Modeling Pressure Relief Devices Mounted on a Common Inlet Manifold

Neil Prophet
ioMosaic
1900 St James Place, Suite 700, Houston, TX 77056
nprophet@iomosaic.com

Charles Lea, P.E.
ioMosaic
401 North 3d St, Minneapolis, MN 55401
Lea.c.mn@iomosaic.com

Indira Samayam, PhD
ioMosaic
1900 St James Place, Suite 700, Houston, TX 77056
samayam.i.tx@iomosaic.com

Prepared for Presentation at
American Institute of Chemical Engineers
2020 Spring Meeting and 16th Global Congress on Process Safety
Houston, TX
March 30 – April 1, 2020

Modeling Pressure Relief Devices Mounted on a Common Inlet Manifold

Neil Prophet
ioMosaic
1900 St James Place, Suite 700, Houston, TX 77056
nprophet@iomosaic.com

Charles Lea, P.E., Indira Samayam, PhD
ioMosaic

Keywords: overpressure protection, pressure relief

Abstract

Large equipment items, such as distillation column systems, compressors, or major pressure vessels, are commonly protected by multiple pressure relief devices mounted on a common inlet manifold. In selecting this type of design, the potential exists to inadvertently overlook the flow characteristics associated with such a common inlet manifold.

ioMosaic has developed a methodology to effectively model flow through multiple pressure relief devices mounted on common inlet manifolds. This approach ensures accurate representation of flow through each pressure relief device while avoiding the potential pitfalls of a simplified approach.

1 Introduction

Large equipment items, such as distillation column systems, compressors, or major pressure vessels, are frequently protected by multiple pressure relief devices. Often, multiple pressure relief devices are needed to provide adequate relief capacity to handle the large relief flowrates from overpressure scenarios affecting these large systems. Additionally, the set pressures of these relief devices can be staggered to better address varied relief requirements and to improve pressure relief device flow stability.

It is also fairly common practice for these multiple relief devices to be mounted on a common inlet manifold. Installing these devices on such a piping manifold can provide easier access for maintenance and inspection by locating these on a platform or deck, as well as providing the strong structural support needed for multiple heavy relief devices.

However, in selecting this type of design, the potential exists to inadvertently overlook the flow characteristics associated with such a common inlet manifold. Modeling the flow hydraulics to multiple relief devices through such a manifold is more complex than most companies realize, and the potential exists to overlook the impact that the inlet manifold has on the stability of each component relief device.

This paper presents a methodology to effectively model flow through multiple pressure relief devices mounted on common inlet manifolds. This approach ensures accurate representation of flow through each pressure relief device and intends to avoid the potential pitfalls of a simplified approach.

2 System Description

Relief systems inlet manifolds are fairly common on systems requiring overpressure protection by multiple large pressure relief devices, such as column systems or compressor systems. An example of a manifold can be found on Figure 1.

