Instructions to Voters/Comments on API 520 Part I Ballot 2 – "Effective Kd for two-phase flow"

BALLOT 2 FOR ACTION ITEM AI-2019-18

1. Your comments should be limited to the **red-line-portions of the ballot only.**
2. This ballot revisits the recommended effective coefficients for two-phase flow provide in Annex C. The new recommendation matches the work recommended by Professor Ron Darby.
3. This ballot addresses 520 Action Item 2019-18.
4. If you are voting negative, please indicate which of your comment or comments are the reason for your negative vote. API's Balloting system will categorize all of your comments as Negative.

Phil Henry

API 520 Task Force Chair

Annex C

(informative)

Sizing for Two-phase Liquid/Vapor Relief

C.1 Sizing for Two-phase Liquid/Vapor Relief

C.1.1 General

The methods for two-phase sizing, presented in this annex, are among several techniques currently in use and newer methods are continuing to evolve as time goes on. It is recommended that the particular method to be used for a two-phase application be fully understood. Note that the methods presented in this annex have not been validated by test, nor is there any recognized procedure for certifying the capacity of PRVs in two-phase flow service.

C.1.2 Application of Equations

C.1.2.1 Many different scenarios are possible under the general category of two-phase liquid/vapor relief. In all of these scenarios either a two-phase mixture enters the PRV or a two-phase mixture is produced as the fluid moves through the valve. As required in 5.11, vapor generation as a result of flashing shall be taken into account, since it may reduce the mass flow capacity of the valve. The methods presented in C.2.1 through C.2.3 can be used for sizing PRVs in two-phase liquid/vapor scenarios. In addition, C.2.1 can be used for supercritical fluids in condensing two-phase flow. Use Table C.1 to determine which section to consult for a particular two-phase relief scenario.

Table C.1—Two-phase Liquid/Vapor Relief Scenarios for Pressure-relief Valves

Two-phase Liquid/Vapor Relief Scenario	Example	Section
Two-phase system (liquid vapor mixtures, including saturated liquid) enters PRV and flashes. No noncondensable [a] gas present. Also includes fluids both above and below the thermodynamic critical point in condensing two-phase flow.	Saturated liquid/vapor propane system enters PRV and the liquid propane flashes.	C.2.1 or C.2.2
Two-phase system (highly subcooled [b] liquid and either noncondensable gas, condensable vapor, or both) enters PRV and does not flash.	Highly subcooled propane and nitrogen enters PRV and the propane does not flash.	C.2.1 or C.2.2
Two-phase system (the vapor at the inlet contains some noncondensable gas and the liquid is either saturated or subcooled) enters PRV and flashes. Noncondensable gas enters PRV.	Saturated liquid/vapor propane system and nitrogen enters PRV and the liquid propane flashes.	C.2.1 or C.2.2
Subcooled liquid (including saturated liquid) enters PRV and flashes. No condensable vapor or noncondensable gas enters PRV.	Subcooled propane enters PRV and flashes.	C.2.1 or C.2.3

[a] A noncondensable gas is a gas that is not easily condensed under normal process conditions. Common noncondensable gases include air, oxygen, nitrogen, hydrogen, carbon dioxide, carbon monoxide, and hydrogen sulfide.

[b] The term “highly subcooled” is used to reinforce that the liquid does not flash passing through the PRV.

C.1.2.2 The equations presented in C.2.1 are based on the Homogeneous Equilibrium Model (HEM) [7], which assumes the fluid mixture behaves as a “pseudo single phase fluid,” with a density that is the volume averaged density of the two phases. This method is based on the assumption that thermal and mechanical equilibrium exist as the two-phase fluid passes through the PRV (other specific assumptions or limitations are presented in the appropriate section). For discharges of two-phase mixtures in nozzles longer than approximately 4 inches [6] with light ends that flash, both thermal and mechanical equilibrium is usually assumed. These assumptions correspond to the HEM.

C.1.2.3 Non-equilibrium effects have been studied by DIERS and are documented in the open literature [10],[20]. Rapid depressuring of two-phase fluids with low quality (vapor mass percentage ≲5%), in addition to subcooled and saturated liquids that flash, may result in nonequilibrium flow [10],[20]. High-pressures, near the thermodynamic critical pressure, in addition to nozzle geometry and other factors, could result in non-equilibrium flow due to the contribution of increased flow acceleration leading to additional pressure drop in nozzles and piping. The user is cautioned that modeling nonequilibrium flow using HEM in these limited circumstances could underpredict the mass flux (therefore, overpredict the PRD required area) due to rapid vaporization effects assumed in the application of HEM.

C.1.2.4 In applications where the homogeneous equilibrium assumption is not valid, the user is encouraged to apply non-equilibrium methods. The Burnell bubble delay factor, if used, can remove some of the conservatism associated with the homogeneous equilibrium assumption [19]. Additional details on non-equilibrium flow and the degree of depressurization in saturated and subcooled liquids flowing through nozzles are available [10] [20].

C.1.2.5 The equations presented in C.2.2 through C.2.3 are based on the Leung Omega Method [13], which is a version of the HEM. In the procedures presented in C.2.2 through C.2.3, the omega parameter is calculated based on specific volume data obtained from a flash calculation. This is often referred to as a two-point method since fluid properties are determined at the inlet relieving conditions and at flashed conditions at a lower pressure. The omega parameter itself is a correlation between the density of the two-phase fluid and the pressure, using the following relationship:

$$\omega = \frac{\frac{\rho_1}{\rho_x} - 1}{\frac{P_1}{P_x} - 1} = \frac{\frac{v_x}{v_1} - 1}{\frac{P_1}{P_x} - 1} \tag{C.1}$$

where

P is the pressure from the flash calculation (absolute);

ρ is the overall two-phase density from the flash calculation;

v is the overall two-phase specific volume from the flash calculation;

1 represents the initial condition (e.g. PRV inlet condition) for the flash;

x represents the flash result at one lower pressure.

C.1.2.6 In most cases, a flash pressure at 90 % of the initial pressure provides a reasonable correlation parameter; however, lower flash pressures may be more appropriate under some conditions (e.g. near the thermodynamic critical point [13]). In some instances, it is possible to estimate the omega parameter using only the fluid properties at the relieving conditions (one-point method) [14]. Based on the assumptions used to develop the one-point omega parameter estimation technique, the use of this technique is generally not valid for any of the following situations:

- the nominal boiling range for a multicomponent system is greater than 150 °F (the nominal boiling range is the difference in atmospheric boiling points of the lightest and heaviest components in the system);
- the fluid is close to its thermodynamic critical point ($T_r \geq 0.9$ or $P_r \geq 0.5$);
- the solubility of a noncondensable gas, if present, in the liquid is appreciable;
- the composition of a multicomponent system contains more than 0.1 weight percent hydrogen;
- the gas fraction of a multicomponent system with noncondensable gas is low.

$$\left(\frac{P_{\mathrm{v1}}}{P_1} \geq 0.9 \text{ or } \frac{P_{\mathrm{g1}}}{P_1} \leq 0.1 \right)$$

where

T_{r} is the reduced temperature at the PRV inlet;

P_{r} is the reduced pressure at the PRV inlet;

T_1 is the temperature at the PRV inlet (°R);

P_1 is the pressure at the PRV inlet (psia); this is the PRV set pressure (psig) plus the allowable overpressure (psi) plus atmospheric pressure;

P_{v1} is the saturation (vapor) pressure corresponding to the inlet relieving temperature T_1 (psia); for a multicomponent system, use the bubble point pressure corresponding to T_1;

P_{g1} is the noncondensable gas partial pressure at the PRV inlet (psia).

