Technical Paper

A Review of Relief Valves in Unsteady Flow

Behavior, Analysis, and Design

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A REVIEW OF RELIEF VALVES IN UNSTEADY FLOW - BEHAVIOR, ANALYSIS, AND DESIGN

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ABSTRACT

Pressure relief devices (PRDs) are used to protect system components from high pressures. Appropriately sized devices eliminate these high pressures while relieving a minimal amount of process fluid. As a result, they are frequently found in both incompressible and compressible systems to relieve overpressures. However, relief devices are historically known to be ineffective for handling surge overpressures. While PRD standards and sources simply encourage the avoidance of surge, it is an inevitability within most systems and the interaction between surge and PRDs, both conventional and surge-mitigating, are investigated here within.

This paper discusses the basics of PRD terminology, mathematical PRD models, and PRD computer simulation modeling with associated examples. Basic design principles, guidelines for identifying at-risk-for-surge systems, and relief valve selection criteria for surge mitigation are presented.

Keywords: relief devices, relief valves, surge, water hammer, unsteady flow

NOMENCLATURE

a	Wavespeed [m s^{-1}]
A	Valve plug area [cm^2]
B^+, B^-	Compatibility impedance [kPa kg^{-1} s]
c	Speed of sound; celerity [m s^{-1}]
C^+, C^-	Compatibility capacity [kPa]
F	Force acting on valve plug [N]
F_s	Force of spring on valve plug [N]
F_w	Weight of valve plug [N]
g	Gravitational acceleration constant [m s^{-2}]
k	Valve plug acting spring stiffness [N m^{-1}]
K	Effective discharge coefficient
K_v	Flow coefficient [m$^3_{\mathrm{H_2O,STP}}$ hr^{-1} bar$^{-0.5}$]
m	Valve plug mass [kg]
$\dot{m}$	Mass flow rate [kg s^{-1}]
p	Static pressure [kPa]
R	Flow resistance coefficient [kPa s^2 kg^{-2}]
u	Flow velocity [m s^{-1}]
x	Valve plug vertical lift [m]
$\ddot{x}$	Valve plug acceleration [m s^{-2}]
x_0	Spring rest position [m]
ρ	Static density [kg m^{-3}]

1. INTRODUCTION

Piping systems are frequently designed for operation at nominally steady-state conditions, with system components to maintain this operation. Fluctuations within and between these operable conditions instigate system overpressures that damage components, create safety hazards, and cause significant economic losses. These fluctuations and overpressures can commonly be mitigated with pressure relief devices (PRDs) – a safety component designed to crack open in response to excess pressure in the system. Ideally, the PRD relieves excess pressure to ensure internal pressures stay below the maximum allowable working pressure (MAWP), where damage and other failure cases normally occur.

Within compressible flow applications, PRDs accompany boilers and pressure vessels to protect them from overfilling, excessive heating, unexpected phase changes, and other events [1–3]. For incompressible flow applications, PRDs are often used to handle overpressures from thermal expansion or flashed process fluid in pressure vessels [4]. Additionally, PRDs can mitigate surge in incompressible systems with very specific types of PRDs – namely surge anticipation valves and surge relief valves. PRDs of incorrect type and size can exacerbate the effects of water hammer in a system, because of instabilities and self-sustained plug oscillations [5–7].

PRDs have interchangeably-used names in their categorization, which can lead to confusion across industries. Though this confusion is recognized [3, 8], the different terms for PRDs rec-

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TABLE 1: PRD Terminology according to API, as referenced by Helleman [4]

Reclosing Pressure Relief Devices	Pressure Relief Valve (PRV)	Generic valve designed to open and relieve excess pressure and reclose once normal operation restored
	Relief Valve (RV)	Externally loaded PRV – opens proportionally in response to inlet pressure rise
	Safety Valve (SV)	Spring-loaded PRV – opens rapidly to inlet pressure rise, often in compressible flow applications
	Safety Relief Valve (SRV)	Spring-loaded PRV – may be used as a safety valve or relief valve, depending on the application
Non-Reclosing Pressure Relief Devices	Rupture Disc	Thin disc that breaks when static pressure difference reaches set value – requires replacement
	Rupture Pin	Pin that bends/breaks at static pressure difference/inlet reaching set value – requires replacement
	Fusible Plug	Non-melting casing with fusible alloy at center – alloy melts at high temperatures to relieve - requires replacement

ognized by the American Petroleum Institute (API) are presented in Table 1 [4].

