# Technical Report on Pressure-relief System Calculations

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# Technical Report on Pressure-relief System Calculations

## 1 Scope

This technical report is not a design code. It only provides equations and examples for performing relief system calculations. Users are responsible for performing their own calculations and using appropriate references for equations. This report contains a variety of calculation examples for equations and methods found in API Standard 520, *Sizing, Selection, and Installation of Pressure-relieving Devices, Part II—Installation.*

## 2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API Standard 520, *Sizing, Selection, and Installation of Pressure-relieving Devices, Part II–Installation*, 7th Edition

## 3 Terms and Definitions

**3.1**
**physical acoustic line length**
The axial linear distance from the PRV inlet flange to the first significant acoustic reflection point. See API 520, Part II, Annex C.

**3.2**
**speed of sound**
The distance traveled per unit time by a sound wave as it propagates through an elastic medium.

**3.3**
**spring constant**
A characteristic of a spring that is the ratio of the force affecting the spring to the displacement caused by it.

## 4 Force Balance Assessment—Vapor Example

### 4.1 General

This is an example of a force balance assessment from API 520, Part II, Section 7.3.6.d for simple installation in vapor service using reference [1] and [4].

### 4.2 Example Calculation

1) Obtain the valve and installation information.

— Valve: 1½·F·2 bellows, vapor certified.

— Relief fluid phase at inlet of PRV: Vapor.

— Certified orifice area ($A_N$) = 0.3568 in$^2$.

— Certified coefficient of discharge value ($K_d$) = 0.855 unitless.

— Disc backpressure area ($A_{pop}$) = 0.4638 in$^2$.

— Lift ($x_{max}$) = 0.182 in.

— Set pressure ($P_{set}$) = 50 psig.

— Vessel MAWP = 50 psig.

— Blowdown ($P_{BD}$) = 7 % of set pressure = 3.5 psi.

— Overpressure ($P_{OP}$) = 10 % of set pressure = 5.0 psi.

— PRV mounted to a 2-in. Schedule 40 [inner diameter (ID) of 2.067 in. and cross-sectional area ($A_p$) of 3.354 in$^2$] inlet line pipe that is routed directly to a pressure vessel with no bends. PRV is not mounted on a process line.

— Physical inlet pipe length from vessel to equipment ($L$) = 15 ft.

— Physical acoustic line length ($L_{pa}$) = 15 ft.

— Non-recoverable frictional inlet pressure loss ($\Delta P_f$) = 6 % of set pressure = 3.0 psi.

— Rated capacity of relief valve (based on hexane and certified values) = 2860 lb/hr.

— The total backpressure ($P_{back}$) = 2.0 psig. This example assumes no effects on set pressure from superimposed backpressure, so the built-up backpressure is equal to the total backpressure. The built-up backpressure is equal to 4 % of the set pressure.

— Total mass of the PRV ($M_{PRV}$) = 45 lb$_m$.

NOTE This is a hypothetical relief valve for which the spring constant, mass in motion, and damped opening time will be estimated.

2) Determine the fluid properties.

At PRV inlet pipe entrance:

— Fluid composition = 100 % n-hexane vapor.

— Relief temperature ($T$) = 300 °F.

— Relief pressure ($P$) = (50 psig *1.1+14.7) = 69.7 psia.

— Vapor density @ 55 psig = 0.8323 lb/ft$^3$.

— Compressibility ($Z$) = 0.8852.

— Isentropic expansion coefficient ($K_v$) = 0.963.

3) Determine the speed of sound in the vapor at the PRV inlet pipe.

Assume that n-hexane behaves as a real gas and ignore the elasticity of the pipe.

The speed of sound for a real gas is given by Equation (1):

USC units:

$$c = \sqrt{\frac{K_v ZR \times 144 in^2 ft^{-2} \times 32.174 lb_m ft s^{-2} lb_f^{-1} \times T}{M}} = 68.06\sqrt{\frac{K_v ZRT}{M}} \tag{1}$$

SI units:

$$c = \sqrt{\frac{K_v ZRT}{M}}$$

Where:

| | |
|---|---|
| $c$ | speed of sound (USC units: *ft.s⁻¹*, SI units: *m.s⁻¹*) |
| $K_v$ | isentropic expansion coefficient (dimensionless) |
| $z$ | compressibility factor (dimensionless) |
| $R$ | gas const. (USC units: *10.731 $ft^3 psiR^{-1} lb\text{-}mol^{-1}$*, SI units: *8314.46 $m^3 PaK^{-1} kmol^{-1}$*) |
| $T$ | absolute temperature (USC units: *R*, SI units: *K*) |
| $M$ | molecular weight (USC units: $lb_m.lbmol^{-1}$, SI units: $kg.kmol^{-1}$) |

$$c = 68.06\sqrt{\frac{0.963(0.8852)10.731\,ft^3\,psi\,R^{-1}\,lbmol^{-1}(300\,F + 459.67)}{86.18\,lb_m/lbmol}} = 611\,ft\,s^{-1}$$