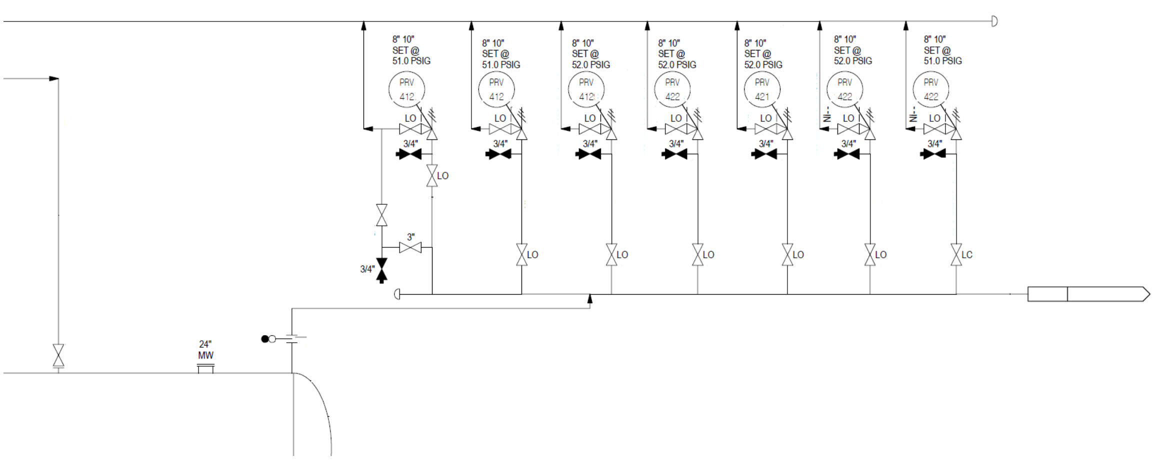

Figure 1. Example of multiple pressure relief valves on common inlet manifold

A typical system involves a separate piping manifold branching off from the process line; for example, a separate manifold may be attached to a vapor overhead line coming from the top of a column. Typically, the overhead process line will flow downwards such that the piping leads to a condenser deck on an elevated platform. The relief piping inlet line manifolds are usually located on this condenser deck, allowing easier access for installation, maintenance and inspection. Figure 2 shows a line of pressure relief valves located together on a common platform.

Figure 2. Example of pressure relief valves located together on platform

One or more of the pressure relief valves on the inlet manifold will typically be a spare. The use of spares is recommended when any interruption to the process for maintenance or replacement of the relief device would be costly or unsafe. With large continuous processes which are designed to run for two or three years without scheduled interruption, it is common to incorporate spares, and this is typically written into the unit design philosophy.

It is also for common manifolds to be located on the discharge piping of multiple pressure relief devices. Based on American Petroleum Institute (API) Standard 520, Part II [1], the discharge piping manifolds must be sized so that in the worst case (i.e. when all the manifolded pressure relief valves are discharging), the pipework is large enough to cope without generating unacceptable levels of backpressure. Ideally, the volume of the manifold should be increased as each valve outlet enters it, and these connections should enter the manifold at an angle of no greater than 45° to the direction of flow. Due to the reaction forces developed during a relieving incident, the manifold may also need be properly secured to a supporting structure; and it should be designed to drain downwards, in the event of two phase or liquid relief.

An example of pressure relief valves discharging to a common manifold is shown in Figure 3 below.

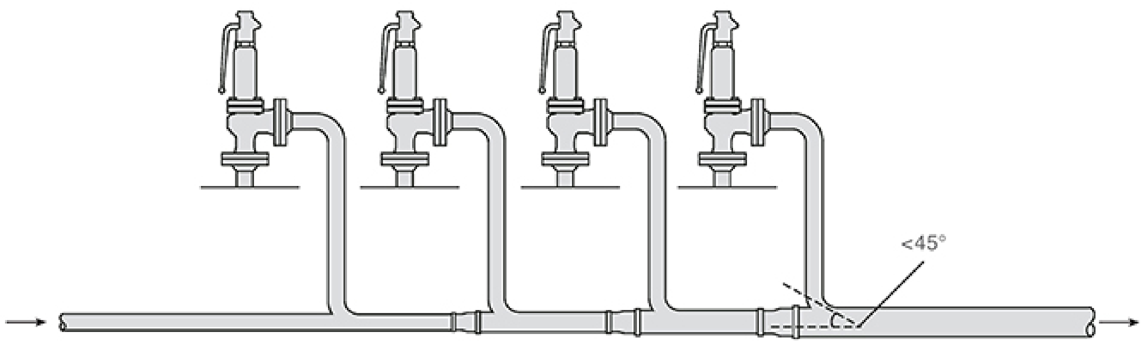

Figure 3. Pressure relief valves discharging to a common manifold

3 Design Considerations

A review of pressure relief systems design codes and standards such as Standard 520 Part II [1], American Society for Mechanical Engineers (ASME) Section VIII Appendix M [2], and Center for Chemical Process Safety (CCPS) Guidelines for Pressure Relief and Effluent Handling [3] shows that inlet piping manifolds are not discussed in detail, even though they are commonly used in facilities. As such, there is minimal guidance on designing these systems. However, there are a few rules which must be followed:

Minimum Diameter

In the event that insufficient flow area is allowed for in the inlet piping, flow to the pressure relief valve will be ‘starved,’ potentially resulting in unstable flow and chatter.

