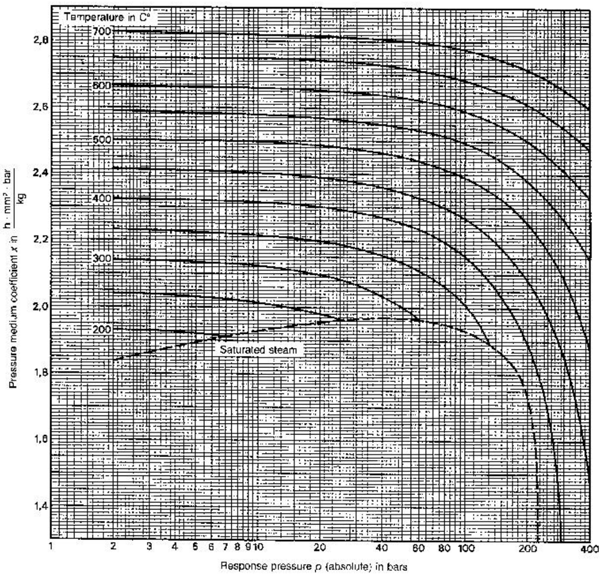


Fig. 7.6.3-1 Pressure medium coefficient for steam in function of the response pressure (set pressure)

7.6.4 Non-Boiling Liquids

$$A_0 = 0.6211 \frac{q_m}{\alpha_w \sqrt{\rho \left(p_0 - p_a\right)}} \quad \text{(Eq. 7.6.4-1)}$$

Non-boiling liquids do not change phase when flowing in the safety valve. AD 2000 A2 gives no reference to a viscosity correction factor for viscous liquids. Nevertheless, VALVESTAR® follows the sizing procedure in ISO 4126-7 for the determination of the viscosity correction factor.

7.6.5 Discharge Coefficient of Valves with Restricted Lift

The discharge coefficient for safety valves with a lift restriction or in case of high back pressures are certified acc. to VdTÜV Merkblatt 100 *Sicherheitsventile* (see section 7.5.8 and 7.5.9). The lift must be at least 1 mm or 30% of the maximum lift, whichever value is greater. For all other details see 7. 5.8.

7.6.6 Discharge Coefficient of Valves at High Back Pressures

Qualitatively identical to Section 7.5.9.

7.6.7 Summary AD 2000 - Merkblatt A2

The AD 2000 Code can be applied to satisfy the basic safety requirements of the Pressure Equipment Directive (PED). That means, sizing a safety valve acc. to AD 2000 A2 is in compliance with the PED requirements. The sizing formulas in the standard AD 2000 A2 are for gases, vapors, liquids not requiring viscosity correction factors are identical to those in ISO 4126-7.

7.6.8 Examples

7.6.8.1 Gas - Critical Flow

Example 7.6.8.1. A safety valve is sized for a mass flow rate of 4200 kg/h ethylene (C_2H_4) at the relieving temperature of 55°C and a set pressure of 55 bar g and back pressure of 10 bar g. The safety valve is the **LESER Type 459** with α_w equal to 0.81.

Solution. The relieving pressure values

$$P_1 = P_{set} + \Delta P_{overpressure} + P_{atm} = 55\ bar + 5.5\ bar + 1\ atm = 61.51\ bar$$

From Example 7.2.6.1 the compressibility factor Z is 0.712. The isentropic coefficient *k* and the molecular weight M are given from the customer as 1.19 and 28.03 kg/k_{mol} and the flow is critical.

The flow function ψ is calculated from the first line of Table 7.6.2-1

$$\psi = \sqrt{\frac{k}{k+1}\left(\frac{2}{k+1}\right)^{\frac{1}{k-1}}} = \sqrt{\frac{1.19}{1.19+1}\left(\frac{2}{1.19+1}\right)^{\frac{1}{1.19-1}}} = 0.4572$$

The required necessary flow area is calculated from Eq. 7.6.2-1

$$A_0 = 0.1791\frac{q_m}{\psi\ \alpha_w p_0}\sqrt{\frac{T\ Z}{M}} = 0.1791\frac{4200}{0.4572 \cdot 0.81 \cdot 61.51}\sqrt{\frac{328.15 \cdot 0.712}{28.03}} = 95.4\ mm^2$$

The flow area of 133 mm² (d_0 = 13 mm) **(4593.2512)**, as already seen using ISO 4126-7, will be large enough to release the given mass flow rate.

7.6.8.2 Gas - Subcritical Flow

Example 7.6.8.2. Same as Example 7.6.8.1 but with a back pressure of 35 bar g (36.01 bar). The discharge coefficient comes from Example 7.5.10.8 and is equal to 0.721.

Solution. From Example 7.5.10.2 we know that the flow in the safety valve is in this case subcritical and therefore the outflow function must be taken from the first line of Table 7.6.2-1

$$\psi = \sqrt{\frac{k}{k-1}}\sqrt{\left(\frac{p_a}{p_0}\right)^{\frac{2}{k}} - \left(\frac{p_a}{p_0}\right)^{\frac{k+1}{k}}} = \sqrt{\frac{1.19}{1.19-1}}\sqrt{\left(\frac{36.01}{61.51}\right)^{\frac{2}{1.19}} - \left(\frac{36.01}{61.51}\right)^{\frac{1.19+1}{1.19}}} = 0.4568$$

The minimum required flow area according to Eq. 7.5.2-1 is

$$A_0 = 0.1791\frac{q_m}{\psi\ \alpha_w\, p_0}\sqrt{\frac{T\ Z}{M}} = 0.1791\frac{4200}{0.4568\cdot 0.721\cdot 61.51}\sqrt{\frac{328.15\cdot 0.712}{28.03}} = 107.2\ \ mm^2$$

which is satisfied again by the LESER Type 459 with a relief area of 133 mm² (d_0 = 13 mm) **(4593.2512).**

7.6.8.3 Saturated Steam

Example 7.6.8.3. A safety valve must be sized for saturated steam at a set pressure of 110.4 bar g with a mass flow of 69800 kg/hr , assuming 10% overpressure. In view of the high pressure and capacity requirements, a safety valve **LESER Type 458** with a discharge coefficient of 0.83 is selected.