4) Estimate the spring constant using Grolmes' equations [1].

$$k_S = \left(\frac{P_{fullflow}}{P_{set}}\right)\left(\frac{A_{pop}}{A_N}\right)\left[\frac{P_{set}A_N}{x_{\max}}\right]$$

$$\left(\frac{P_{fullflow}}{P_{set}}\right) = 1.1 \text{ and } \left(\frac{A_{pop}}{A_N}\right) = 1.3$$

$$k_S = (1.1)(1.3)\left[\frac{P_{set}A_N}{x_{\max}}\right] = 1.43\frac{P_{set}A_N}{x_{\max}}$$

Where:

| | |
|---|---|
| $k_S$ | Valve spring constant (USC units: $lb_f in^{-1}$, SI units: $N.m^{-1}$) |
| $P_{fullflow}$ | Pressure which rated capacity was calculated (USC units: *psig*, SI units: *Pa(g)*) |
| $T$ | Set pressure of the relief valve (USC units: *psig*, SI units: *Pa(g)*) |
| $A_N$ | Minimum flow area (USC units: $in^2$, SI units: $m^2$) |
| $A_{pop}$ | Disc backpressure area (USC units: $in^2$, SI units: $m^2$) |
| $x_{max}$ | Maximum valve lift, or restricted lift (USC units: *in*, SI units: *m*) |

$$k_S = 1.43\frac{50\,psig * (0.3568\,in^2)}{0.182\,in} = 140.2\,lb_f/in$$

5) Estimate the mass in motion from the Grolmes' equations [1].

$$m_D \approx \frac{M_{PRV}}{100}\left(1.8 + 0.022 \times M_{PRV}\right)$$

Where:

| | |
|---|---|
| $m_D$ | mass in motion (USC units: $lb_m$) |

$M_{PRV}$ total mass of PRV (USC units: $lb_m$)

$$m_D \approx \frac{45\,lb_m}{100}(1.8 + 0.022 \times 45\,lbs) = 1.26\,lb_m$$

6) Estimate the PRV opening time.

USC units:

$$\tau_n = \frac{2\pi}{\omega_n} = 2\pi\sqrt{\frac{m_D}{K_S \times 12\,in\,ft^{-1} \times 32.174\,lb_m ft\,s^{-2}\,lb_f^{-1}}} = 0.3198\sqrt{\frac{m_D}{K_S}}$$

$$f_n = \frac{1}{\tau_n} = \frac{1}{0.3198}\sqrt{\frac{K_S}{m_D}}$$

$$f_n = \frac{1}{0.3198} = \sqrt{\frac{140.2\,lb_f/in}{1.26\,lb_m}} = 33\,s^{-1}$$

SI units:

$$\tau_n = \frac{2\pi}{\omega_n} = 2\pi\sqrt{\frac{m_D}{K_S}}$$

$$f_n = \frac{1}{\tau_n} = \frac{1}{2\pi}\sqrt{\frac{K_S}{m_D}}$$

Where:

$\tau_n$ undamped natural period ($s$)

$\omega_n$ undamped natural frequency ($radians.s^{-1}$)

$f_n$ natural frequency of the valve ($s^{-1}$ or $Hz$)

$K_S$ spring constant (USC units: $lb_f in^{-1}$, SI units: $N.m^{-1}$)

$m_D$ mass in motion (USC units: $lb_m$, SI units: $kg$)

$$t_{open} \approx \frac{1}{2\pi f_n}\sqrt{\frac{2}{A_{pop}/A_N - 1}} \approx \frac{1}{2f_n}$$

$t_{open}$ undamped valve opening time ($s$)

$$t_{open} \approx \frac{1}{2(33\,s^{-1})} \approx 0.01515\,s = 15.15\text{ ms}$$

$$t_{open,d} = \frac{t_{open}}{\sqrt{1-\zeta^2}}$$

$t_{open,d}$ damped valve opening time ($s$)