For inlet piping to multiple relief valves, the piping that is common to multiple valves shall have a flow area that is at least equal to the combined inlet areas of the multiple PRVs connected to it."

This is also covered in ASME Section VIII Appendix M, Section M-6 paragraph b [2], which states "When two or more required safety, safety relief, or pilot operated pressure relief valves are placed on one connection, the inlet internal cross-sectional area of this connection shall be either sized to avoid restricting flow to the pressure relief valves or made at least equal to the combined inlet areas of the safety valves connected to it. The flow characteristics of the upstream system shall meet the requirements of (a) above with all valves relieving simultaneously."

Set Pressure

In cases with multiple pressure relief valves in parallel, it is a good practice to have staggered set pressures of the pressure relief valves in service. This is due to the fact that the installed pressure relief valves may be exposed to a variety of scenarios with significant capacity variations. With a staggered arrangement, the PRV with the lowest setting will open first, and should be capable of handling minor upsets itself. Additional pressure relief valves will then open as the capacity requirement increases.

For example, both ASME Section VIII [2] and API Standard 520, Part 1 [1] state that the maximum allowable set pressure for a single pressure relief valves shall equal the maximum allowable working pressure (MAWP) of the protected equipment. However, for additional pressure relief valves, the maximum allowable set pressure for additional pressure relief valves is either 5% above the MAWP for process overpressure or 10% above the MAWP for external fire exposure. This arrangement is intended to ensure stable pressure relief valve operation in the case of a multi-valve system and avoid the potential for chatter.

It must also be observed that, if the first pressure relief valve lifts and relieves into a common manifold, this could result in the additional, staggered pressure relief valves experiencing higher backpressures than their design bases.

Inherently Problematic Pressure Relief Valves

Inlet piping manifolds tend to incorporate large pressure relief valves; due to the very nature of their application, large pressure systems generally require large relief areas. However, these larger pressure relief valves are inherently more problematic when it comes to inlet pressure loss issues, and they can commonly exceed 3% inlet pressure loss between the protected equipment and the pressure relief valve. It is important that this is understood and accounted for when performing pressure relief design calculations.

The inherently problematic nature of certain pressure relief valves is due to some pressure relief valves having a beta (area) ratio greater than 0.66, where the beta ratio (d/D) is calculated as the ratio of the valve throat / nozzle diameter (d) to the valve inlet diameter (D).

Table 1 below illustrates which valves may or may not experience a higher likelihood of inlet pressure drop issues due to a high beta ratio (those shown in yellow). It may be necessary to consider alternatives to inherently problematic spring-loaded pressure relief valves, such as the use of pilot operated pressure relief valves, or the use of reducers at the pressure relief valve inlet.

Table 1. Common standard pressure relief valve sizes (higher likelihood of pressure drop issues shown in yellow)

Letter Designation	ASME Area [in²]	API Area [in²]	Nominal Pipe Size (Inlet x Outlet) 1 x 2	1½ x 2	1½ x 2½	1½ x 3	2 x 3	2½ x 4	3 x 4	4 x 6	6 x 8	6 x 10	8 x 10
D	0.1279	0.110	☑	☑	☑								
E	0.2279	0.196	☑	☑	☑								
F	0.3568	0.307	☑ (yellow)	☑	☑								
G	0.5489	0.503			☑	☑	☑						
H	0.9127	0.785				☑ (yellow)	☑						
J	1.496	1.287					☑ (yellow)	☑	☑				
K	2.138	1.838							☑				
L	3.317	2.853							☑ (yellow)	☑			
M	4.186	3.600								☑			
N	5.047	4.340								☑			
P	7.417	6.380								☑ (yellow)			
Q	12.85	11.05									☑ (yellow)		
R	18.60	16.00									☑ (yellow)	☑ (yellow)	
T	28.62	26.00											☑ (yellow)

Performing Calculations for the Pressure Relief Valve with Longest Inlet Piping

In simple design calculations, it is typical to perform sizing calculations for the furthest pressure relief valve in the inlet manifold system, i.e. the one with the longest section of inlet piping. The logic being that this will yield the highest inlet pressure drop for the system. While this may be true, modeling just one pressure relief valve in the system can overlook the potential for unstable flow during relief. In reality, when multiple pressure relief valves may flow more than what the system can provide, causing the pressure to drop to below each pressure relief valve's reseating pressure.