C.1.2.7 If any of these situations apply, the methods presented in sections C.2.1 through C.2.3 should be used.

C.1.2.8 A more rigorous approach using a fluid property database or vapor/liquid equilibrium thermodynamic models incorporated into analytical or numerical methods based on HEM can be considered. See C.2.1 for more information.

C.1.3 Saturated Water Capacity for ASME Certified Safety Valves

For information about saturated water, see ASME *BPVC*, Section VIII, Appendix 11.

C.1.4 Effective Coefficient of Discharge

The value for the effective coefficient of discharge for two-phase flow is a subject of current debate [7, 9, 10] and is not likely to be resolved without actual testing of PRV behavior with two-phase fluids. Current guidance diverges from the ~~historic~~ past usage of 0.85 and adopts the practice to use ~~is to use~~ the PRV's vapor coefficient ~~of 0.975~~ if the expansion behavior of the two-phase fluid (including saturated or sub-cooled liquid) ~~chokes~~ results in choking across the orifice and use the liquid coefficient ~~of 0.65~~ if the ~~flow~~ expansion behavior does not result in choking across the orifice ~~is not choked~~ [6, 8]. See 5.2 for discussion on when to use effective versus certified coefficients of discharge.

For cases where the fluid is slightly subcooled and chokes across the orifice at the critical pressure, this approach creates a discontinuity in the predicted device capacity upon switching the two discharge coefficients. At the choke point, good experimental data is difficult to obtain and there can be significant uncertainty in the vapor/liquid calculations. Other methods for determining the coefficient of discharge near the choke point, such as using a volume-weighted average of the liquid and vapor coefficients may be used to account for the fluid's behavior [8].

Using the PRV's vapor coefficient for critical flow is a reasonable prediction, since for choked flow, the valve capacity for a full-lift device is determined only by flow in the nozzle and is independent of the flow conditions downstream of the nozzle ~~in the valve body~~. In non-choked vapor (sub-critical) or liquid flows, the flow ~~in~~ through the valve body has a significant impact on the valve capacity [8].

As a result, this recommendation regarding an estimate of the effective coefficient of discharge and determining whether the flow is choked has been provided within the guidance on sizing methods; see C.2.1, C.2.2, and C.2.3.

C.2 Sizing Methods

C.2.1 Sizing by Direct Integration of the Isentropic Nozzle Flow

C.2.1.1 General

C.2.1.1.1 The inlet nozzle of a relief device is commonly assumed to be the limiting flow element of a fully opened relief device and thus provides the model on which to determine the flow capacity of that relief device. To determine the maximum mass flux through a converging nozzle, the nozzle is assumed to be adiabatic and reversible (both constraints are needed for the isentropic assumption), a common assumption that has been borne through various experimental evidence for well-formed nozzles. The general energy balance for isentropic nozzle flow forms the basis for the mass flux calculation, as shown in Equation (C.2) and Equation (C.3).

In USC units:

$$G^2 = \left[\frac{-2 \times \int_{P_1}^{P} 4633 \times v \times dP}{v_\mathrm{t}^2} \right]_{\max} = \left[\left(\rho_\mathrm{t}^2 \right) \times \left(-2 \times \int_{P_1}^{P} \frac{4633 \times dP}{\rho} \right) \right]_{\max} \tag{C.2}$$

In SI units:

$$G^2 = \left[\frac{-2 \times \int_{P_1}^{P} v \times dP}{v_\mathrm{t}^2} \right]_{\max} = \left[\left(\rho_\mathrm{t}^2 \right) \times \left(-2 \times \int_{P_1}^{P} \frac{dP}{\rho} \right) \right]_{\max} \tag{C.3}$$

where

$\max$ represents the maximization of this calculation, which accounts for potential choking of the fluid;

G is the mass flux, lb/s·ft^2 (kg/s·m^2);

v is the specific volume of the fluid, ft^3/lb (m^3/kg);

ρ is the mass density of the fluid, lb/ft^3 (kg/m^3);

P is the stagnation pressure of the fluid, psia (Pa);

1 represents conditions at the inlet to the nozzle;

t represents the conditions at the throat of the nozzle where the cross-sectional area is minimized.

C.2.1.1.2 It is important to note that this energy balance is irrespective of the nonideality or compressibility of the fluid. As a result, this equation forms the basis for the two-phase flow calculations in the HEM employed in PRV calculations.

C.2.1.1.3 With the generic nozzle flow equation, the density of the fluid at various stagnation pressures from the inlet of the nozzle to the throat of the nozzle is needed. Given these values, the numerical integration calculation can be performed to determine the maximum mass flux through the nozzle. Using a suitable physical property database or an appropriate thermodynamic model, one can generate the values for the density at various pressures by starting with the fluid at the inlet stagnation conditions to determine the inlet stagnation entropy, S_1, and then performing successive isentropic flashes at lower pressures (P, S_1). The path followed for the fluid over this range is normally assumed to be isentropic; however, an isenthalpic path may be acceptable for many conditions (specifically, for low-quality mixtures that are far from the thermodynamic critical point). The pressure and density data points are generated for successively lower pressures until either the mass flux correlation reaches a maximum (representing choked conditions) or the actual backpressure on the nozzle is reached, whichever occurs first. It is at this point that the pressure at the minimal cross-sectional area at the nozzle (the throat pressure) is taken. For a known throat pressure, P_t, the energy balance can be written as shown in Equation (C.4) and Equation (C.5).

In USC units:

$$G^2 = \left(\rho_t^2\right) \times \left(-9266.1 \times \int_{P_1}^{P_t} \frac{dP}{\rho}\right) \tag{C.4}$$

In SI units:

$$G^2 = \left(\rho_t^2\right) \times \left(-2 \times \int_{P_1}^{P_t} \frac{dP}{\rho}\right) \tag{C.5}$$

C.2.1.1.4 The integral can be readily evaluated numerically for any fluid by direct summation over small pressure intervals.

$$\int_{P_1}^{P_t} \frac{dP}{\rho} \approx \sum_{i=1}^{t} 2 \times \left(\frac{P_{i+1} - P_i}{\rho_{i+1} + \rho_i}\right) \tag{C.6}$$

where

G is the mass flux, lb/s·ft^2 (kg/s·m^2);

v is the specific volume of the fluid, ft^3/lb (m^3/kg);

P is the stagnation pressure of the fluid, psia (Pa);

1 represents conditions at the inlet to the nozzle;

t represents the conditions at the throat of the nozzle where the cross-sectional area is minimized;

ρ is the overall mass density of the fluid, lb/ft^3 (kg/m^3).