Solution. The relieving pressure is

$$P_1 = P_{set} + \Delta P_{overpressure} + P_{atm} = 110.4\ \ bar + 11.04\ \ bar + 1.01\ \ bar = 122.45\ \ bar$$

The specific volume and the isentropic exponent of saturated steam at 122.45 bar are taken from IAPWS tables equal to 0.013885 m³/kg and 0.966. The outflow function ψ from Table 7.6.2-1 equals

$$\psi = \sqrt{\frac{k}{k+1}}\left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} = \sqrt{\frac{0.966}{0.966+1}}\left(\frac{2}{0.966+1}\right)^{\frac{1}{0.966-1}} = 0.4233$$

The pressure medium coefficient is calculated from Eq. 7.6.3-2 as

$$x = 0.6211\frac{\sqrt{p_0 v}}{\psi} = 0.6211\frac{\sqrt{122.45\cdot 0.013885}}{0.4233} = 1.9128\ \ \frac{h\cdot mm^2\cdot bar}{kg}$$

The required flow area is finally calculated from Eq. 7.6.3-1

$$A_0 = \frac{x\ q_m}{\alpha_w\, p_0} = \frac{1.9128\cdot 69800}{0.83\cdot 122.45} = 1313.7\ \ mm^2$$

The required relief area would be 1964 mm² (d_0 = 40 mm) **DN 80/100 (4582.6142.**

7.6.8.4 Non-Boiling Liquid

Example 7.6.8.4. A safety valve Type 441 must be sized for a flow rate of 5 l/s of water (density :998 kg/m³) and a set pressure is 10 bar g with atmospheric back pressure and 10% accumulation.

Solution The required mass capacity is

$$q_m = 5 \ l/s * 998 \ kg/m^3 * 3600 \ s/h * 0.001 \ m^3/l = 17964 \ kg/h$$

The relieving pressure is

$$P_1 = P_{set} + \Delta P_{overpressure} + P_{atm} = 10 \ bar + 1 \ bar + 1.01 \ bar = 12.01 \ bar$$

The required flow area according to Eq. 7.6.4-1 is equal to

$$A_0 = 0.6211 \frac{q_m}{\alpha_w \sqrt{\rho (p_0 - p_a)}} = 0.6211 \frac{17964}{0.45 \sqrt{998 (12.01)}} = 226.5 mm^2$$

The required relief area is 254 mm², which corresposnds to the size **DN 20/32 (4411.4372)**

7.7 Sizing Standards Applying to Cryogenic Applications

In this section the norms are based on following edition:
ASME Section XIII (2021), EN 13136 (2013), ISO 4126-7 (2016), ISO 21013-3 (2016), EN 12693 (2008)

ASME Section XIII, ISO 4126-7 and AD 2000 Merkblatt A2 apply to the general sizing occurrence of a gas, vapor or liquid in a pressurized unit. However, in the specific case of pressurized vessels for LNG, LPG or similar, where high pressures and very low temperatures occur, special standards have been developed to estimate the mass flow rate to the safety devices.
The standards presented in this section are useful to calculate the mass flow rate to the safety valve used in the protection of these vessels.

7.7.1 Sizing acc. to ISO 21013-3

This standard applies to vacuum-insulated and non-vacuum insulated cryogenic vessels under different conditions of intactness of the insulation system (outer jacket + insulating material). The outer jacket temperature is ambient temperature and the inner vessel is at the temperature of the contained medium. It applies also for vessels with a totally lost insulation system and fire engulfment.

7.7.1.1 List of Symbols/Nomenclature

Symbols	Description	Units [SI]
L	Latent heat of vaporization of the cryogenic liquid at relieving conditions	kJ/kg
L'	Specific heat input , defined as $v\left[\frac{\partial h}{\partial v}\right]_p$ at the relieving pressure p_0 and temperature which maximizes $\sqrt{v}\Big/v\left[\frac{\partial h}{\partial v}\right]_p$	kJ/kg
v_G	Specific volume of saturated vapor at relieving pressure	m³/kg
v_L	Specific volume of saturated liquid at relieving pressure	m³/kg
W	Quantity of heat per unit time	W

Table 7.7.1.1-1: List of symbols for sizing according to ISO 21013-3

For the determination of the minimum mass flow requirements follow Table 7.7.1.1-2 which relates it to the ratio p_0/p_c of the relieving pressure p_0 to the (thermodynamical) critical pressure p_c (see sect. 2.3)

p_0/p_c [-]	Q_m [kg/h]
less than 0.4	$3.6\ W/L$
between 0.4 and 1	$3.6\left(\frac{v_G - v_L}{v_G}\right) W/L$
more than or equal to 1	$3.6\ W/L'$

Table 7.7.1.1-2 Criteria to select the mass flow rate into the safety valve. for standard

The required heat input should be provided as input data, following the calculation scheme in the norm.

The minimum required flow area is determined acc. to ISO 4126-7. The sum of the relieving capacities of all the safety valves must be equal or exceed the minimum required mass flow Q_m. from Table 7.7.1.1-2.

7.7.1.2 Example

Example 7.7.1.2. Determine the mass flow rate to the safety valve for a vessel of liquid hydrogen at a relieving pressure of 2.8 bar. Consider an heat input of 15000 W.

Solution. The critical point of hydrogen is 13 bar and 33.2 K and the relieving pressure is les than 40 % of the thermodynamic critical pressure.

The latent heat L at that relieving pressure acc. to NIST is 417.274 kJ/kg.
The mass flow rate of hydrogen vapor to the safety valve is
$Q_m = 3.6 W / L = 3.6 \cdot 15000 / 417.274 = 129.4$ kg/h

7.7.2 Sizing acc. To DIN EN 13136

The standard DIN EN 13136[13] describes calculation procedures to estimate the required mass flow rates of refrigerants in the gaseous phase.