A mild case of this occurring results in cycling. Cycling occurs when a pressure relief valve opens and closes at a relatively low frequency (e.g. a few cycles per second to a few seconds per cycle). Once the pressure relief valve is closed, the system pressure rebuilds to the pressure relief valve set pressure and the cycle repeats. The cycling frequency is dependent on the upstream system's ability to keep the valve open and is much lower than the natural frequency of the valve. Cycling does not typically cause damage to the pressure relief valve, since the seat is not impacting the disk at each cycle; however, the valve's ability to reseat tightly may be affected and it may cause some wear over time.

In more severe cases where flow to the pressure relief valves cannot be sustained, the resulting effect is chatter, rather than cycling. Problems associated with chatter are discussed later in this paper.

Acoustic Induced Vibration

Pressure reducing devices, such as pressure relief valves, can generate high acoustic energy that excite the pipe shell vibration modes. This acoustic-induced vibration (AIV) leads to fatigue failure in the process piping or small-bore connections and generates broadband sound radiation in the range of 500 Hz to 2000 Hz.

Unless controlled, AIV results in catastrophic piping failures; and is listed as a requirement of relief systems documentation in API Standard 521 [4].

In some cases, multiple smaller pressure relief valves connected on a common inlet manifold have been selected as a mitigation to replace large individual pressure relief valves which were experiencing inlet pressure loss, chatter and/or AIV problems.

Chatter

Chattering is an abnormal reciprocating motion of the movable parts of a pressure relief valve, where the valve disk contacts the seat. The pressure relief valve opens and closes at a very high frequency (in the range of the natural frequency of the valve's spring/mass system).

The effect of chatter can result in loss of containment due to component damage caused by pressure pulsation or impact loading from rapid hammering of the valve disk onto the valve seat. Chattering can also result in reduced pressure relief valve flow capacity. Additionally, the chattering can cause valve seat damage and mechanical failure of valve internals (such as galling and bellows failure).

The purpose of the 3% inlet pressure loss rule found in both ASME [2] and API [1] codes is to reduce the likelihood of chatter from occurring, although it must be observed that chatter can occur in systems with inlet pressure losses lower than 3%. For this reason, it is important that every pressure relief valve in a common relief valve inlet manifold is accurately modeled and understood.

4 ioMosaic Methodology

ioMosaic has developed an iterative steady-state methodology to effectively model flow through multiple pressure relief devices mounted on common inlet manifolds. This approach ensures accurate representation of flow through each pressure relief device and avoids the potential pitfalls of a simplified approach.

In order to accurately model flow through a manifold, it is necessary to determine the required rate that will limit the pressure in the upstream protected equipment to the allowable accumulation. Figure 4 shows a simple common inlet arrangement.