C.2.1.1.5 The overall mass density for a mixture in thermal and mechanical equilibrium can be calculated based on the density of each phase and the volume fraction of the vapor phase in the mixture.

$$\rho = \left(\alpha \times \rho_{\mathrm{v}}\right) + \left(1 - \alpha\right)\rho_{\mathrm{l}} \tag{C.7}$$

where

ρ is the density of the two-phase mixture, lb/ft^3 (kg/m^3);

ρ_{v} is the density of the vapor, lb/ft^3 (kg/m^3);

ρ_{l} is the density of the liquid, lb/ft^3 (kg/m^3);

α is the volume fraction of vapor phase in the mixture.

C.2.1.1.6 The volume fraction of the vapor phase in the mixture is related to the mass quality of the mixture (mass fraction of the vapor phase) by the following.

$$\frac{\alpha}{1-\alpha} = \frac{x}{1-x} \times \frac{\rho_{\mathrm{l}}}{\rho_{\mathrm{v}}} \tag{C.8}$$

C.2.1.1.7 Once the value for the mass flux has been determined, the required orifice area can be calculated using Equation (C.9) or Equation (C.10).

In USC units:

$$A = \frac{0.04W}{K_d K_b K_c K_v G} \tag{C.9}$$

In SI units:

$$A = \frac{277.8\ x\ W}{K_d K_b K_c K_v G} \tag{C.10}$$

where

A is the required discharge area, in.^{2} (mm^2);

W is the required mass flow rate, lb/h (kg/h);

K_{d} is the coefficient of discharge; for a sizing estimation, an effective coefficient of discharge of 0.975 can be used if the flow is choked (critical) ~~for a two-phase mixture that chokes~~ across the orifice . A value of 0.65 can be used for unchoked (subcritical) flow ~~When the two-phase mixture does not choke across the orifice, a coefficient of discharge equal to 0.65 can be used~~, see C.1.4. This is consistent with the single-phase method in Equation (33) and Equation (34). ~~Note that a value of 0.65 may result in a conservative valve size for liquids that are only slightly subcooled. The user may select other methods for determining a coefficient of discharge [8, 9, 10];~~

K_{b} is the backpressure correction factor for vapor that should be obtained from the valve manufacturer; for~~ a~~ preliminary sizing estimation, use Figure 31. The backpressure correction factor applies to balanced-bellows valves only;

K_c is the combination correction factor for installations with a rupture disk upstream of the PRV (see 5.12.2);

- the combination correction factor is 1.0, when a rupture disk is not installed;
- the combination correction factor is 0.9, when a rupture disk is installed in combination with a PRV and the combination does not have a certified value;

K_v is the viscosity correction factor; for two-phase flows where the liquid has a viscosity of 100 cP (0.1 Pa-s) or less, the viscosity correction factor can be set to 1.0;

G is the mass flux, lb/s·ft^2 (kg/s·m^2).

C.2.1.2 Example

C.2.1.2.1 In this example, the following data are given.

- Required two-phase flow rate caused by an operational upset of 300,000 lb/h (136,000 kg/h); the relief fluid is from a hydro-desulfurization vessel and contains a significant amount of hydrogen at a high pressure.
- Temperature at the PRV inlet of 80.4 °F (26.9 °C).
- PRV set at 1958 psi (13,500 kPag), the design pressure of the equipment.
- Downstream total backpressure of 29 psig (200 kPag) (superimposed backpressure = 0 psig, built-up backpressure = 29 psi).
- Allowable overpressure (accumulation) of 10 %.

C.2.1.2.2 A viscosity correction factor, K_v, of 1.0 is assumed.n this example, the following values are calculated.

- Relieving pressure of 1.10 × 1958 = 2153.8 psig (14,850 kPag).
- Percent of gauge backpressure = (29/1958) × 100 = 1.5 %; thus, the backpressure correction factor K_b = 1.0 (from Figure 31).

C.2.1.2.3 The following is a step-by-step procedure.

a) Step 1—Evaluate the stagnation entropy, S_1. Given the relief fluid composition, relief pressure, and relief temperature, the inlet stagnation entropy was determined by a thermodynamic engine to be –8.178 Btu/lb-mol-°R. Note that the entropy reference state may be different for various thermodynamic engines; therefore, this value may not be the same value obtained from other thermodynamic engines. As long as the same thermodynamic engine and models are used, the reference state is consistent and the flash calculations will be appropriate.

b) Step 2—Perform successive isentropic flashes to generate fluid properties and numerically evaluate nozzle flow integral. Without a known throat pressure, a number of successive isentropic flashes were performed to generate the fluid properties. A step size of 4 % of the absolute relief pressure was arbitrarily chosen to generate the flash pressures. Note that the smaller the step size, the closer the summation will be to the actual integration. With the fluid properties obtained from the isentropic flashes, Equation (C.6) was used to numerically evaluate the nozzle flow integral. The isentropic flashes were performed until the mass flux reached a maximum value. Results are presented in Table C.2.

Table C.1—Results for Direct Integration Example C.2.1.2

Pressure psia (Pa)	**Temperature** °F (K)	**Mass Quality**	**Density** lb/ft^3 (kg/m^3)	**Integrand** ft^2/s^2 (m^2/s^2)	**Summation** ft^2/s^2 (m^2/s^2)	**Mass Flux** lb/s-ft^2 (kg/s-m^2)
2168.5 (14,951,325)	80.3 (300.0)	1.000	5.18 (83.04)	0 (0)	0 (0)	0.0 (0.0)
2081.8 (14,353,272)	75.0 (297.0)	1.000	5.05 (80.88)	–78,546 (–7297.2)	–78,546 (–7297.2)	2001.1 (9770.4)
1995.0 (13,755,219)	69.4 (293.9)	1.000	4.91 (78.67)	–80,696 (–7496.9)	–159,243 (–14,794.1)	2771.6 (13,532.1)
1908.3 (13,157,166)	63.6 (290.7)	1.000	4.77 (76.41)	–83,019 (–7712.7)	–242,261 (–22,506.8)	3320.5 (16,212.3)
1821.5 (12,559,113)	57.6 (287.4)	1.000	4.63 (74.11)	–85,535 (–7946.4)	–327,796 (–30,453.2)	3745.9 (18,289.1)
1734.8 (11,961,060)	52.6 (284.6)	0.995	4.46 (71.46)	–88,443 (–8216.6)	–416,239 (–38,669.9)	4070.5 (19,874.2)
1648.1 (11,363,007)	48.2 (282.1)	0.988	4.28 (68.63)	–91,899 (–8537.7)	–508,138 (–47,207.6)	4319.4 (21,089.0)
1561.3 (10,764,954)	43.5 (279.5)	0.982	4.11 (65.76)	–95,801 (–8900.2)	–603,939 (–56,107.7)	4511.7 (22,027.9)
1474.6 (10,166,901)	38.6 (276.8)	0.975	3.92 (62.84)	–100,120 (–9301.5)	–704,059 (–65,409.2)	4654.8 (22,726.8)
1387.8 (9,568,848)	33.5 (274.0)	0.969	3.74 (59.86)	–104,930 (–9748.3)	–808,989 (–75,157.5)	4753.7 (23,209.5)
1301.1 (8,970,795)	28.1 (271.0)	0.963	3.55 (56.84)	–110,319 (–10,249.0)	–919,307 (–85,406.5)	4811.6 (23,492.3)
1214.4 (8,372,742)	22.5 (267.9)	0.958	3.36 (53.77)	–116,401 (–10,814.0)	–1,035,709 (–96,220.5)	4830.8 (23,585.8)
1127.6 (7,774,689)	16.5 (264.6)	0.952	3.16 (50.63)	–123,323 (–11,457.1)	–1,159,032 (–107,677.6)	4812.6 (23,497.1)
1040.9 (7,176,636)	10.2 (261.1)	0.946	2.96 (47.44)	–131,274 (–12,195.8)	–1,290,306 (–119,873.4)	4757.8 (23,229.5)