$\zeta$ damping coefficient (dimensionless) = 0.5 based on best fit [1]

$$t_{open,d} = \frac{0.01515\,s^{-1}}{\sqrt{1-0.5^2}} = 0.0175\text{ s} = 17.5\text{ ms}$$

7) Calculate the inlet line pressure drop [1, 4] $\left(\Delta P_{inlet}\right)$.

$$\Delta P_{inlet} = \Delta P_{wave} + \Delta P_{f,wave}$$

Where:

| | |
|---|---|
| $\Delta P_{inlet}$ | inlet line pressure drop (USC units: *psi*, SI units: *Pa*) |
| $\Delta P_{wave}$ | wave pressure drop (USC units: *psi* or SI units: *Pa*) |
| $\Delta P_{f,wave}$ | frictional wave pressure drop (USC units: *psi* or SI units: *Pa*) |

USC units:

$$\Delta P_{wave}(psi) = \tau \frac{c_0 \times \dot{M}_{open}}{A_p \times 32.174 lb_m ft s^{-2} lb_f^{-1}} + \tau^2 \frac{\dot{M}_{open}^{\ 2} \times 144\, in^2 ft^{-2}}{2\rho_0 \times 32.174 lb_m ft s^{-2} lb_f^{-1} \times A_p^{\ 2}}$$

$$\Delta P_{wave}(psi) = 3.108 \times 10^{-2}\, \tau \frac{c_0 \times \dot{M}_{open}}{A_p} + 2.2378\, \tau^2 \frac{\dot{M}_{open}^{\ 2}}{\rho_0 A_p^{\ 2}}$$

SI units:

$$\Delta P_{wave}(Pa) = \tau \frac{c_0 \times \dot{M}_{open}}{A_p} + \tau^2 \frac{\dot{M}_{open}^{\ 2}}{2\rho_0 A_p^{\ 2}}$$

| | |
|---|---|
| $\dot{M}_{open}$ | mass flow rate of the relief valve at 10 % overpressure, during PRV opening (USC units: $lb_m s^{-1}$, SI units: $kg.s^{-1}$) |
| $A_p$ | inlet line inside pipe area (USC units: $in^2$, SI units: $m^2$) |
| $c_0$ | speed of sound of the fluid at the pressure source (USC units: $ft.s^{-1}$, SI units: $m.s^{-1}$) |
| $\rho_0$ | density of the fluid at the pressure source (USC units: $lb_m ft^{-3}$, SI units: $kg.m^{-3}$) |
| $\tau$ | ratio of wave travel time ($t_{wave}$) to damped valve opening time ($t_{open,d}$) |

$$\tau = min\left(\frac{t_{wave}}{t_{open,d}}, 1\right)$$

$$0 \le \tau \le 1$$

$$t_{wave} = 2L_{pa}/c_0$$

| | |
|---|---|
| $L_{pa}$ | acoustic inlet line length (USC units: *ft*, SI units: *m*) |
| $c_0$ | speed of sound in relieving fluid (USC units: $ft.s^{-1}$, SI units: $m.s^{-1}$) |
| $t_{open,d}$ | damped opening time (*s*) |

$t_{wave} = 2(15 ft)/611 ft s^{-1}$ 0.0491 sec

$$\tau = min\left(\frac{0.0491}{0.0175} = 2.806, 1\right) = 1$$

$$\dot{M}_{open} = \frac{2860\, lb_m\, hr^{-1}}{3600\, s\, hr^{-1}} = 0.794\ \mathrm{lb_m s^{-1}}$$

$$\Delta P_{wave}(psi) = 3.108 \times 10^{-2}\, 1 \frac{611\, ft\, s^{-1}(0.794 lbm\, s^{-1})}{3.354\, in^2} + 2.2378\,(1)^2 \frac{\left(0.794^2\, lb_m\; s^{-1}\right)^2}{0.8323\, lb_m\, ft^{-3}\,(3.354\, in^2)^2}$$

$$\Delta P_{wave}(psi) = 4.65\, psi$$

$$\Delta P_{f,wave} = \tau^2 \Delta P_f$$

$$\Delta P_{f,wave} = 1^2(3\, psi) = 3\, psi$$

$$\Delta P_{inlet} = 3\, psi + 4.65\, psi = 7.65\, psi$$

8) Calculate the force balance.

From API 520, Part II, Section 7.3.6:

The total inlet pressure loss + 0.1 * the built-up backpressure ≤ overpressure + blowdown. The adjustment to the built-up backpressure term recognizes that the bellows area isolates a large percentage of the disk area from the backpressure.

