The Importance of Using Rated Capacity for PRV Stability Calculations

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Abstract

PRV stability, inlet pressure drop and built-up backpressure, should be evaluated at the rated capacity of the PRV. The rated capacity of the PRV corresponds to a specific overpressure, which is 10% of the set pressure or 3 psi, whichever is greater, for ASME VIII certified relief devices. Evaluating PRV stability at overpressure other than that for which the PRV is certified may lead to missed opportunities for improvement.

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Introduction

Whether designing new or evaluating existing pressure relief systems it is important to use the correct basis for PRV stability (inlet and outlet pressure loss) calculations. Using the incorrect basis can raise concerns where there are none and, conversely, overlook potential concerns. A common miscue is using the allowable accumulation as a basis for PRV capacity calculations and subsequent stability analyses.

Use the Rated Capacity and Corresponding Overpressure

Pressure relief valves capacity certified to ASME Section VIII - Division I are tested at 10% or 3 psi overpressure, whichever is greater in accordance with ¶UG-131(c)(1). According to Appendix M (¶M-6) the non-recoverable inlet pressure losses shall not exceed 3% of the valve set pressure and the inlet losses are to be based on the aforementioned nameplate capacity corrected for the flowing fluid characteristics. Although the 3% "rule" originated with API, API 520 Part II (5th Edition) §4.2.2 simply states that the total non-recoverable pressure loss between the protected equipment and the PRV should not exceed 3% of the set pressure, and is silent on the flow rate or overpressure.

Consider a pressure relief system properly designed to meet the 3% non-recoverable inlet pressure loss and 10% built-up backpressure at 10% overpressure that includes a conventional spring loaded PRV relieving choked vapor.

The flow rate through a properly designed pressure relief system is limited by the PRV. Relieving an ideal gas with a specific heat ratio between 1.1 and 1.4 yields a typical choking pressure ratio of 0.55:

$$\frac{P_c}{P_1} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \approx 0.55$$

Where:
P_1 is the inlet pressure,
P_c is the choke pressure, and
k is the ideal gas specific heat ratio

The driving force that governs the flow through the PRV, and therefore the entire system, is essentially the difference between P_1 and P_c (dP). In compressible fluid service, the flow rate (w) is proportional to the square root of the pressure drop, which is an easy relationship to remember and helps put the issue in perspective.

$$w \propto \sqrt{dP}$$

If this system were revalidated with P_1 based on 21% overpressure, instead of the originally designed 10% overpressure, the calculated flow through the relief system may be 3-5% higher. The additional flow rate is a benefit when evaluating relief system capacity; however, the additional capacity will necessarily result in 7-10% greater non-recoverable inlet pressure loss.

Illustrative Example

For example, consider a typical conventional PRV set at 100 psig and relieving choked ideal gas (k=1.27) with a critical pressure ratio of 0.55. At 10% overpressure the following equations show the flow rate to pressure drop proportionality:

$$P_c = (110 + 14.7) * (0.55) = 68.6\, psia$$

$$w \propto \sqrt{dP} = \sqrt{110 + 14.7 - 68.6} = 7.49$$

At 21% overpressure we see the following:

$$P_c = (121 + 14.7) * (0.55) = 74.6\, psia$$

$$w \propto \sqrt{dP} = \sqrt{121 + 14.7 - 74.6} = 7.81$$

The increase in flow is then:

$$\frac{w_{21\%}}{w_{10\%}} = \frac{7.81}{7.49} = 1.043 \;\; (a\ 4.3\%\ increase)$$

This example PRV will have approximately 4.3% greater flow at 21% overpressure than at 10% overpressure. Were the inlet piping designed to meet the 3% rule at 10% overpressure (3 psi inlet loss), this increased flow rate will result in an inlet pressure drop of 3.26 psi, which is an 8.8% increase.

$$w_{21\%} = 1.043 * w_{10\%} \propto 1.043 * \sqrt{3\,psi} = 1.81$$

$$1.81 = \sqrt{dP_{21\%}}$$

$$dP_{21\%} = 1.81^2 = 3.26\,psi\ (an\ 8.8\%\ increase)$$

Refer to Table 1 and Table 2 for consideration of a PRV relieving Air or n-Hexane designed to meet the pressure loss criteria at 10% overpressure, but re-evaluated at 21% overpressure.