c) Step 3—Find the maximum mass flux. The mass flux is maximized at a throat pressure of 1214.4 psia (8.373 kPa) for a value of 4830.8 lb/s-ft^2 (23,586 kg/s-m^2). This throat pressure is greater than the total backpressure indicated above; therefore, the flow is critical (choked) through the nozzle.

d) Step 4—Calculate the required orifice area. As the flow of this two-phase fluid is critical (choked), an effective coefficient of discharge of 0.975 can be used. The required area A of the PRV is calculated from Equation (C.9) as follows:

$$A = \frac{0.04x300{,}000}{0.975x1.0x1.0x1.0x4830.8} = 2.548\ in.^2 \qquad \text{(C.11)}$$

e) Step 5—Select an L orifice PRV (2.853 in.^{2}).

C.2.2 Sizing for Two-phase Flashing or Nonflashing Flow Using the Omega Method

C.2.2.1 General

The method presented in this section can be used for sizing PRVs handling either flashing or nonflashing flow. These methods are also appropriate for fluids both above and below the thermodynamic critical point in condensing two-phase flow. Finally, the methods presented in this section can be used for liquids that are saturated as they enter the relief device.

Note that for saturated liquids, the methods presented in C.2.3 are equivalent to the methods presented in C.2.2.

In all cases, the omega parameter is determined using the specific volume data obtained using fluid property data or flash calculations for a mixture at the stagnation conditions and one additional pressure (two-point method). The following procedure can be used.

a) Step 1—Calculate the omega parameter, ω. To calculate the omega parameter using two pressure specific volume data points, use Equation (C.12).

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

where

ω is the omega parameter;

v_9 is the specific volume evaluated at 90 % of the PRV inlet pressure, P_1 in ft^3/lb (m^3/kg); when determining v_9, the flash calculation should be carried out isentropically, but an isenthalpic (adiabatic) flash is sufficient for low-quality mixtures far from the thermodynamic critical point;

v_1 is the specific volume of the two-phase system at the PRV inlet, ft^3/lb (m^3/kg).

b) Step 2—Determine if the flow is critical or subcritical:

$$P_{cf} = \eta_c P_1 \qquad \text{(C.10)}$$

$P_{cf} \geq P_2 \Rightarrow$ critical flow

$P_{cf} < P_2 \Rightarrow$ subcritical flow

where

P_{cf} is the critical pressure, psia (Pa);

P_1 is the pressure at the PRV inlet (psia or Pa); this is the PRV set pressure (psig or Pag) plus the allowable overpressure (psi or Pa) plus atmospheric pressure;

P_2 is the downstream backpressure (psia or Pa);

η_c is the critical pressure ratio from Figure C.1.

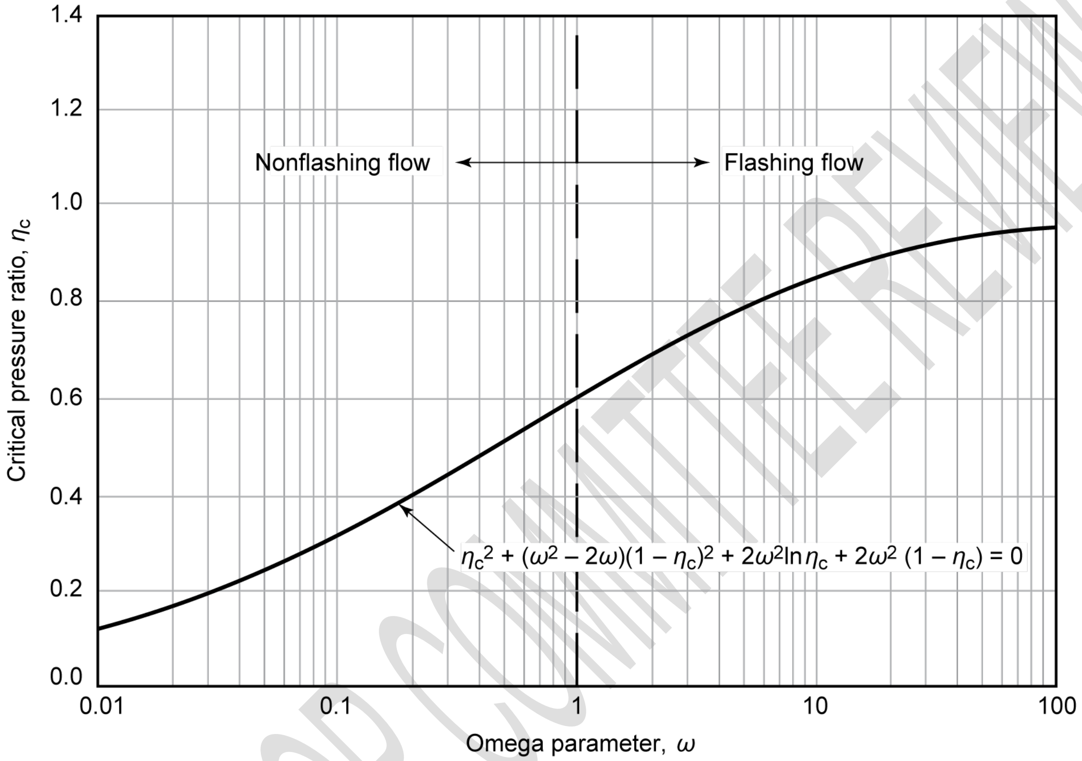

Figure C.1—Correlation for Nozzle Critical Flow of Flashing and Nonflashing Systems

NOTE This ratio can also be obtained from the following expression:

$$\eta_c^2 + \left(\omega^2 - 2\omega\right)\left(1 - \eta_c\right)^2 + 2\omega^2 \ln \eta_c + 2\omega^2\left(1 - \eta_c\right) = 0 \tag{C.11}$$

or from the following approximation:

$$\eta_c = \left[1 + \left(1.0446 - 0.0093431 \times \omega^{0.5}\right) \times \omega^{-0.56261}\right]^{\left(-0.70356 + 0.014685 \times \ln \omega\right)} \tag{C.12}$$

c) Step 3—Calculate the mass flux. For critical flow, use Equation (C.16) or Equation (C.18). For subcritical flow, use Equation (C.17) or Equation (C.19).