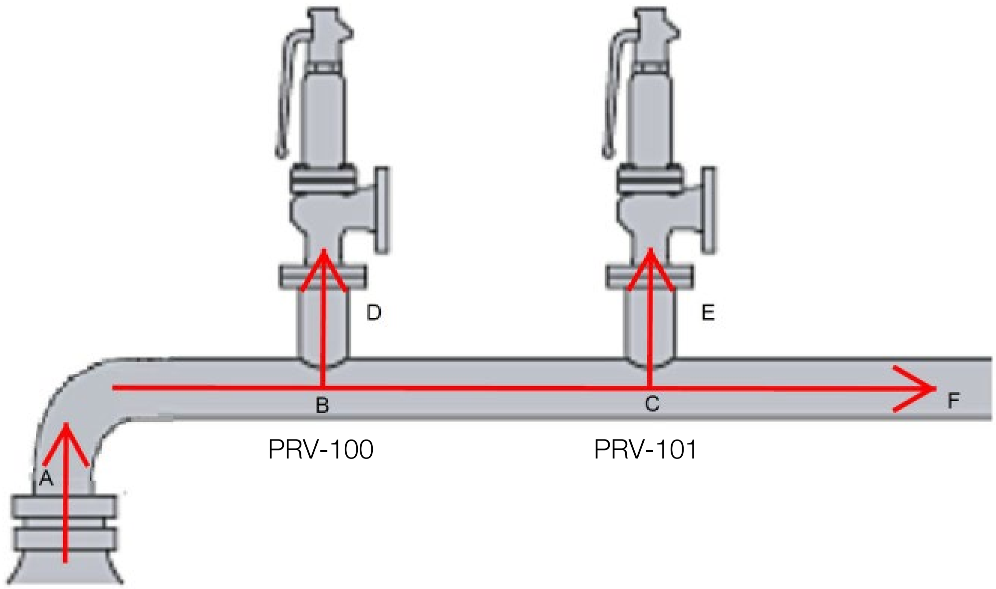

Figure 4. Example common inlet manifold

The system should be designed to provide the necessary capacity to handle the required flow rate, considering the combined flow through pressure relief valves at D & E, in addition to the continued flow downstream at F. Calculating the relief system performance starts at the exit of the protected equipment (A). From A to B, the design flow rate is the full required rate needed to maintain pressure.

The irreversible pressure loss attributable to pressure relief valve D in accordance with the 3% "rule" is determined by adding the pressure drop from normal flow from A to B to the pressure drop of the normally non-flowing segment from B to D at the greater of either the required rate or the capacity of pressure relief valve D.

If the required relief rate is met, no further analysis is necessary. However, if pressure relief valve D capacity does not meet the relief requirement, then the difference in flow continues downstream to the relief device at E.

The irreversible pressure drop for pressure relief valve E is then determined by adding pressure drop through the normally non-flowing segment from C to E with the added pressure drop determined for A to C.

It is common when performing pressure relief systems calculations, to assume that downstream processes will maintain normal set flowrates (rather than allow for a favorable system response) and therefore increased or decreased pressure drops in the normal process piping is not considered.

The required inputs in this methodology include:

- Relief temperature of the fluid for the overpressure scenario
- Relief pressure
- Superimposed backpressure
- Discharge coefficient for the relief
- Flow area of the relief device
- Composition of the fluid to be relieved
- Relief piping layout

Worked Example

To illustrate this approach, consider a system relieving a light hydrocarbon mixture through two 4” P 6” pressure relief valves which share a common inlet manifold. The inlet manifold starts as 8” diameter and expands to 10”. Input design parameters used in this example are provided in Table 2:

Table 2. Worked example design input parameters

Tag	Set Pressure (psig)	Orifice Letter	Kd	A (in2)	Relief Temp (°F)	Relief Pressure (psig)*
PRV-100	185	P	0.878	7.417	170.5	214.6
PRV-101	185	P	0.878	7.417		

*based on 16% allowable overpressure

For this manual steady-state iterative approach, the following steps are necessary:

1. The user must first establish the flow capacity through the relief devices assuming an inlet pressure to the branch connections, B and C shown in Figure 3. A good first guess is to assume zero pressure drop between the protected equipment and the pressure relief valve. This will give the maximum possible flux through the system. Using the direct integration method to solve for the mass flow yields a value of 23,050 lb/hr/in^2 in this example. Using the mass flux, together with the relief area and discharge coefficient in Table 2, shows that the maximum mass flow rate through one pressure relief valve is approximately 150,100 lb/hr. Since this relief system has two pressure relief valves of the same size, the estimated total relief rate is 300,200 lb/hr. This total relief rate is used as an estimate of the total flow in the common inlet piping (Path A-B in Figure 4).