In equation form:

$\Delta P_{inlet} + 0.1\, P_{back} \leq P_{OP} + P_{BD}$ for bellows valves

Where:

| | |
|---|---|
| $\Delta P_{inlet}$ | total inlet pressure loss, including both the wave component and the frictional (non-recoverable) component of pressure loss (USC units: *psi*; SI units: *Pa*) |
| $P_{OP}$ | overpressure (USC units: *psi*; SI units: *Pa*) |
| $P_{BD}$ | blowdown (USC units: *psi*; SI units: *Pa*) |
| $P_{back}$ | built-up backpressure at the relief device discharge (USC units: *psi*, SI units: *Pa*) |

$7.65\, psi + 0.1 \cdot 2\, psi \leq 5 psi + 3.5 psi$

$7.85\, psi \leq 8.5\, psi$ is true; therefore, the PRV passes the force balance assessment.

Note that the force balance may only be one criterion of many in an engineering analysis for the acceptability of elevated inlet pressure drops. Refer to API Standard 520, Part II, Section 7.3.6 for more information.

# 5 Force Balance Assessment—Liquid Example

## 5.1 General

This is an example of a force balance assessment from API 520, Part II, Section 7.3.6.d for a simple installation in liquid service using reference [1].

## 5.2 Example Calculation

1) Obtain the valve and installation information.

— Valve: 1·D·2 bellows, liquid certified.

— Relief fluid phase at inlet of PRV: Liquid.

— Certified orifice area ($A_N$) = 0.128 in$^2$.

— Certified coefficient of discharge value ($K_d$) = 0.67 unitless.

— Disc backpressure area ($A_{pop}$) = 0.1664 in$^2$.

— Lift ($x_{max}$) = 0.095 in.

— Set pressure ($P_{set}$) = 50 psig.

— Vessel MAWP = 50 psig.

— Blowdown ($P_{BD}$) = 10 % of set pressure = 5.0 psi.

— Overpressure ($P_{OP}$) = 10 % of set pressure = 5.0 psi.

— PRV mounted to a 2-in Schedule 40 [inner diameter ($ID$) of 2.067 in. and cross-sectional area ($A_p$) of 3.354 in$^2$] inlet line pipe that is routed directly to a pressure vessel with no bends. PRV is not mounted on a process line.

— Physical inlet pipe length from vessel to equipment ($L$) = 15 ft.

— Physical acoustic line length ($L_{pa}$) = 15 ft.

— Non-recoverable frictional inlet pressure loss ($\Delta P_f$) = 8 % of set pressure = 4.0 psi.

— Rated capacity of relief valve (based on liquid hexane and certified values) = 29 USGPM = 9287 lb$_m$/hr.

— The total backpressure ($P_{back}$) = 4.0 psig. This example assumes no effects on set pressure from superimposed backpressure so the built-up backpressure is equal to the total backpressure. The built-up backpressure is equal to 8 % of the set pressure.

— Total mass of the PRV ($M_{PRV}$) = 40 lb$_{m.}$

NOTE This is a hypothetical relief valve for which the spring constant, mass in motion, and damped opening time will be estimated.

2) Determine the fluid properties.

At PRV inlet pipe entrance:

— Fluid composition = 100 % n-Hexane liquid.

— Relief temperature ($T$) = 100 °F.

— Relief pressure = (50 psig *1.1+14.7) = 69.7 psia

— Liquid density @ 55 psig ($\rho$) = 40.3 lb/ft$^3$

— Specific gravity (60 F/60 F) ($S$) = 0.647

— Real heat capacity ratio ($C_p/C_v$) = 1.31

3) Determine the speed of sound of the liquid at the PRV inlet pipe.

Ignore the elasticity of the pipe.

The speed of sound for a liquid is given by the following equation (API 520, Part II, C.4).

USC units:

$$c = 8.62 \times \sqrt{\frac{\kappa_S}{S}}$$

SI units:

$$c = \sqrt{\frac{\kappa_S}{S}}$$

The isentropic bulk modulus of elasticity may be calculated as:

$$\kappa_S = \frac{C_P}{C_V} \cdot \frac{1}{\kappa_T}$$

$$\kappa_S = \frac{C_P}{C_V} \cdot \kappa_T = \frac{C_P}{C_V} \cdot \frac{1}{\beta_T}$$