In USC units:

$$G = 68.09 \times \eta_c \sqrt{\frac{P_1}{v_1 \omega}} \tag{C.13}$$

$$G = \frac{68.09 \times \left\{-2\left[\omega \ln \eta_{\mathrm{a}} + (\omega - 1)(1 - \eta_{\mathrm{a}})\right]\right\}^{1/2}}{\omega\left(\frac{1}{\eta_{\mathrm{a}}} - 1\right) + 1} \sqrt{P_1/v_1} \qquad \text{(C.14)}$$

In SI units:

$$G = \eta_{\mathrm{c}} \sqrt{\frac{P_1}{v_1 \omega}} \qquad \text{(C.15)}$$

$$G = \frac{\left\{-2 \times \left[\omega \ln \eta_{\mathrm{a}} + (\omega - 1)(1 - \eta_{\mathrm{a}})\right]\right\}^{1/2}}{\omega\left(\frac{1}{\eta_{\mathrm{a}}} - 1\right) + 1} \sqrt{P_1/v_1} \qquad \text{(C.16)}$$

where

G is the mass flux, lb/s·ft^2 (kg/s·m^2);

η_{c} is the critical pressure ratio from Figure C.1;

P_1 is the pressure at the PRV inlet, psia (Pa);

v_1 is the specific volume of the two-phase system at the PRV inlet in ft^3/lb (m^3/kg);

ω is the omega parameter;

η_{a} is the actual backpressure ratio, $\eta_{\mathrm{a}} = \frac{P_2}{P_1}$.

d) Step 4—Calculate the required area of the PRV.

In USC units:

$$A = \frac{0.04W}{K_d K_b K_c K_v G} \qquad \text{(C.20)}$$

In SI units:

$$A = \frac{277.8 \ x \ W}{K_d K_b K_c K_v G} \qquad \text{(C.21)}$$

where

A is the required discharge area, in.^{2} (mm^2);

W is the mass flow rate, lb/h (kg/h);

K_d is the coefficient of discharge; for a sizing estimation, an effective coefficient of discharge of 0.975 can be used if the flow is choked (critical) across the orifice, see Step 2. A value of 0.65 can be used for unchoked (subcritical) flow. See 5.2 for a discussion on the use of effective vs. certified values of Kd;

K_b is the backpressure correction factor for vapor that should be obtained from the valve manufacturer; for ~~a~~ preliminary sizing estimation, use Figure 31; the backpressure correction factor applies to balanced-bellows valves only. The user is cautioned that applying the Kb when the Kd of 0.65 for unchoked (subcritical) flow is used may be conservative when determining the required discharge area.;

K_c is the combination correction factor for installations with a rupture disk upstream of the PRV (see 5.12.2);

- the combination correction factor is 1.0, when a rupture disk is not installed;
- the combination correction factor is 0.9, when a rupture disk is installed in combination with a PRV and the combination does not have a certified value;

K_v is the viscosity correction factor; for two-phase flows where the liquid has a viscosity of 100 cP (0.1 Pa-s) or less, the viscosity correction factor can be set to 1.0;

G is the mass flux, lb/s·ft^2 (kg/s·m^2).

C.2.2.2 Example

C.2.2.2.1 In this example, the following relief requirements are given.

- Required crude column overhead two-phase flow rate caused by an operational upset of 477,430 lb/h (216,560 kg/h). This flow is downstream of the condenser.
- Temperature at the PRV inlet of 200 °F (659.7 °R = 366.5 K).
- PRV set at 60 psig (413.7 kPag), the design pressure of the equipment.
- Downstream total backpressure of 15 psig (29.7 psia) (204.7 kPa) (superimposed backpressure = 0 psig, built-up backpressure = 15 psi).
- Two-phase specific volume at the PRV inlet of 0.3116 ft^3/lb (0.01945 m^3/kg).
- Allowable overpressure (accumulation) of 10 %.
- For this example problem, a viscosity correction factor, K_v, of 1.0 is assumed.

C.2.2.2.2 In this example, the following values are calculated.

— Relieving pressure of 1.10 × 60 = 66 psig (80.7 psia) (556.4 kPa).

— Percent of gauge backpressure = (15/60) × 100 = 25 %; thus, the backpressure correction factor, K_b = 1.0 (from Figure 31).

— Since the downstream backpressure is greater than 10 % of the set pressure, a balanced-bellows PRV is used.

C.2.2.2.3 The following is a step-by-step procedure.

a) Step 1—Calculate the omega parameter, ω. Equation (C.12) is used to calculate the omega parameter, ω. The specific volume evaluated at 0.9 × 80.7 = 72.63 psia (500.8 kPa) using the results of an isenthalpic (adiabatic) flash calculation from a process simulator is 0.3629 ft³/lb (0.02265 m³/kg). The omega parameter is calculated from Equation (C.12) as follows.

In USC units:

$$\omega = 9\left(\frac{0.3629}{0.3116} - 1\right) = 1.482 \tag{C.17}$$

In SI units:

$$\omega = 9\left(\frac{0.02265}{0.01945} - 1\right) = 1.482 \tag{C.18}$$

b) Step 2—Determine if the flow is critical or subcritical. The critical pressure ratio η_c is 0.66 (from Figure C.1). The critical pressure, P_{cf}, is calculated from Equation (C.13) as follows.

In USC units:

$$P_{cf} = 0.66 \times 80.7 = 53.26 \text{ psia} \tag{C.19}$$

In SI units:

$$P_{cf} = 0.66 \times 556{,}379 = 367{,}210 \text{ Pa} \tag{C.20}$$

The flow is determined to be critical since $P_{cf} > P_2$.

53.26 > 29.7

c) Step 3—Calculate the mass flux. The mass flux, G, is calculated from Equation (C.16) or Equation (C.18) as follows.

In USC units:

$$G = 68.09 \times 0.66 \times \sqrt{\frac{80.7}{0.3116 \times 1.482}} = 594.1 \text{ lb/s}\cdot\text{ft}^2 \tag{C.21}$$

In SI units:

$$G = 0.66 \times \sqrt{\frac{556{,}379}{0.01945 \times 1.482}} = 2900\ \text{kg/s} \cdot \text{m}^2 \qquad \text{(C.22)}$$

d) Step 4—Calculate the required area of the PRV. As the flow of this two-phase fluid is ~~critical~~ choked, an effective coefficient of discharge of 0.975 can be used. The required area of the PRV, A, is calculated from Equation (C.20) or Equation (C.21) as follows.