2. The next step is to determine the pressure drop in the common inlet line (Path A-B). For this example, the layout in Figure 5 is used:

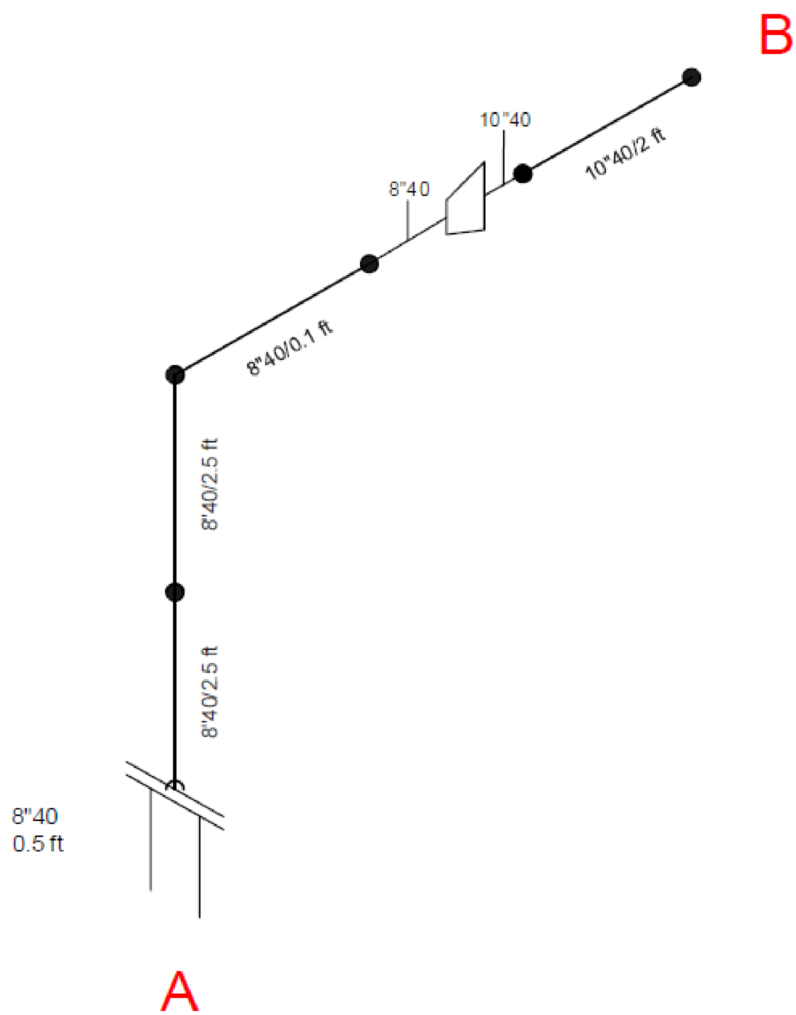

Figure 5. Common Inlet Piping Example

The pressure and temperature at A are assumed to be relief conditions and the mass flow rate is estimated in Step 1 above. With this information the pressure and temperature at B can be computed. For this example, the pressure and temperature at B are determined to be 213.4 psig, and 170.5°F.

3. For this step the individual pressure relief valve layouts are split into Figures 6 and 7. Note that both layouts start at B, whose conditions were computed in Step 2. Since the inlet conditions and outlet conditions (atmosphere in this example) of each pressure relief valve layout are known, the approach is to compute the mass flow rate through each layout individually. The goal is to result in the combined mass flow rate through each of the individual pressure relief valve layouts be similar to the flow rate that was determined in Step 1 and used in the common inlet piping calculation (Path A-B) in Step 2.

Table 3. Results of Step 3 – 1st Iteration

	Common Inlet	PRV-100	PRV-101
Inlet Pressure (psig)	214.60	213.37	213.37
Inlet Temperature (°F)	170.54	170.53	170.53
Mass Rate (lb/hr)	300,200	146,300	146,300
Pressure losses (psi)	2.35	4.39	4.39

Total Flow (lb/hr)	292,600	
Total irreversible pressure losses (psi)	6.74	6.74
Total pressure losses, % of Set Pressure	3.64	3.64

The calculated mass flow rate through the pressure relief valves (downstream of B) is 292,600 lb/hr versus the 300,200 lb/hr used to compute the pressure drop in the common inlet piping (upstream of B). The mass balance around B does not match up exactly but is within 2-3%. Since the initial 'guessed' mass flow rate in Step 1 was the maximum flow rate through the pressure relief valves, the solution is effectively bracketed between the mass flow rates listed in the table above.