Where:

| | |
|---|---|
| $\kappa_s$ | isentropic bulk modulus of elasticity (USC units: *psi*, SI units: *Pa*) |
| $C_p / C_v$ | real heat capacity ratio (dimensionless) |
| $\kappa_T$ | isothermal bulk modulus of elasticity (USC units: *psi*, SI units: *Pa*) |
| $\beta_T$ | isothermal compressibility (USC units: $psi^{-1}$, SI units: $Pa^{-1}$) |
| $S$ | specific gravity of the fluid |

The isothermal compressibility can be obtained from a process simulator directly or by calculating the slope of the density to pressure at constant temperature, then dividing by the density. A recommended range is ±20 % of the set pressure at the relief temperature.

$$\beta_T = -\frac{1}{V}\left(\frac{\delta V}{\delta P}\right)_T = \frac{1}{\rho}\left(\frac{\delta \rho}{\delta P}\right)_T$$

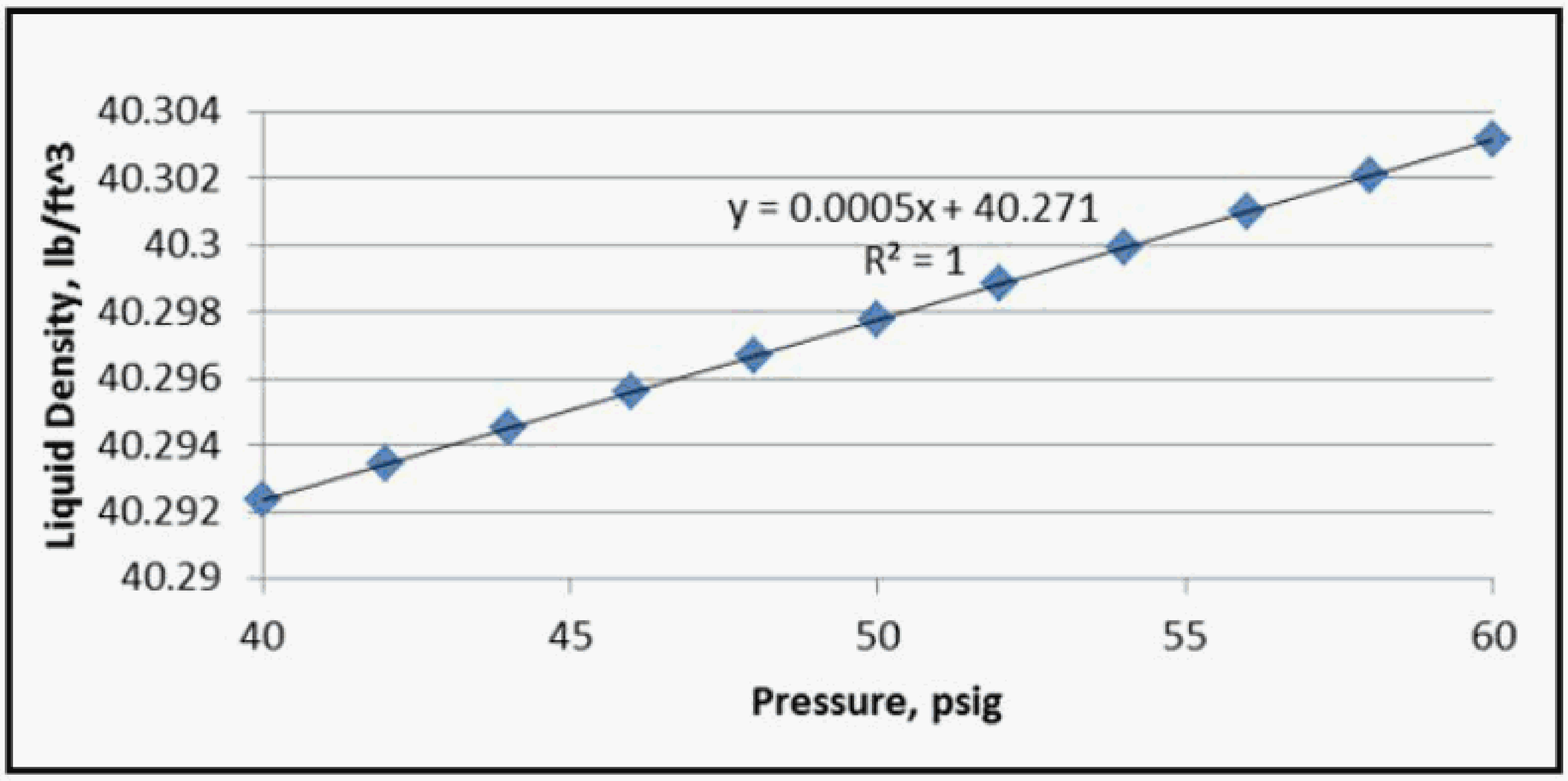


**Figure 1—Isothermal Bulk Modulus of Elasticity at 100 °F**

$$\beta_T = \frac{1}{40.3\, lb ft^{-3}}(0.0005)_T = 1.24 \times 10^{-5} psi^{-1}$$