In USC units:

$$A = \frac{0.04\ x\ 477{,}430}{0.975\ x 1.0 x 1.0 x 1.0 x 594.1} = 33.0\ \ in.^2 \qquad \text{(C.28)}$$

In SI units:

$$A = \frac{277.8\ x\ 216{,}560}{0.975\ x 1.0 x 1.0 x 1.0 x 2900} = 21{,}280\ mm^2 \qquad \text{(C.29)}$$

e) Step 5—Select the orifice area. This area requirement may be met by selecting three (3) Q orifice PRVs (3 × 11.05 = 33.15 in.^{2}). Since this example resulted in multiple valves, the required area could be recalculated at 16 % overpressure.

C.2.3 Sizing for Subcooled Liquid at the Pressure-relief Valve Inlet Using the Omega Method

C.2.3.1 Pressure-relief Valves Requiring Capacity Certification

The method presented in this section can be used for sizing PRVs handling a subcooled (including saturated) liquid at the inlet. No condensable vapor or noncondensable gas can be present at the inlet. The subcooled liquid either flashes upstream or downstream of the PRV throat depending on which subcooling region the flow falls into. The equations in this section also apply to all liquid scenarios. The following procedure can be used.

a) Step 1—Calculate the omega parameter for saturated liquid, ω_s. To calculate the omega parameter for saturated liquid using two pressure density data points, use Equation (C.30).

$$\omega_s = 9\left(\frac{\rho_{l1}}{\rho_9} - 1\right) \qquad \text{(C.23)}$$

where

ω_s is the omega parameter for saturated liquid;

ρ_{l1} is liquid density at the PRV inlet, lb/ft^3 (kg/m^3);

ρ_9 is density, lb/ft^3 (kg/m^3) evaluated at 90 % of the saturation (vapor) pressure, P_s, corresponding to the PRV inlet relieving temperature, T_1, lb/ft^3 (kg/m^3).

For a multicomponent system, use the bubble point pressure corresponding to T_1 for P_s. When determining ρ_9, the flash calculation should be carried out isentropically, but an isenthalpic (adiabatic) flash is sufficient for low-quality mixtures far from the thermodynamic critical point.

b) Step 2—Determine the subcooling region.

$P_s \geq \eta_{st} P_1 \Rightarrow$ low subcooling region (flashing occurs upstream of throat)

$P_s < \eta_{st} P_1 \Rightarrow$ high subcooling region (flashing occurs at the throat) (C.24)

$$\eta_{st} = \frac{2\omega_s}{1+2\omega_s} \tag{C.25}$$

where

η_{st} is transition saturation pressure ratio;

ω_s is the omega parameter for saturated liquid;

P_s is the saturation (vapor) pressure (psia or Pa);

P_1 is pressure at the PRV inlet, psia (Pa); this is the PRV set pressure, psig (Pag) plus the allowable overpressure (psi or Pa) plus atmospheric pressure.

c) Step 3—Determine if the flow is critical or subcritical. For the low subcooling region, use the following comparisons:

$P_{cf} \geq P_2 \Rightarrow$ critical flow

$P_{cf} < P_2 \Rightarrow$ subcritical flow (C.26)

For the high subcooling region, use the following comparisons:

$P_s \geq P_2 \Rightarrow$ critical flow

$P_s < P_2 \Rightarrow$ subcritical flow (all-liquid flow) (C.27)

where

P_{cf} is the critical pressure in psia (Pa).

$$P_{cf} = \eta_c P_1 \tag{C.28}$$

where

η_c is the critical pressure ratio from Figure C.2 using the value of η_s.

For $\eta_s \leq \eta_{st}$, the critical pressure ratio $\eta_c = \eta_s$. (C.29)

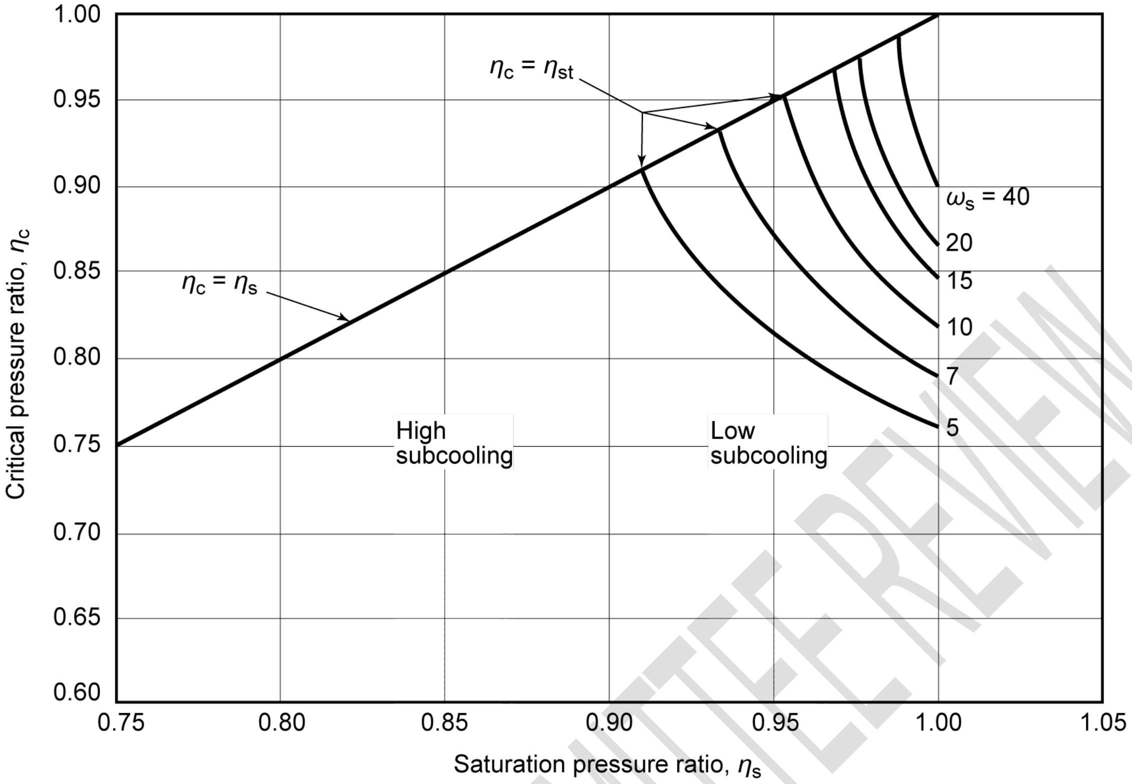

Figure C.2—Correlation for Nozzle Critical Flow of Inlet Subcooled Liquid

For $\eta_s > \eta_{st}$, the critical pressure ratio, η_c, can be calculated implicitly using Equation (C.37) or approximated using Equation (C.38).

$$\frac{\left(\omega_s+\frac{1}{\omega_s}-2\right)}{2\times\eta_s}\times\eta_c^2-2\times\left(\omega_s-1\right)\times\eta_c+\omega_s\times\eta_s\times\ln\left(\frac{\eta_c}{\eta_s}\right)+\frac{3}{2}\times\omega_s\times\eta_s-1=0 \qquad \text{(C.30)}$$

$$\eta_c=\eta_s\times\left(\frac{2\times\omega_s}{2\times\omega_s-1}\right)\times\left[1-\sqrt{1-\frac{1}{\eta_s}\times\left(\frac{2\times\omega_s-1}{2\times\omega_s}\right)}\right] \qquad \text{(C.31)}$$

where

ω_s is the omega parameter for saturated liquid;

η_c is the critical pressure ratio;

η_s is the saturation pressure ratio as calculated in Equation (C.39).

$$\eta_\mathrm{s} = \frac{P_\mathrm{s}}{P_1} \tag{C.32}$$

where

P_s is the saturation (vapor) pressure (psia or Pa);

P_1 is pressure at the PRV inlet, psia (Pa); this is the PRV set pressure, psig (Pag) plus the allowable overpressure (psi or Pa) plus atmospheric pressure.

d) Step 4—Calculate the mass flux. In the low subcooling region, use Equation (C.40) or Equation (C.42). If the flow is critical, use η_c for η, and if the flow is subcritical, use η_a for η. In the high subcooling region, use Equation (C.41) or Equation (C.43). If the flow is critical, use P_s for P, and if the flow is subcritical (all liquid flow), use P_2 for P.