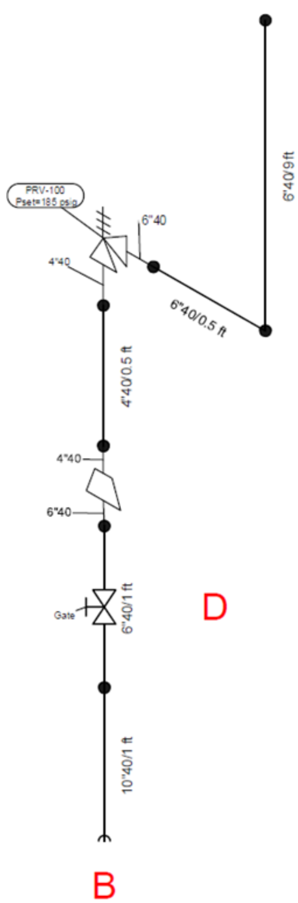

Figure 6. PRV-100 Layout from B

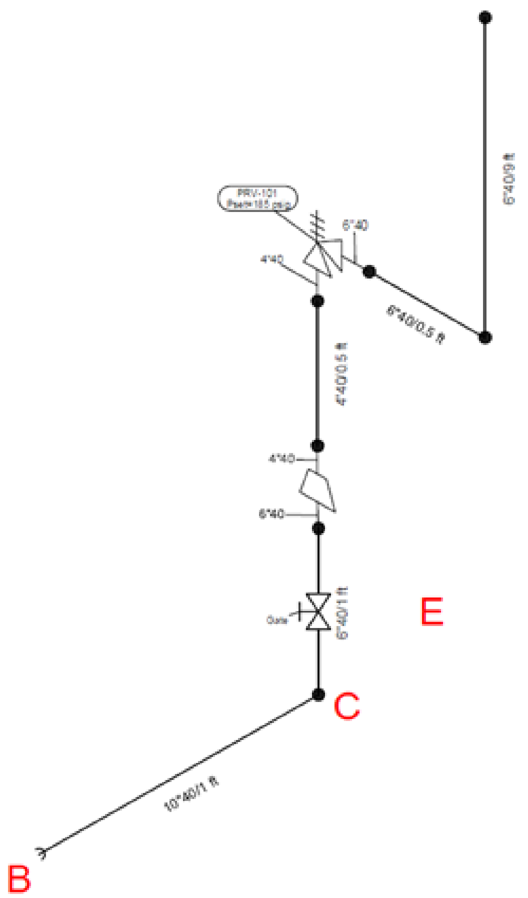

Figure 7. PRV-101 Layout from B

4. Steps 2 & 3 are repeated with a new 'guessed' flow rate and branch connection pressure at B until the flow through the common inlet piping system matches the flow through the pressure relief valve layouts.

Table 4 – Final Iteration

	Common Inlet	**PRV-100**	**PRV-101**
Inlet Pressure (psig)	214.60	213.42	213.42
Inlet Temperature (°F)	170.54	170.53	170.53
Mass Rate (lb/hr)	293,000	146,346	146,346
Pressure losses (psi)	2.24	4.39	4.39

Total Flow (lb/hr)	292,692	
Total irreversible pressure losses (psi)	6.63	6.63
Total pressure losses, % of Set Pressure	3.58	3.58

The methodology is considered completed when a reasonable convergence of mass and pressure has been met. Table 4 shows the results when the mass rates are within 0.5% convergence. Now that the pressure profile has been developed, the irreversible inlet losses can be totaled. This consists of the irreversible pressure drop in the common inlet piping in addition to the pressure drop through the individual pressure relief valve layouts. In this worked example the 3% inlet line pressure drop has been exceeded. It is interesting to note that without considering the irreversible losses in the common inlet piping (path A to B), the pressure relief valves would not exceed the 3% limit.

The common inlet piping (path A to B) can be large diameter process piping or part of a large diameter manifold system. Additionally, the pressure relief valve piping, which branches off the common inlet piping can be small by comparison.