7.7.2.1 List of Symbols /Nomenclature

Symbol	Description	Units [SI]
φ	Density of heat flow rate	[kW/m²]
η_v	Volumetric efficiency estimated at suction pressure and discharge pressure equivalent to the safety valve setting	[--]
ρ_{10}	Vapor density at refrigerant saturation pressure/dew point at 10°C	[kg/m³]
A	Flow area of the safety valve	[mm²]
A_c	Calculated flow area	[mm²]
A_{surf}	External surface area of the vessel	[m²]
h_{vap}	Heat of vaporization calculated at 1.1 times the set pressure of the safety valve	[kJ/kg]
K_{dr}	Derated coefficient of discharge	[--]
n	Rotational frequency	[min⁻¹]
Q_h	Rate of heat production, internal heat source	[kW]
Q_m	Calculated mass flow rate	[kg/h]
Q_{md}	Minimum required capacity of refrigerant of the safety valve	[kg/h]
V	Theoretical displacement	[m³]

Table 7.2-1: List of symbols for sizing according to EN 13136

If heat, which is either internally generated or transmitted from an external source, warms up the tank, overpressure may arise from a partial evaporation of the liquid. The minimum required vapor discharge capacity of the safety valve is determined by either Eq. 7.7.2-1 if the heat source is external or Eq. 7.7.2-2 if internal.

$$Q_{md} = 3600 \frac{\varphi \cdot A_{surf}}{h_{vap}} \quad \text{(external heat sources) (7.7.2-1)}$$

If no better value is known, the density of heat flow rate φ can be assumed as 10 kW/m².

$$Q_{md} = 3600 \frac{Q_h}{h_{vap}} \quad \text{(internal heat sources) (7.7.2-2)}$$

The minimum discharge area of the safety valve in case of overpressure in the vessel caused by compressor inflow is determined using Eq. 7.7.2-3

$$Q_{md} = 60 \cdot V \cdot n \cdot \rho_{10} \cdot \eta_v \quad \text{(compressors) (7.7.2-3)}$$

The standard EN 12693[14] covers the case of compressors running against a closed discharge valve.

[13] EN 13136 Refrigerating systems and heat pumps – Pressure relief devices and their associated piping – Method for calculation, 2013.
[14] EN12693 Refrigerating systems and heat pumps – Safety and environmental requirements – Refrigerant compressors, 2008.

The minimum flow area of the safety valve is calculated from the minimum required mass flow rate determined from Eq. 7.7.2-1 to Eq. 7.7.2-3 using Eq. 7.7.2-4. To determine *C* and $K_{b,}$ see Paragraph 7.5.3 and 7.5.6

$$A_c = 3.469 \frac{Q_{md}}{C \cdot K_{dr} \cdot K_b} \sqrt{\frac{v_0}{p_0}} \quad (7.7.2\text{-}4)$$

The minimum product of area coefficient of discharge $A \cdot K_{dr}$ in case of thermal expansion of trapped liquids shall be at least 0.02 mm² per liter of trapped volume.

7.8 Guidelines for Specific Applications

In this section the norms are based on following edition:
ASME Section XIII (2021), API RP 520 (2020), API 521 (2020), ISO 4126-1 (2016), ISO 4126-7 (2016), ISO 23251(2020)

In this chapter the user is given some quick but reliable guidance to determine the mass flow rate to the safety valve for some practical cases of overpressure, which are not expressively discussed in the above cited standards.

7.8.1 Shell Boilers and Tube Boilers

There are two types of boilers, namely tube boilers and shell boilers. In tube boilers water is carried in tubes exposed to combustion gases, while in shell boilers the hot gases flow in tubes immersed in a water bath. Both types of boilers can be either used for steam or hot water generators.

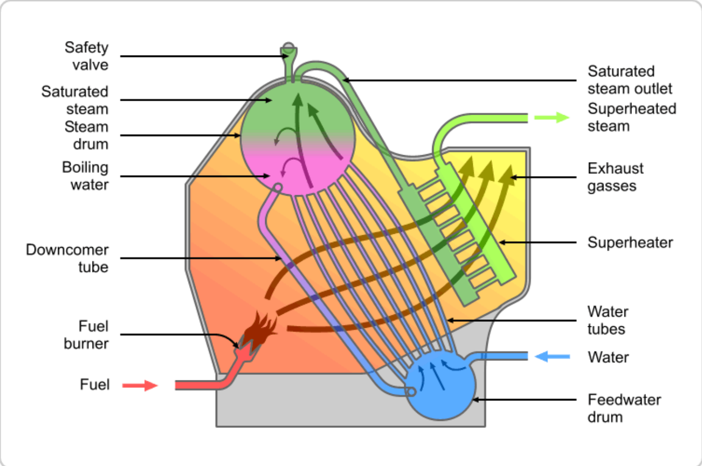


Fig. 7.8.1-1 Marine type tube boiler for steam generation: steam generator (feedwater drum, steam drum, downcomer tube) and superheater (Source : Wikipedia Images)

Acc. to EN 12952-10[15] (2020) every steam generator as well as all isolable heated vessels in a **tube boiler steam generator,** see Fig. 7.8.1-1, incl. reheaters and economizers, must be protected by at least one pressure relieving device. The minimum diameter of the flow area of the safety valves must be 15 mm. The position of the safety valve for the protection of the vessels in a tube boiler steam generator is given in Table 7.8.1-1.

[15] Water-tube boilers and auxiliary installations – Part 10: Requirements for safeguards against excessive pressure, 2020.

Tube boiler steam generator	Position of safety valve in EN 12952-10 (2020)
Steam generator (feedwater and steam drum)	For a generator with no superheater the safety valves or the main valve of CSPRS[16] valves must be placed on the steam side (EN 12952-10). The cumulative certified capacity of the safety valves installed on the steam generator must be at least equal to the max. steam generation (EN 12952-10).
Non-isolable superheater no control valve is present between superheater and steam generator	A safety valve at the superheater outlet must prevent the release capacity to exceed the allowable wall temperature. Direct-loaded and supplementary loaded safety valves on the steam generator must discharge at least 75 % of the required release capacity. CSPRS valves instead at least 25 %: however, the CSPRS on the superheater can discharge the whole capacity provided that it is monitoring the pressure of the steam drum as well (EN 12952-10).
Isolable superheater a control valve is placed between superheater and steam generator	These superheaters must be protected with safety valves or the main valves of the CSPRS at the outlet of a superheater, which must be sized for at least 20 % of the required release capacity. The main valve of the CSPRS on the steam generator must discharge the whole allowable steam generation (EN 12952-10).

Table 7.8.1-1: Position of the safety valve for the protection of the vessels in a tube boiler steam generator

Every reheater must be equipped with a safety valve as well. The release capacity of the safety valve or of the main valve of the CSPRS must correspond to the max. design steam mass flow through the reheater (EN 12952-10).