Table 1: Implication of Higher Overpressure on Inlet Loss for 1E2 PRV set at 100 psig Designed at 10% Overpressure

	Fluid	Air		n-Hexane	
	Overpressure	10%	21%	10%	21%
Relief Pressure	psig	110	121	110	121
Relief Temperature	°F	81	81.4	317	325
Flow Rate	lb/h	1,951	2,123	2,654	2,871
Inlet Pipe	ft (1" Sch80S)	3.25		5.25	
Outlet Pipe	ft (2" Sch80S)	95		112.5	
Non-recoverable Inlet Loss	psi & % of set	3	3.3	3	3.2
Built-up Backpressure	psig & % of set	10	11.5	9.9	11.4

Table 2: Implication of Higher Overpressure on Inlet Loss for 4P6 PRV set at 100 psig Designed at 10% Overpressure

	Fluid	Air		n-Hexane	
	Overpressure	10%	21%	10%	21%
Relief Pressure	psig	110	121	110	121
Relief Temperature	°F	81	81.4	317	325
Flow Rate	lb/h	65,876	71,742	88,417	96,597
Inlet Pipe	ft (4" Sch40)	8		12	
Outlet Pipe	ft (6" Sch40)	13		12	
Non-recoverable Inlet Loss	psi & % of set	2.9	3.2	3	3.3
Built-up Backpressure	psig & % of set	9.9	12.1	10	12.5

Refer to Figure 1 for consideration of the implications of this extra flow rate on the inlet pressure drop.