$$\kappa_S = 1.31 \frac{1}{1.24 \times 10^{-5} psi^{-1}} = 105{,}586\, psi$$

$$c = 8.62 \times \sqrt{\frac{105{,}586\, psi}{0.647}} = 3{,}482\, ft\, s^{-1}$$

4) Estimate the spring constant using Grolmes' equations [1].

$$k_S = \left(\frac{P_{fullflow}}{P_{set}}\right)\left(\frac{A_{pop}}{A_N}\right)\left(\frac{P_{set}A_N}{x_{max}}\right)$$

$$\left(\frac{P_{fullflow}}{P_{set}}\right) = 1.1 \text{ and } \left(\frac{A_{pop}}{A_N}\right) = 1.3$$

$$k_S = (1.1)(1.3)\left[\frac{P_{set}A_N}{x_{max}}\right] = 1.43\frac{P_{set}A_N}{x_{max}}$$

Where:

| | |
|---|---|
| $k_S$ | valve spring constant (USC units: $lb_f in^{-1}$, SI units: $N.m^{-1}$) |
| $P_{full\,flow}$ | Pressure which actual capacity was calculated (USC units: *psig*, SI units: *Pa(g)*) |
| $P_{set}$ | Set pressure of the relief valve (USC units: *psig*, SI units: *Pa(g)*) |
| $A_N$ | Minimum flow area (USC units: $in^2$, SI units: $m^2$) |
| $A_{pop}$ | Disc backpressure area (USC units: $in^2$, SI units: $m^2$) |
| $x_{max}$ | Maximum valve lift, or restricted lift (USC units: *in*, SI units: *m*) |

$$k_S = 1.43\frac{50\, psig * (0.128\, in^2)}{0.095\, in} = 96.3\, lb_f in^{-1}$$

5) Calculate the mass in motion from the Grolmes equation [1].

$$m_D \approx \frac{M_{PRV}}{100}\left(1.8 + 0.022 \times M_{PRV}\right)$$

Where:

| | |
|---|---|
| $m_D$ | mass in motion (USC units: $lb_m$) |
| $M_{PRV}$ | total mass of PRV (USC units: $lb_m$) |

$$m_D \approx \frac{40\,lb_m}{100}(1.8 + 0.022 \times 40\,lbs) = 1.07\ \mathrm{lb_m}$$

6) Estimate the PRV opening time.

USC units:

$$\tau_n = \frac{2\pi}{\omega_n} = 2\pi\sqrt{\frac{m_D}{K_S \times 12\,in\,ft^{-1} \times 32.174\,lb_m ft\,s^{-2}\,lb_f^{-1}}} = 0.3198\sqrt{\frac{m_D}{K_S}}$$

$$f_n = \frac{1}{\tau_n} = \frac{1}{0.3198}\sqrt{\frac{K_S}{m_D}}$$

$$f_n = \frac{1}{0.3198}\sqrt{\frac{96.3\,lbf/in}{1.07\,lbm}} = 29.6\,s^{-1}$$

SI units:

$$\tau_n = \frac{2\pi}{\omega_n} = 2\pi\sqrt{\frac{m_D}{K_S}}$$

$$f_n = \frac{1}{\tau_n} = \frac{1}{2\pi}\sqrt{\frac{K_S}{m_D}}$$

Where:

| | |
|---|---|
| $\tau_n$ | undamped natural period (*s*) |
| $\omega_n$ | undamped natural frequency (*radians.s*$^{-1}$) |
| $f_n$ | natural frequency of the valve (*s*$^{-1}$ or *Hz*) |
| $k_S$ | spring constant (USC units: $lb_f\,in^{-1}$, SI units: $N.m^{-1}$) |
| $m_D$ | mass in motion (USC units: $lb_m$, SI units: *kg*) |

$$t_{open} \approx \frac{1}{2\pi f_n}\sqrt{\frac{2}{A_{pop}/A_N - 1}} \approx \frac{1}{2f_n}$$

| | |
|---|---|
| $t_{open}$ | undamped valve opening time (*s*) |

$$t_{open} \approx \frac{1}{2(29.6)} \approx 0.0169\,s = 16.9\,ms$$

$$t_{open,d} = \frac{t_{open}}{\sqrt{1-\zeta^2}}$$

| | |
|---|---|
| $t_{open,d}$ | damped valve opening time (*s*) |

$\zeta$ damping coefficient (dimensionless) = 0.5 based on best fit

$$t_{open,d} = \frac{0.0169\,s^{-1}}{\sqrt{1-0.5^2}} = 0.0195\text{ s} = 19.5\text{ ms}$$