In EN 12952-10[17] (2020) every **tube boiler hot water generator** must be protected by at least one pressure relieving device. The cumulative certified mass flow of several safety valves must be at least equal to the generated mass flow rate of steam (EN 12952-10), which is calculated using Eq. 7.8.1-1 assuming that no heat is lost

$$q_m = 3600 \cdot Q / L_{vap} \quad (7.8.1\text{-}1) \quad \text{with}$$

q_m	Steam mass flow rate	[kg/h]
Q	Heat flow to the saturated water	[kW]
L_{vap}	Latent heat of evaporation	[kJ/kg]

The minimum diameter of the flow area of the safety valves must be 15 mm (EN 12952-10). The safety valves must be placed on or in proximity of the highest point of the feed line or on the feed line as close to the boiler as possible (EN 12952-10). The safety valves must be sized for saturated steam flows at relieving conditions even for boilers where the valve is under water pressure (EN 12952-10).

[16] CSPRS : Controlled Safety Pressure Relief Systems

[17] Water-tube boilers and auxiliary installations – Part 10: Requirements for safeguards against excessive pressure, 2020.

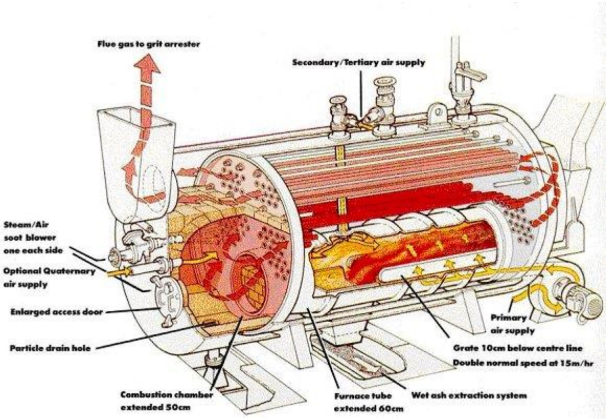


Figure 7.8.1-2 Shell boiler ; Source: [RISE , Murdoch University, Perth (AUS)]

In **shell boilers** the control of the liquid and steam filling levels in the boiler should guarantee that the pressure in the shell boiler does not exceed the set value. In EN 12953-8[18] (2002) every vessel in the shell boiler must be protected by a safety valve, which should be able to discharge the allowable steam mass flow. (EN 12953-8, Par 4.1.1) The minimum seat diameter of the safety valve must be 15 mm (EN 12953-8, Par. 4.1.5). The position of the safety valve for the protection of the vessels in a shell boiler is given in Table 7.8.1-2.

General shell boiler	Position of safety valve in EN 12953-8 (2002)
Isolable economizer	The min. relieving capacity of the safety valve must be determined on the base of the heat inflow to the economizer using Eq. 7.8.1.1 (EN 12953-8, Par. 4.1.4).
Non-isolable superheater no control valve is present between superheater and steam generator	The release capacity of the superheater may be added to that of the steam generator in order to determine the min. relieving flow rate of the safety valves (EN 12953-8, Par 4.1.2). The superheater must have a safety valve at the outlet, whose release capacity must be at least 25 % of the whole capacity of the boiler (EN 12953-8, Par 4.1.1). This condition may fall, when the max. expected wall temperature does not exceed the sizing temperature (EN 12953-8, Par 4.1.1)
Isolable superheater a control valve is placed between superheater and steam generator	The superheater must have an additional safety valve at the outlet, whose release capacity must be at least 25 % of the whole capacity of the boiler (EN 12953-8, Par 4.1.1).

Table 7.8.1-2: Position of the safety valve for the protection of the vessels in a shell boiler as well as the particular requirements for steam generators and hot water generators

For **steam generator shell boilers** the certified steam capacity of the safety valves must exceed the allowable steam production. The calculation of the steam capacity of the safety valve for the steam conditions, for which no certified steam capacity is available, must comply with ISO 4126-7 and it must exceed the allowable steam production (EN 12953-8, Par 4.2.1).

In **hot water generator shell boilers,** the safety valve must be sized under the assumption of saturated steam flows at relieving conditions. In alternative (EN 12953-8, Par 4.2.2) the safety valves for oil- or gas-fired hot water generators may be sized for the maximum possible volumetric

[18] Shell boilers – Part 8: Requirements for safeguard against excessive pressure, 2002.

expansion of water and for the water feed coming from the feeder at the allowable operating pressure in case that respectively two pressure and two temperature limiters reduce or shut down the firing, when the respective thresholds are exceeded.

Set pressure selection of multiple safety valves: For the protection of boilers with more than one safety valve LESER's experience shows that the set pressures of the safety valves are not always the same but a slightly different, indicatively either 1 bar for set pressures above 30 bar-g or 3 % otherwise, is usually considered. By doing so, the safety valve with the lower set pressure protects the other safety valves by releasing a part of the mass flow rate and mitigate the pressure peaks in the unit. This solution avoids also conflicts among the safety valves like vibrations, pressure shocks etc., which would occur if they open simultaneously.
In the case of communicating steam drum and superheater, the safety valve on the superheater is the one which is set at a slightly lower pressure, so that it opens before the safety valve on the steam drum. The released mass flow rate by wetting the superheater walls prevents their overheating. Otherwise, if the safety valve on the steam drum opens first while the one on the superheater remains closed, no steam flow would pass through the superheater with the consequent overheating of its walls exposed to the hot exhaust gases. In the determination of the set pressures of steam drum and superheater, the frictional pressure losses between the units should be accounted for.

7.8.2 Pressure Side of a Pump

In case of pump blockage the mass flow to the safety valve must be at least the mass flow that would be flowing in the pump at relieving conditions (API 521 and ISO 23251). It is determined from the characteristic curves of the pump manufacturer. The safety valve must be placed on the pressure side of the pump. If the safety valve outlet is connected to the suction side of the pump, the suction pressure must be accounted as back pressure during sizing.

7.8.3 Control Valve Failure

A control valve regulates the flow to a unit or user and it takes normally a partially open position in accordance to the required mass flow rate. The flow rate to the safety valve postulates worst-case malfunction of the control valve, considering it as fully opened when placed before the safety valve or fully closed when located after the safety valve in the output line to the users. The safety valve must be sized for the case of maximum malfunction. For complex lines with more inlets and outlets the determination of the relieving capacity can be determined respectively using either ISO 23251 for input control valves or for output control valves.