In USC units:

$$G = \frac{68.09 \times \left\{2\left(1-\eta_\mathrm{s}\right)+2\left[\omega_\mathrm{s}\eta_\mathrm{s}\ln\left(\frac{\eta_\mathrm{s}}{\eta}\right)-\left(\omega_\mathrm{s}-1\right)\left(\eta_\mathrm{s}-\eta\right)\right]\right\}^{1/2}}{\omega_\mathrm{s}\left(\frac{\eta_\mathrm{s}}{\eta}-1\right)+1}\sqrt{P_1 \cdot \rho_\mathrm{l1}} \tag{C.33}$$

$$G = 96.3 \times \left[\rho_\mathrm{l1}\left(P_1 - P\right)\right]^{1/2} \tag{C.34}$$

In SI units:

$$G = \frac{\left\{2\left(1-\eta_\mathrm{s}\right)+2\left[\omega_\mathrm{s}\eta_\mathrm{s}\ln\left(\frac{\eta_\mathrm{s}}{\eta}\right)-\left(\omega_\mathrm{s}-1\right)\left(\eta_\mathrm{s}-\eta\right)\right]\right\}^{1/2}}{\omega_\mathrm{s}\left(\frac{\eta_\mathrm{s}}{\eta}-1\right)+1}\sqrt{P_1 \cdot \rho_\mathrm{l1}} \tag{C.35}$$

$$G = 1.414\left[\rho_\mathrm{l1}\left(P_1 - P\right)\right]^{1/2} \tag{C.36}$$

where

G is the mass flux, lb/s·ft^2 (kg/s·m^2);

ω_s is the omega parameter for saturated liquid;

ρ_l1 is liquid density at the PRV inlet, lb/ft^3 (kg/m^3);

η_s is the saturation pressure ratio;

η is the backpressure ratio;

η_c is the critical pressure ratio;

η_a is the subcritical pressure ratio per Equation (C.44):

$$\eta_\mathrm{a} = \frac{P_2}{P_1} \tag{C.37}$$

P_1 is pressure at the PRV inlet, psia (Pa);

P_2 is the downstream backpressure in psia (Pa).

e) Step 5—Calculate the required area of the PRV. Equation (C.45) and Equation (C.46) are only applicable to turbulent flow systems. Most two-phase relief scenarios will be within the turbulent flow regime.

In USC units:

$$A = 0.3208 \frac{Qx\rho_{l1}}{K_d K_w K_c K_v G} \tag{C.45}$$

In SI units:

$$A = 16.67 \frac{Qx\rho_{l1}}{K_d K_w K_c K_v G} \tag{C.46}$$

where

A is the required discharge area, in.^{2} (mm^2);

G is the mass flux, lb/s·ft^2 (kg/s·m^2);

Q is the volumetric flow rate, gal/min (L/min);

ρ_{l1} is liquid density at the PRV inlet, lb/ft^3 (kg/m^3);

K_d is the coefficient of discharge; for a sizing estimation, an effective coefficient of discharge of 0.975 can be used if the flow is choked (critical) across the orifice, see Step 3. A value of 0.65 can be used for unchoked (subcritical) flow, see C.1.4.~~; a value of 0.65 for slightly subcooled liquids may result in a conservative valve size.~~ See 5.2 for a discussion on the use of effective vs. certified values of Kd. The user may select other methods for determining a coefficient of discharge [8, 9, 10];

K_w is the backpressure correction factor for liquid that should be obtained from the valve manufacturer; for preliminary sizing estimation, use Figure C.3; the backpressure correction factor applies to balanced-bellows valves only;

K_c is the combination correction factor for installations with a rupture disk upstream of the PRV (see 5.12.2);

- the combination correction factor is 1.0, when a rupture disk is not installed;
- the combination correction factor is 0.9, when a rupture disk is installed in combination with a PRV and the combination does not have a certified value;

K_v is the viscosity correction factor; for two-phase flows where the liquid has a viscosity of 100 cP

(0.1 Pa-s) or less, the viscosity correction factor can be set to 1.0.

Step 6—Select the orifice size.

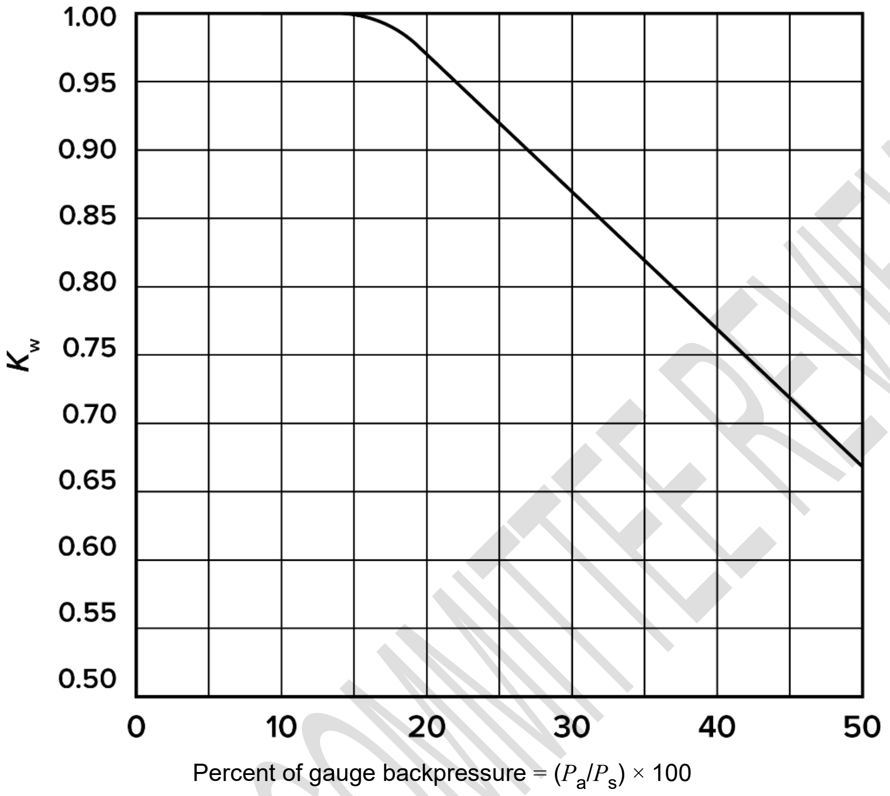

Figure C.3—Backpressure Correction Factor, K_W, for Balanced-bellows Pressure-relief Valves (Liquids)

C.2.3.2 Example

C.2.3.2.1 In this example, the following relief requirements are given.