7) Calculate the inlet line pressure drop $(\Delta P_{inlet})$ [1].

$$\Delta P_{inlet} = \Delta P_{wave} + \Delta P_{f,wave}$$

Where:

| | |
|---|---|
| $\Delta P_{inlet}$ | inlet line pressure drop (USC units: *psi*, SI units: *Pa*) |
| $\Delta P_{wave}$ | wave pressure drop (USC units: *psi* or SI units: *Pa*) |
| $\Delta P_{f,wave}$ | frictional wave pressure drop (USC units: *psi* or SI units: *Pa*) |

USC units:

$$\Delta P_{wave}(psi) = \tau\frac{c_0 \times \dot{M}_{open}}{A_p \times 32.174 lb_m ft s^{-2} lb_f^{-1}} + \tau^2\frac{\dot{M}_{open}{}^2 \times 144\, in^2 ft^{-2}}{2\rho_0 \times 32.174 lb_m ft s^{-2} lb_f^{-1} \times A_p{}^2}$$

$$\Delta P_{wave}(psi) = 3.108 \times 10^{-2}\,\tau\frac{c_0 \times \dot{M}_{open}}{A_p} + 2.2378\,\tau^2\frac{\dot{M}_{open}{}^2}{\rho_0 A_p{}^2}$$

SI units:

$$\Delta P_{wave}(Pa) = \tau\frac{c_0 \times \dot{M}_{open}}{A_p} + \tau^2\frac{\dot{M}_{open}{}^2}{2\rho_0 A_p{}^2}$$

Where:

| | |
|---|---|
| $\dot{M}_{open}$ | mass flow rate of the relief valve at 10 % overpressure, during PRV opening (USC units: $lb_m s^{-1}$, SI units: $kg.s^{-1}$) |
| $A_p$ | inlet line inside pipe area (USC units: $in^2$, SI units: $m^2$) |
| $c_0$ | speed of sound of the fluid at the pressure source (USC units: $ft.s^{-1}$, SI units: $m.s^{-1}$) |
| $\rho_0$ | density of the fluid at the pressure source (USC units: $lb_m ft^{-3}$, SI units: $kg.m^{-3}$) |
| $\tau$ | ratio of wave travel time ($t_{wave}$) to damped valve opening time ($t_{open,d}$) |

$$\tau = min\left(\frac{t_{wave}}{t_{open,d}}, 1\right)\quad 0 \le \tau \le 1$$

$$t_{wave} = 2L_p/c_0$$

Where:

| | |
|---|---|
| $L_p$ | Acoustic inlet line length (USC units: *ft*, SI units: *m*) |
| $c_0$ | speed of sound in relieving fluid (USC units: $ft.s^{-1}$, SI units: $m.s^{-1}$) |
| $t_{open,d}$ | damped opening time (*s*) |

$$t_{wave} = 2(15\,ft)/3482\,ft\,s^{-1} = 0.0086\text{ sec}$$

$$\tau = min\left(\frac{0.0086}{0.0195} = 0.44, 1\right) = 0.44$$

$$\dot{M}_{open} = \frac{9287\,lbm\,hr^{-1}}{3600\,s\,hr^{-1}} = 2.58\ \text{lb}_m\text{s}^{-1}$$

$$\Delta P_{wave}(psi) = 3.108 \times 10^{-2}(0.44)\frac{3482\,ft\,s^{-1}\left(2.58\,lb_m\,s^{-1}\right)}{3.354\,in^2} + 2.2378\,(0.44)^2\frac{\left(2.58\,lb_m\,s^{-1}\right)^2}{40.3\,lbm\,ft^{-3}\,(3.354\,in^2)^2}$$

$$\Delta P_{wave}(psi) = 36.64\,psi$$

$$\Delta P_{f,wave} = \tau^2 \Delta P_f$$

$$\Delta P_{f,wave} = 0.44^2(4\,psi) = 0.78\,psi$$

$$\Delta P_{inlet} = 36.64\,psi + 0.78\,psi = 37.4\,psi$$

8) Calculate the force balance.