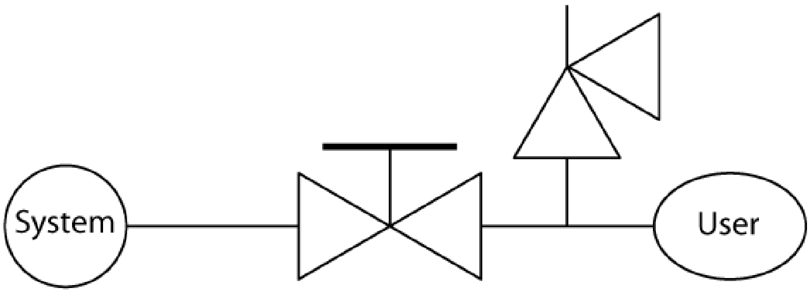


Fig. 7.8.3-1: Example of protection against malfunction of control valve

7.8.4 Pressure Reducing Valve

In pressure reducing stations the safety valve has to be placed downstream the pressure reducing valve. The discharge capacity of the safety valve must exceed that through the pressure reducing device.

7.8.5 Heat Exchanger

From API 521 and ISO 23251 in consequence of rupture steam from the hot pressure tubes may overpressurize equipment. on the low-pressure side.

LESER recommends the installation of the pressure relieving valve on the cold side of a shell-and-tube heat exchanger. The reason is to prevent thermal expansion or even vaporizing of the cold liquid, in the case that it is trapped by a blocked line.

7.8.6 Pressurized Hot Water (T > 100°C)

Beside the ISO 4126-10, our experience proved that the formula in Eq. 7.8.6-1 for pressurized (liquid) water at temperatures above 100°C leads to a reliable estimation of the flow area of the safety valve.

$$A_0 = \left(\frac{0.6211 \frac{\sqrt{p_0 v}}{\psi} \frac{h-h'}{r}}{K_{dD} p_0} + \frac{0.6211 \sqrt{v} \left(1 - \frac{h-h'}{r}\right)}{K_{dL} \sqrt{p_0 - p_a}} \right) \quad (7.8.6\text{-}1)$$

with the following meaning of the symbols

h	Enthalpy of water at operating condition	kj/kg
h’	Enthalpy of water at 99.6°C and 1 bar	417.51 kj/kg
K_{dD}	Derated discharge coefficient Vapor	--
K_{dL}	Derated discharge coefficient Water	--
p_a	Absolurte back pressure	bar
p_0	Absolute relieving pressure	bar
r	Latent heat of evaporation at p_0	kj/kg
v	Specific volume	m^3/kg
ψ	See Table 7.6.2-1 on Page 7.6-2	--

The basic assumption is that a partial evaporation of the liquid will take place in the safety valve.

7.8.7 Indicative Values for Physical Quantities (k, Z, μ, ν)

In case physical properties of gases or liquids are missing, the following values can be used.

Physical property	**Value**	**Comments**
Isentropic coefficient Gas – k	1.0	See API RP 520 (2020) Section 5.6.3.1.1* and Fig. 33
Compressibility factor Gas - Z	1.0	Conservative and adequate, when the relieving pressure is equal or less than – indicatively - 10 times the thermodynamic critical pressure p_{crit} . Values of p_{crit} for most common gases can be found in API RP 520 (2020) Table 10 or in ISO 4126-7 (2020) Table 5. Further references are written in Chapter 10.
Viscosity Liquid – μ, ν	0 mPa s 0 m²/s 0 mm²/s	Optimal case, it would lead to the smallest orifice area, LESER suggests to use this value for liquids with a viscosity assumed to be close to that of water

7.8.8 Undersizing (not less than – 3%)

Since the selected orifice area is typically larger than the required orifice, a larger mass flow than the required one will be released. In this sense the sizing procedures are precautionary in regard of the safety of the protected item. However, an excessive release of product may be unwanted or an oversized valve may cause excessive pressure losses in the inlet or outlet line.
LESER's experience shows that a modest undersizing with a certified mass flow, which does not deviate for more than about 3 % from the required mass flow, can be eventually taken into consideration, given that the actual mass flow rate is around 10 % larger than the certified one and therefore the actual flow rate is still larger than the required one .Nevertheless, if a safety valve is undersized, an approval from the supervising certifying authority, like TÜV in Germany, is required for the individual application.
Alternatively the assumptions for the determination of the required mass flow may be reviewed critically. A more detailed engineering analysis can lead to more precise eventually lower values.

7.8.9 Pressure Loss Considerations

Pressure losses in the inlet and outlet piping of the safety valve depend from the actual mass flow discharged by the selected safety valve and not from the required one, which is based on process requirements. VALVESTAR® calculates the effective pressure loss with the actual discharge from the valve. For calculation of pressure losses see chapter 6, Installation and Plant Design.

7.9 Conversion Between US and Metric Units

In this section the norms are based on following edition:
ASME Section XIII (2021) and API RP 520 (2020)

This section presents some tables to convert from US to metric units and vice versa the physical quantities required by the sizing standards. Source: http://www.onlineconversion.com
In addition to these tables, VALVESTAR® provides the possibility to convert a broad range of units

How to read the tables: the target dimension is written in a vertical column; each cell in a horizontal line contains how much of that quantity equals the target. For example, in Table 7.8.1-1 you need 304.8 mm, 0.3048 m or 12 in to make one foot.

7.9.1 Length

To / From	mm	m	ft	in
mm	1	1000	304.8	25.4
m	0.001	1	0.3048	0.0254
ft	0.00328	3.28	1	0.0833
in	0.03937	39.370	12	1

Table 7.9.1-1: Conversion of lengths

7.9.2 Area

To / From	mm²	in²	m²	ft²
mm²	1	645.16	10^6	92903
in²	0.00155	1	1550.00	144
m²	10^{-6}	$6.4516 \cdot 10^{-4}$	1	0.092903
ft²	$1.0764 \cdot 10^{-5}$	0.00694	10.764	1

Table 7.9.2-1: Conversion of surfaces

7.9.3 Mass

To / From	g	kg	lb	oz
g	1	1000	453.592	28.350
kg	0.001	1	0.453592	0.02835
lb	$2.205 \cdot 10^{-3}$	2.205	1	0.0625
oz	0.035274	35.274	16	1

Table 7.9.3-1: Conversion of masses

7.9.4 Temperature

From \ To	°C	°F	°R	K
°C	-	[°F] = [°C] × ⁹⁄₅ + 32	[°R] = ([°C] + 273.15) × ⁹⁄₅	[K] = [°C] + 273.15
°F	[°C] = ([°F] − 32) x ⁵⁄₉	-	[°R] = [°F] + 459.67	[K] = ([°F] + 459.67) × ⁵⁄₉
°R	[°C] = ([°R] − 491.67) × ⁵⁄₉	[°F] = [°R] − 459.67	-	[K] = [°R] × ⁵⁄₉
K	[°C] = [K] − 273.15	[°F] = [K] × ⁹⁄₅ − 459.67	[°R] = [K] × ⁹⁄₅	-