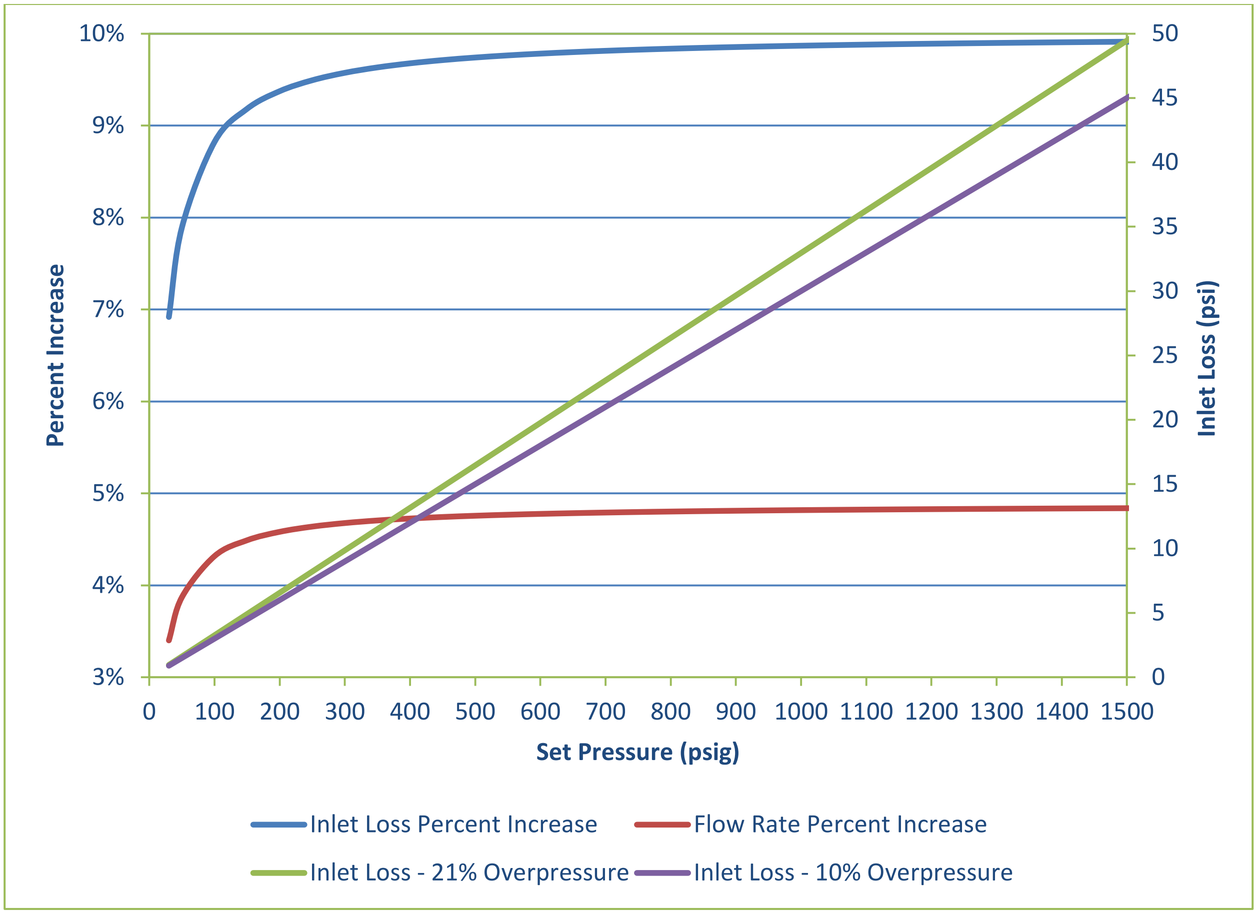

Figure 1: Percent Increase in Flow Rate and Inlet Pressure Loss at 21% Overpressure vs 10% Overpressure

From a practical engineering perspective, this is just noise. However, from the standpoint of black-and-white "rules" this is the difference between adequate and deficient.

Beware of Built-up Backpressure

Now, consider if a PRV piping system were designed based on guidance in API 520 Part I (9th Edition) §5.3.3.1.3, which states that a higher maximum allowable built-up backpressure may be used for allowable overpressures greater than 10%. As an example, API 520 Part I suggests allowing 21% built-up backpressure for conventional PRVs in the fire case where 21% overpressure is expected for a PRV set at the protected system MAWP.

To further illustrate, consider a 1E2 PRV set at 100 psig and relieving air with a piping system designed to meet 3% non-recoverable inlet loss and 21% built-up backpressure at 21% overpressure. When evaluated at 10% overpressure the inlet loss is expected to be within allowable limits, but the backpressure may be excessive. Refer to calculation data in Table 3 and Table 4.

Table 3: Implication of Piping Designed at 21% Overpressure on Force Balance for 1E2 set at 100 psig

	Fluid	Air		n-Hexane	
	Overpressure	21%	10%	21%	10%
Relief Pressure	psig	121	110	121	110
Relief Temperature	°F	81.4	81	325	317
Flow Rate	lb/h	2,130	1,960	2,891	2,645
Inlet Pipe	ft (1" Sch80S)	2.75		4.75	
Outlet Pipe	ft (2" Sch80S)	220		250	
Non-recoverable Inlet Loss	psi & % of set	2.9	2.7	3	2.7
Built-up Backpressure	psig & % of set	20.9	18.6	20.3	17.8

Table 4: Implication of Piping Designed at 21% Overpressure on Force Balance for 4P6 set at 100 psig

	Fluid	Air		n-Hexane	
	Overpressure	21%	10%	21%	10%
Relief Pressure	psig	121	110	121	110
Relief Temperature	°F	81.4	81	325	317
Flow Rate	lb/h	71,858	65,985	96,837	88,672
Inlet Pipe	ft (4" Sch40)	7.5		11	
Outlet Pipe	ft (6" Sch40)	33		44	
Non-recoverable Inlet Loss	psi & % of set	3	2.8	3	2.8
Built-up Backpressure	psig & % of set	20.9	18	20.9	17.9

One can clearly see that at 10% overpressure, the subject 1E2 PRV will fail the force balance test as the inlet pressure loss plus built-up backpressure is greater than the overpressure plus typical blowdown.

Conclusions

While in principle a conventional PRV will tolerate higher backpressure at higher overpressure, the PRV must still pass through the rated 10% overpressure point before reaching higher overpressure. If a PRV is chattering or exhibiting other signs of instability during opening when at 10% overpressure it may not necessarily stabilize at higher overpressure.

A PRV may transition from the instability at 10% overpressure by simply jumping to stable operation as higher overpressure is applied; however, a prudent relief system designer will first ensure the inlet and outlet pressure losses are within recommended limits at rated capacity before verifying built-up backpressure is within allowable overpressure at higher allowances.

To avoid misidentifying non-issues or missing opportunities for improvement, when performing relief system design and updating design basis documentation in accordance with OSHA 29CFR 1910.119, inlet and outlet pressure drop should be calculated based on the rated PRV capacity and 10% overpressure.