From API 520, Part II, Section 7.3.6:

The total inlet pressure loss + 0.1 * the built-up backpressure ≤ overpressure + blowdown. The adjustment to the built-up backpressure term recognizes that the bellows area isolates a large percentage of the disk area from the back pressure.

In equation form:

$$\Delta P_{inlet} + 0.1\,P_{back} \le P_{OP} + P_{BD}$$

Where:

| | |
|---|---|
| $\Delta P_{inlet}$ | total inlet pressure loss, including both the wave component and the frictional (non-recoverable) component of pressure loss (USC units: *psi*; SI units: *Pa*) |
| $P_{OP}$ | overpressure (USC units: *psi*; SI units: *Pa*) |
| $P_{BD}$ | blowdown (USC units: *psi*; SI units: *Pa*) |
| $P_{back}$ | built-up backpressure at the relief device discharge (USC units: *psi*, SI units: *Pa*) |

$$37.4\,psi + 0.1 \cdot 4\,psi \le 5\,psi + 5\,psi$$

$37.8\,psi \le 10\,psi$ is false; therefore, the PRV does not pass the force balance assessment.

# 6 Critical Line Length—Vapor Example

## 6.1 General

This is an example of a critical line length calculation for a simple installation in vapor service using references [1] and [2].

## 6.2 Example

The critical line length calculation is calculated based on the Izuchi criteria [1][2]. It can be expressed as:

$$L_{crit} = \frac{c_0}{4f_n}\sqrt{\frac{x}{x+x_0}}\text{(USC units: } ft\text{, SI units: } m\text{)}$$

Where:

| | |
|---|---|
| $c_0$ | speed of sound in fluid (USC units: *ft.s*$^{-1}$, SI units: *m.s*$^{-1}$) |
| $f_n$ | natural frequency of the valve ($s^{-1}$ or *Hz*) |
| $x$ | valve lift (USC units: *in*, SI units: *m*) |
| $x_o$ | initial compression of the spring (USC units: *in*, SI units: *m*) |

When the overpressure is set at 10 %, the initial compression of the spring ($x_o$) can be simplified. As a result, the critical length calculation becomes:

$$L_{crit} = \frac{c_0}{4f_n}\sqrt{\frac{1.43x}{1.43x + x_{max}}}$$

The equation above shows how the critical length ($L_{crit}$) is dependent on the valve lift ($x$).

Where:

| | |
|---|---|
| $c_0$ | speed of sound in fluid (USC units: *ft.s*$^{-1}$, SI units: *m.s*$^{-1}$) |
| $f_n$ | natural frequency of the valve ($s^{-1}$ or *Hz*) |
| $x_{max}$ | maximum valve lift (USC units: *in*, SI units: *m*) |
| $x$ | valve lift (USC units: *in*, SI units: *m*) |

1) Determine the properties.

$c_0$ 611 ft s$^{-1}$ from Section 4 example

$f_n$ 33 s$^{-1}$ from Section 4 example

$x_{max}$ 0.182 in. from Section 4 example

Assume that the valve is at full lift.

$$x = x_{max} = 0.182\, in$$

2) Calculate critical line length [1].

$$L_{crit} = \frac{c_0}{4f_n}\sqrt{\frac{1.43x}{1.43x + x_{max}}}$$

$$L_{crit} = \frac{611\, ft\, s^{-1}}{4(33\, s^{-1})}\sqrt{\frac{1.43(0.182\, in)}{1.43(0.182\, in) + 0.182\, in}}$$

$$L_{crit} = 3.55 \text{ ft}$$

$$L_p = 15 \text{ ft}$$

Since $L_p > 1.2 * L_{crit}$, the valve is expected to cycle at full lift.

# Bibliography

[1] Melhem, G.A., "*Analysis of PRV Stability in Relief Systems, Part II—Screening*," ioMOSAIC white paper, November 2016

[2] Hisao Izuchi, "Stability analysis of safety valve," 10th Topical Conference on Gas Utilization, AIChE, 2010.

[3] NB-18,[1] *Pressure Relief Device Certification*

[4] Darby R. "The dynamic response of pressure relief valves in vapor or gas service, part I: Mathematical model," *Journal of Loss Prevention in the Process Industries*, November 2013, 26(6):1262-1268.

[1] The National Board of Boiler and Pressure Vessel Inspectors, 1055 Crupper Avenue, Columbus, Ohio 43229, www.nationalboard.org.

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