Table 7.9.4-1: Conversion of temperatures

Temperature examples				
From \ To	°C	°F	°R	K
Absolute zero	-273.15	−459.67	0	0
Freezing point (water) (1.013 bar)	0	32	491.67	273.15
Boiling point (water) (1.013 bar)	99.984	211.971	671.641	373.134

Table 7.9.4-2: Examples for conversion of temperatures

7.9.5 Density

From \ To	kg/m³	g/cm³	lb/ft³	oz/in³	lb/in³
kg/m³	1	1000	16.018	1729.99	27680
g/cm³	0.001	1	0.016018	1.72999	27.680
lb/ft³	0.06243	62.43	1	108	1728
oz/in³	$5.780*10^{-4}$	0.5780	0.00926	1	16
lb/in³	$3.613*10^{-5}$	0.03613	$5.787*10^{-4}$	0.0625	1

Table 7.9.5-1: Conversion of densities

7.9.6 Mass flow

From \ To	kg/s	kg/h	lb/s	lb/h
kg/s	1	$2.778*10^{-4}$	0.454	$1.260*10^{-4}$
kg/h	3600	1	1632.931	0.454
lb/s	2.205	$6.124*10^{-4}$	1	$2.778*10^{-4}$
lb/h	7936.648	2.205	3600	1

Table 7.9.6-1: Conversion of mass flow

7.9.7 Volume Flow – Operating Conditions

From \ To	m³/s	m³/h	l/h	ft³/s	ft³/h	gal US/ min	gal UK/ min	cfm (ft³/min)
m³/s	1	$2.778*10^{-4}$	$2.778*10^{-7}$	0.0283	$7.866*10^{-6}$	$6.309*10^{-5}$	$7.577*10^{-5}$	$4.719*10^{-4}$
m³/h	3600	1	0.001	101.941	0.028317	0.22712	0.27277	1.69901
l/h	$3.6*10^{6}$	1000	1	101941	28.317	227.12	272.77	1699.01
ft³/s	35.315	0.00981	$9.810*10^{-6}$	1	$2.778*10^{-4}$	0.00223	0.00268	0.0167
ft³/h	127132.798	35.315	0.035315	3600	1	8.0208	9.633	60
gal US/ min	15850.323	4.403	0.004403	448.831	0.125	1	1.201	7.481
gal UK/ min	13198.155	3.666	0.003666	373.730	0.104	0.833	1	6.229
cfm	2118.880	0.5886	$5.886*10^{-4}$	60	0.0167	0.134	0.161	1

Table 7.9.7-1: Conversion of volume flow

7.9.8 Volume Flow – Standard Conditions

Operating conditions		Standard conditions	
m³/h	cubic meters per hour	Nm³/h	*Normal* cubic meters per hour = m³/h at standard conditions of temperature and pressure (STP)
cfm	cubic feet per minute	scfm	*Standard* cubic feet per minute = cfm at standard conditions of temperature and pressure (STP).

Table 7.9.8-1: Operating and standard conditions

The standard temperature and pressure (STP) establish a reference to enable cross comparisons between sets of experimental data, for instance gas mass flow rates at different relieving pressures.

When stating that a gas volume or flow is in **Normal Cubic Meters (Nm³)** or **Standard Cubic Feet (scf)** or any other notation (nm, Scf, STP, etc.), the user should state the value of the reference temperature and pressure to which he refers. Not to do so can lead to confusion since there is no universally accepted set of reference conditions.

- In VALVESTAR® the reference conditions are 60°F and 14.7 psi for API RP 520 and ASME Section XIII 15°C and 1 atm for ISO 4126 and AD 2000 A2

However, sizing standards normally refer to mass flow rates in the operating conditions.

7.9.9 Pressure

From \ To	atm	bar	Pa	kPa	MPa	psi (=lb/in²)	torr (=mmHg 0°C)	kg_f/cm^2 (= kgsi)	mmH_2O 4°C
atm	1	0.9869	$9.869*10^{-6}$	$9.869*10^{-3}$	9.869	0.0680	0.00132	0.9678	$9.678*10^{-5}$
bar	1.01325	1	10^{-5}	0.01	10	0.068948	$1.3332*10^{-3}$	0.980665	$9.80665*10^{-5}$
Pa	101325	10^{5}	1	1000	10^{6}	6894.8	133.32	98066.5	9.80665
kPa	101.325	100	0.001	1	1000	6.8948	0.1332	98.0665	$9.80665*10^{-3}$
MPa	0.101325	0.1	10^{-6}	0.001	1	$6.8948*10^{-3}$	$1.3332*10^{-4}$	0.0980665	$9.80665*10^{-6}$
psi	14.696	14.50	$1.450*10^{-4}$	0.145	145.0	1	0.0193	14.22	0.001422
torr (mmHg (0°C))	760.000	750.06	$7.5006*10^{-3}$	7.5006	7500.6	51.715	1	735.56	0.073556
kg_f/cm^2 (= kgsi)	1.0332276	1.0197	$1.01972*10^{-5}$	0.0101972	10.1972	0.070307	0.00136	1	10^{-4}
mmH_2O (4°C)	10332.276	10197	0.101972	101.972	101972	703.07	13.6	10^{4}	1

Table 7.9.9-1: Conversion of pressure

Gauge and absolute pressure
It is common practice in the design of plants to indicate the set pressure in units as *gauge* (unit: bar-g or psig), meaning its deviation from the atmospheric pressure. However, common sizing procedures require the knowledge of the relieving pressure in absolute terms (unit: bar or psi). The relationship between the two of them: is

Absolute pressure = Gauge pressure + Atmospheric pressure (14.7 psi ; 1.013 bar)

7.9.10 Dynamic and Kinematic Viscosity

Dynamic viscosity (Symbol: μ)				Kinematic viscosity (Symbol: v)			
To / From	Pa s	cP = mPa s	P (Poise)		m²/s	cSt = mm²/s	St
Pa s	1	0.001	0.1	m²/s	1	10^{-6}	10^{-4}
cP= mPa s	1000	1	100	cSt = mm²/s	10^{6}	1	100
P (Poise)	10	0.01	1	St	10000	0.01	1
				St	10000	0.01	1

Table 7.9.10-1: Conversion of dynamic and kinematic viscosity

In science there are two types of viscosity: the so-called *dynamic viscosity*, which is what usually people refer to, and *kinematic viscosity,* that is the ratio of dynamic viscosity and density. Indeed, the user, may be confronted with some commonly used technical units for the kinematic viscosity, referenced here as engineering units. The most well known engineering units are the Saybolt Universal Second, Engler Degree and Redwood seconds. Among them the Saybolt Universal Second finds the widest application in petroleum technology and related industries.