Another point to note is that API Standard 520, Part 2 [1] states that 'when a pressure-relief valve is installed on a normally flowing process line, the 3% limit should be applied to the sum of the loss in the normally nonflowing pressure relief valve inlet pipe and the incremental pressure loss in the process line caused by the flow through the pressure relief valve'. In other words, relief flow may not be the only consideration when computing pressure drop through a process line with normal flow. The method provided above can accommodate this requirement by adding other flow in the process line in addition to the flow through the pressure relief valves in Step 2.

The outputs from this approach include:

- Relief temperature of the fluid for the overpressure scenario
- Discharge pressure
- Flow capacity through each pressure relief valve in the protected system
- Inlet pressure losses for each pressure relief valve
- Total backpressure in discharge piping (superimposed and built-up)
- Piping reaction forces
- Consideration of acoustic induced vibration

5 Further Work

In the event that the steady state analysis described in Section 4 shows inlet pressure losses exceeding 3%, further analysis can be conducted through either a steady state "force balance" analysis or a more detailed one-dimensional fluid dynamic analysis.

The detailed pressure relief valve one-dimensional dynamic analysis methodology exists for the evaluation of complex piping arrangements for all types of flow including vapor, liquid, two-phase, supercritical, and subcooled flows.

Dynamic methods exist for analyzing pressure relief systems including vessels, and the associated relief systems (inlet line, pressure relief valve, and discharge line). These detailed dynamics are extremely useful when analyzing systems with very long inlet lines, systems packed with liquid or high-pressure fluid, and where multiple pressure relief valves are involved.

The dynamic analysis method can provide insight a variety of considerations, such as:

- how long it takes to fill the discharge piping
- how the discharge pipe can continue to flow during pressure relief valve cycling or chatter
- whether the rapid cycling is likely to damage pressure relief valve bellows
- if air or other fluids can be ingested into the discharge line during a downsurge
- retrograde and phase changes during wave phenomenon for pressure upsurge and downsurge, i.e. vapor bubble collapse and liquid column separation
- how the system volume/capacitance can influence pressure relief valve stability
- how acoustic reflection points associated with area changes impact pressure relief valve lift
- how pressure rise rate at the source influences pressure relief valve lift, flow capacity of pressure relief valves at reduced lift
- interaction between multiple pressure relief valves with different set points
- how rapid pressure drop from small volumes can sometimes outpace pressure relief valves closing and, as a result, the pressure relief valves will close at much lower pressure than the actual blowdown pressure (dynamic blowdown), etc.

The theory and application of the dynamic analysis are discussed further in separate papers developed by Dr. Georges Melhem of ioMosaic Corporation [5].

6 Conclusions

This paper concludes with the following thoughts:

1. Piping manifolds are commonly used but complex to calculate, and present opportunities for errors.

2. Large pressure relief valves, common in use on piping manifolds, are more susceptible to inlet pressure losses.

3. The current calculational methods commonly in effect are not as accurate as they should be.

4. Modeling inlet piping manifolds inaccurately can lead to problems such as acoustic inducted vibration, structural issues, or chatter.

5. This paper presented an iterative approach to evaluating flow and inlet pressure losses that addresses gaps in the current methodologies.

6. In some cases the use of more complex tools, such as dynamic modeling, can be employed if more advanced assessment is required.

The methodology presented in this paper offers an easily applied steady state approach to checking stable operations of each pressure relief valve in a protected system.

7 References

[1] "Sizing, Selection, and Installation of Pressure Relief Devices in Refineries" 6th Edition, API Standard 520 Parts I and II, 2013, 2015

[2] ASME Section VIII, Division 1 - Design and Fabrication of Pressure Vessels, Appendix M, 2019

[3] CCPS, Guidelines for Pressure Relief and Effluent Handling, 2nd Edition, 2017

[4] "Pressure Relieving and Depressuring Systems", 6th Edition, API Standard 521, 2014

[5] G.A Melhem, PhD, "Analysis of PRV Stability In Relief Systems Part V – Get a Handle on PRV Stability", 2019