- Required propane volumetric flow rate caused by blocked in pump of 100 gal/min (378.5 L/min).
- PRV set at 260 psig (1792.6 kPag), the design pressure of the equipment.
- Downstream total backpressure of 10 psig (24.7 psia) (170.3 kPa) (superimposed backpressure = 0 psig, built-up backpressure = 10 psi).
- Temperature at the PRV inlet of 60 °F (519.67 °R) (288.7 K).
- Liquid propane density at the PRV inlet of 31.920 lb/ft^3 (511.3 kg/m^3).
- Liquid propane specific heat at constant pressure at the PRV inlet of 0.6365 Btu/lb×°R (2.665 kJ/kg·K).

- Saturation pressure of propane corresponding to 60 °F of 107.6 psia (741.9 kPa).
- Specific volume of propane liquid at the saturation pressure of 0.03160 ft^3/lb (0.00197 m^3/kg).
- Specific volume of propane vapor at the saturation pressure of 1.001 ft^3/lb (0.0625 m^3/kg).
- Latent heat of vaporization for propane at the saturation pressure of 152.3 Btu/lb (354.2 kJ/kg).

C.2.3.2.2 For this example, a viscosity correction factor, K_v, of 1.0 is assumed. In this example, the following values are calculated:

- Overpressure of 10 %.
- Relieving pressure of 1.10 × 260 = 286 psig (300.7 psia) (2073.3 kPa).
- Percent of gauge backpressure = (10/260) × 100 = 3.8 %.
- Since the downstream backpressure is less than 10 % of the set pressure, a conventional PRV may be used. Thus, the backpressure correction factor $K_b = 1.0$.

C.2.3.2.3 The following is a step-by-step procedure.

a) Step 1—Calculate the omega parameter for saturated liquid, ω_s. Since the propane system is a single component system far from its thermodynamic critical point, the omega parameter for saturated liquid, ω_s, could be calculated using the one-point projection technique; however, in this example, Equation (C.30) is chosen to calculate ω_s. The specific volume evaluated at 0.9 × 107.6 = 96.84 psia (667.7 kPa) using the results of an isenthalpic (adiabatic) flash calculation from a process simulator is 0.06097 ft^3/lb (0.00381 m^3/kg). This gives a fluid density of 16.40 lb/ft^3 (262.7 kg/m^3). The omega parameter is calculated from Equation (C.30) as follows.

In USC units:

$$\omega_s = 9 \times \left(\frac{31.920}{16.402} - 1 \right) = 8.515 \tag{C.38}$$

In SI units:

$$\omega_s = 9 \times \left(\frac{511.3}{262.7} - 1 \right) = 8.515 \tag{C.39}$$

b) Step 2—Determine the subcooling region. The transition saturation pressure ratio, η_{st}, is calculated from Equation (C.32) as follows:

$$\eta_{st} = \frac{2 \times 8.515}{1 + 2 \times 8.515} = 0.9445 \tag{C.40}$$

The liquid is determined to fall into the high subcooling region since:

$$P_s < \eta_{st} P_1$$

$$107.6 < 0.9445 \times 300.7 = 284.0 \qquad \text{(C.41)}$$

c) Step 3—Determine if the flow is critical or subcritical. The flow is determined to be critical since:

$$P_s > P_2$$

$$107.6 > 24.7 \qquad \text{(C.42)}$$

d) Step 4—Calculate the mass flux. The mass flux, G, is calculated from Equation (C.41) or Equation (C.43) as follows.

In USC units:

$$G = 96.3 \times \left[31.92(300.7 - 107.6)\right]^{1/2} = 7560 \text{ lb/s} \cdot \text{ft}^2 \qquad \text{(C.43)}$$

In SI units:

$$G = 1.414 \times \left[511.3 \times (2{,}073{,}250 - 741{,}875)\right]^{1/2} = 36{,}890 \text{ kg/s} \cdot \text{m}^2 \quad \text{(C.44}$$

e) Step 5—Calculate the required area of the PRV. ~~As the liquid flow is critical (see Step 3) and flashing may occur, an effective coefficient of discharge of 0.975 can be used.~~ Even though the propane flow is highly subcooled, due to choked flow through the PRV (see Step 3), an effective coefficient of discharge, Kd of 0.975 can be used. The required area, A, of the PRV is calculated from Equation (C.45) or Equation (C.46) as follows.

In USC units:

$$A = 0.3208 \frac{100\ x\ 31.92}{0.975\ x1.0x1.0x1.0x7560} = 0.139\ in.^2 \qquad \text{(C.54)}$$

In SI units:

$$A = 16.67 \frac{378.5\ x\ 511.3}{0.975\ x1.0x1.0x1.0x36{,}890} = 89.7\ mm^2 \qquad \text{(C.55)}$$

~~e)~~f) Step 6—Select an E orifice PRV (0.196 in.^{2}).

C.2.3.3 Pressure-relief Valves Not Requiring Capacity Certification

If the PRV is one that was never certified in liquid service (see 5.9 for a discussion on noncertified PRVs), then the area calculated using Equation (C.45) or Equation (C.46) needs to be adjusted to account for the higher overpressures required to get the valve to go to full lift. Equation (C.45) and Equation (C.46) are modified as shown in Equation (C.56) and Equation (C.57) to handle liquid PRVs that have never been certified:

In USC units:

$$A = 0.3208 \frac{Q\rho_{l1}}{K_d K_b K_c K_v G} x \frac{\sqrt{P_1 - P_2}}{\sqrt{1.25xP_S - P_2}} \tag{C.56}$$

In SI units:

$$A = 16.67 \frac{Qx\rho_{l1}}{K_d K_b K_c K_v G} \frac{\sqrt{P_1 - P_2}}{\sqrt{1.25xP_S - P_2}} \tag{C.57}$$

where

A	is the required effective discharge area, in.^{2} (mm^2);
Q	is the volumetric flow rate, gal/min (L/min);
ρ_1	is liquid density at the PRV inlet, lb/ft^3 (kg/m^3);
K_d	is the effective coefficient of discharge and shall be 0.62;
K_b	is the backpressure correction factor;
K_c	is the combination correction factor;
K_v	is the viscosity correction factor;
K_p	is the correction factor due to overpressure; at 25 % overpressure, K_p = 1.0. For overpressures other than 25 %, K_p is determined from Figure 39;
P_s	is the set pressure, psig (Pag);
P_1	is the upstream relieving pressure, psig (Pag); this is the set pressure plus allowable overpressure;
P_2	is the total backpressure, psig (Pag).

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