Viscosity in Engler Degree (°E, E, E°) is the ratio of the time required by 200 cm³ of the liquid, whose viscosity is being measured, to flow in an capillary viscometer to the time of flow of the same amount of water at the same temperature.

The Saybolt Universal Second (Often SUS or SSU) is the time it takes for 60 cm³ of the liquid under consideration to flow through a calibrated tube at a controlled temperature.

The Redwood Second (R.I.) has an identical definition to that of the SSU, differing only in the quantity of test liquid, which is 50 cm³.
The following table permits a quick conversion between the kinematic viscosity, expressed either in mm²/s or using one of the three engineering units.

Engler Degree [°E]	Saybolt Universal Second [SSU]	Redwood Second [R.I.]	mm²/s
1.119	32.6	30.2	2.0
1.307	39.1	35.3	4.0
1.479	45.5	40.5	6.0
1.651	52.0	46.0	8.0
1.831	58.8	51.7	10.0
2.020	65.9	57.9	12.0
2.220	73.4	64.4	14.0
2.430	81.1	71.1	16.0
2.640	89.2	78.1	18.0
2.870	97.5	85.4	20.0

Table 7.9.10-2:: Comparison of kinematic viscosity and common engineering units for viscosity

As an alternative to the table the following conversion formulas can be employed

[mm²/s] = [SSU] x ¼.55
[mm²/s] = [°E] x 7.45
[mm²/s] = [R.I.] x 0.2469

Table 7.9.10-3:: Conversion of different viscosity units

7.9.11 Energy

From \ To	kJ	BTU_{IT}	BTU_{th}	kWh	$kcal_{IT}$	$kcal_{th}$
kJ	1	1.0551	1.0544	3600	4.187	4.184
BTU_{IT}	0.948	1	0.999	3412.141	3.968	3.966
BTU_{th}	0.948	1.00067	1	3414.425	3.971	3.968
kWh	$2.778*10^{-4}$	$2.931*10^{-4}$	$2.929*10^{-4}$	1	0.00116	0.00116
$kcal_{IT}$	0.239	0.252	0.252	859.845	1	0.999
$kcal_{th}$	0.239	0.252	0.252	860.421	1.001	1

Table 7.9.11-1: Conversion of energy units

The British Thermal Unit or BTU (calorie) is the amount of heat required to raise the temperature of one pound (one kg) of water by 1°F (1°C) at one atmosphere. Several definitions of the BTU and of the calorie exist due to the different boiling water temperatures of reference. In the table the BTU_{IT} ($kcal_{IT}$) adopts the definition in the International [Steam] Table[19] (IT), while the BTU_{th} ($kcal_{th}$) represents the common "thermo chemical value".

7.9.12 Specific Energy

From \ To	kJ/kg	BTU_{IT}/lb	BTU_{th}/lb
kJ/kg	1	2.330	2.324
BTU_{IT}/lb	0.430	1	0.999
BTU_{th}/lb	0.430	1.00067	1

Table 7.9.12-1: Conversion of specific energy

7.9.13 Specific Heat

From \ To	kJ/(kg K)	BTU_{IT}/(lb °R)	BTU_{th}/(lb °R)
kJ/(kg K)	1	1.292	1.291
BTU_{IT}/(lb °R)	0.774	1	0.999
BTU_{th}/(lb °R)	0.774	1.00067	1

Table 7.9.13-1: Conversion of specific heat

[19] W. Wagner , H. Kretzschmar Ed., *International steam tables: Properties of water and steam based on the industrial formulation IAPWS-IF97,* Springer, Berlin, 2008

7.10 Physical Property Databases

In this section the norms are based on following edition:
ASME Section XIII (2021) and API RP 520 (2020), EN 13136 (2013), ISO 4126-7 (2016)

In this chapter references are given for the data present in VALVESTAR for gases and liquids as well as additional sources, if some of the readers wish to collect more data about some specific media.

7.10.1 Physical Properties of Gases

The properties for the gases are extracted from ISO 4126-7, API RP 520, EN 13136, the NIST Chemistry WebBook (http://WebBook.nist.gov/chemistry) and for cryogenics also from Medard, L. *Gas Encyclopaedia*, Air Liquide/Elsevier Science Publishing, 1976 (encyclopedia.airliquide.com).

7.10.2 Physical Properties of Liquids

The density of the liquids are extracted from ISO 4126-7, API RP 520, EN 13136, the NIST Chemistry WebBook and the *CRC Handbook of Chemistry and Physics*, D.R. Lide Editor, 85th Edition, CRC Press, 2004.

7.10.3 Additional Literature Sources

[1)] Wang, B.H.; Adcock, J.L.; Mathur, S.B.; Van Hook, W.A., *Vapor pressures, liquid molar volumes, vapor non-idealities, and critical properties of some fluorinated ethers: CF3OCF2OCF3, CF3OCF2CF2H, c-CF2CF2 CF2O, CF3OCF2H, and CF3OCH3; and of CCl3F and CF2CI*, J. Chem. Thermodyn., 1991, 23, 699-710.

[2)] Altunin, V.V.; Geller, V.Z.; Kremenvskaya, E.A.; Perel'shtein, I.I.; Petrov, E.K., Thermophysical Properties of Freons, Methane Ser. Part 2, Vol. 9, NSRDS-USSR, Selover, T. B., Ed., Hemisphere, New York, 1987.

[3)] Krauss, R.; Stephan, K., *Thermal Conductivity of Refrigerants in a Wide Range of Temperature and Pressure*, J. Phys. Chem. Ref. Data, 1989, 18, 43.

[4)] Weber, L.A., Simple Apparatus for Vapor-Liquid Equilibrium Measurements with Data for the Binary Systems of Carbon Dioxide with n-Butane and Isobutane, J. Chem. Eng. Data, 1989, 34, 171.

[5)] Higashi, Y.; Uematsu, M.; Watanabe, K., *Measurements of the Vapor-liquid Coexistence Curve and Determination of the Critical Parameters for Refrigerant 13B1*, Bull. JSME, 1985, 28, 2660-6.

[6)] Ohgaki, K.; Umezono, S.; Katayama, T., *Pressure-density-temperature (p-ρ-T) relations of fluoroform, nitrous oxide, and propene in the critical region*, J. Supercrit. Fluids, 1990, 3, 78-84.

[7)] Hori, K.; Okazaki, S.; Uematsu, M.; Watanabe, K., *An Experimental Study of Thermodynamic Properties of Trifluoromethane* in Proc. Symp. Thermophys. Prop., 8th, 1981, Gaithersburg, Vol. II, Sengers, J. V., Ed., ASME: New York, p. 370-6, 1982.

[8)] Garcia-Sanchez, F.; Romero-Martinez, A.; Trejo Rodriguez, A., *Vapour Pressure, Critical Temperature, and Critical Pressure of Dichloro- methane*, J. Chem. Thermodyn., 1989, 21, 823-6.

[9)] Shi, L.; Zhu, M.; Han, L.; Duan, Y.; Sun, L.; Fu, Y.-D., *Thermophysical Properties of Difluoromethane (HFC-32)*, Science in China, Ser. E, 1998, 41, 435-42.

[10)] Mastroianni, M.J.; Stahl, R.F.; Sheldon, P.N., *Phys. and Thermo. Prop. of 1,1,2-Trrifluorotrichloromethane (R-113) 113)*, J. Chem. Eng. Data, 1978, 23, 113-118.

[11)] Yada, N.; Uematsu, M.; Watanabe, K., *Measurements of the vapor pressure and PVT properties for refrigerant 115*, Nippon Kikai Gakkai Ronbunshu, B-hen, 1989, 55, 2426.

[12)] Mears, W.H.; Rosenthal.E.; Sinka, J.V., *Pressure-Volume-Temperature Behavior of Pentafluoromonochlorethane*, J. Chem. Eng. Data, 1966, 11, 338.

[13)] Fukushima, M.; Watanabe, N.; Kamimura, T., *Measurements of the PVT properties of HCFC123 and HFC134a*, Nippon Reito Kyokai Ronbunshu, 1990, 7, 243-56.

[14)] Yamashita, T.; Kubota, H.; Tanaka, Y.; Makita, T.; Kashiwagi, H., *Physical properties of new halogenated hydrocarbons*, Proc. Symp. Thermophys. Prop. 10th, 1989,, 1989, p 75-8.

[15)] Fukushima, M.; Watanabe, N., *Thermodynamic properties of HCFC-124*, Nippon Reito Kyokai Ronbunshu, 1993, 10, 75-86.

[16)] Higashi, Y., Critical parameters for HFC134a, HFC32 and HFC125, Int. J. Refrig., 1994, 17, 524-531.

[17)] Wilson, L.C.; Wilding, W.V.; Wilson, G.M.; Rowley, R.L.; Felix, V.M.; Chisolm-Carter, T., *Thermophysical properties of HFC-125*, Fluid Phase Equilib., 1992, 80, 167-77.

[18)] Duarte-Garza, H.A.; Hwang, C.-A.; Kellerman, S.A.; Miller, R.C.; Hall, K.R.; Holste, J.C.; Marsh, K.N.; Gammon, B.E., *Vapor pressure, vapor density, and liquid density for 1,1-dichloro-1- fluoroethane(R-141b)*, J. Chem. Eng. Data, 1997, 42, 497-501.

[19)] Sako, T.; Sato, M.; Nakazawa, N.; Oowa, M.; Yasumoto, M.; Ito, H.; Yamashita, S., *Critical Properties of Fluorinated Ethers*, J. Chem. Eng. Data, 1996, 41, 802-805.

[20)] Fukushima, M.; Watanabe, N., *Thermodynamic properties of HCFC-142b (1-chloro-1,1-difluoroethane)*, Nippon Reito Kyokai Ronbunshu, 1992, 9, 247-55.

[21)] Fujiwara, K.; Nakamura, S.; Noguchi, M., *Critical Parameters and Vapor Pressure Measurements for 1,1,1-Trifluoroethane (R-143a)*, J. Chem. Eng. Data, 1998, 43, 55-9.

[22)] Fukushima, M., Measurements of vapor pressure , vapor-liquid coexistence curve and critical parameters of HFC-143a, Nippon Reito Kyokai Ronbunshu, 1993, 10, 87-93.

[23)] Fransson, E.; Barreau, A.; Vidal, J., *Vapor-liquid equilibrium in binary systems of n-pentane + chlorodifluoromethane or + 1,1-difluoroethane*, J. Chem. Eng. Data, 1992, 37, 521-5.

[24)] Tamatsu, T.; Sato, T.; Sato, H.; Watanabe, K., *An experimental study of the thermodynamic properties of 1,1-difluoroethane*, Int. J. Thermophys., 1992, 13, 985-97.

[25)] Berthoud, A., Determination of Critical Temperatures and Pressures of Amines and Alkyl Chlorides, J. Chim. Phys. Phys.-Chim. Biol., 1917, 15, 3.

[26)] Leu, A.D.; Robinson, D.B., *High-pressure vapor-liquid equilibrium phase properties of the octafluoropropane (K-218)-chlorodifluoromethane (Freon-22) binary system*, J. Chem. Eng. Data, 1992, 37, 7-10.

[27)] Young, S., The Internal Heat of Vaporization constants of thirty pure substances, Sci. Proc. R. Dublin Soc., 1910, 12, 374.

[28)] Sato, H.; Watanabe, K.; Levelt Sengers, J.M.H.; Gallagher, J.S.; Hill, P.G.; Straub, J.; Wagner, W., *Sixteen Thousand Evaluated Experimental Thermodynamic Property Data for Water and Steam*, J. Phys. Chem. Ref. Data, 1991, 20, 1023.

[29)] Morita, T.; Sato, H.; Uematsu, M.; Watanabe, K., *PVT Properties and Vapor-Pressures of Ordinary Water Substance in the Critical Region*, Physica A: (Amsterdam), 1989, 156, 436.

[30)] Lide, D.R.: *CRC Handbook of Chemistry & Physics* 85th Edition, CRC Press, 2004