However, even API 521 recognizes that the terms pressure relief valves, pressure safety valves, relief valves, safety valves, and safety relief valves are all exchangeable with one another in industry. It is important to understand that engineers may have preconceived and incorrect notions about the terminology above. Unless otherwise specified for this paper, the term PRD will refer to all reclosing and non-reclosing relief devices and PRV will be used as a generic term for any reclosing PRD, as specified in Table 1 [8].

For generic PRDs, there is vast array of terminology to describe the different pressure setpoints of importance. However, unless otherwise specified, the relevant terms are those referenced by Helleman [4] and outlined below:

- *Set pressure/Pressure set point*: Increasing inlet static pressure at which a PRD operates with respect to its rated specifications (most often, the PRD opens)
- *Resealing/Reseating pressure*: Decreasing inlet static pressure at which the PRD is closed and no further leakage is detected
- *Opening/Cracking pressure*: Increasing inlet static pressure at which the PRD disc is fully loose from the nozzle
- *Blowdown*: Pressure difference between set pressure and reseating pressure, often expressed as a percentage of the set pressure or differential decrease below the set pressure
- *Overpressure*: Pressure increase over the set pressure at which the PRD flows nominal flow (usually at the point of full disc lift), often expressed as a percentage of the set pressure or differential increase over the set pressure

2. FUNDAMENTAL OPERATION

2.1 Steady Operation

All pressure-driven PRDs open similarly. The device has a pressure setpoint – such that when this setpoint is exceeded at the inlet, the device opens and relieves fluid. Once cracked open, the fluid relief rate is often proportional to the pressure difference across the device. The voided, moving fluid will cause the static pressure upstream of the inlet to decrease and will renormalize the line pressure with time. For reclosing devices, the plug will reseat once the inlet pressure drops below the resealing/reseating (sometimes referred to as blowdown) pressure. Non-reclosing devices remain open and relieve fluid until replaced.

When sizing a PRD, two steady-operating conditions are often considered. One case is trivial – the system is in normal operation, the valve is sealed, and no process fluid is relieved. While still trivial, it is important to ensure that normal operation does not crack the valve open and relieve fluid. The second case is the worst-case scenario for overpressure experienced by the relief valve in the system. This overpressure is determined in accordance with a standard such as API Standard 521 [8], and the PRD is sized for a flowrate to relieve that overpressure as specified in the correlating standard.

2.2 Transient Operation

Though PRDs are sized according to steady-state operation, they are passively transient devices. As the system experiences alterations of pressure, flowrate, and temperature, the valve cracks or closes (if reclosing) in response. Because the system actuates the valve, triggering transients may be the designed-for overpressure scenario or unexpected scenarios impacting the system.

Commonly in sources detailing PRD sizing [3, 4, 8–10], overpressures from water hammer are mentioned only insofar as to state that they should be avoided (with minimal insight on how), and that conventional PRDs do not control these transients. Transient pressure surges, such as water hammer, are inevitable transient phenomena in all systems – and any PRDs in the system will still be actuated by water hammer events.

Effects may be relatively minor - i.e. a relief valve cracking at inappropriate times. However, possible major impacts include relief valve chatter and generation of additional surge from the valve actuation [6, 11–14]. These issues lead to concerns about component and human safety, relief valve lifespan, and system reliability. With these issues in mind, it cannot be understated how important it is for engineers to understand surge as well as how surge interacts with passively transient components, such as PRDs.

2.2.1 Acoustic wave propagation. Transitions between steady operations cause transient disturbances to the flow. These disturbances propagate in acoustic waves that travel down the pipe – moving at a finite speed of sound throughout piping networks. These acoustic waves are coupled packets of pressure and velocity information, with magnitudes related proportionally to the speed of sound, c. On an infinitesimal scale, this relationship is characterized by the instantaneous water hammer equation,

$$dp = -\rho c du \tag{1}$$

For large amplitude acoustic waves (surge), the infinitesimal expression is unsatisfactory. Instead, the relationship is better characterized by the Joukowsky Equation for transient pressure rise [15],

$$\Delta p = -\rho a \Delta u \tag{2}$$

Note that the speed of sound is replaced with a wave speed, a, which also accounts for pertinent effects impacting the acoustic traveling speed, such as the surrounding pipe and pressure vessel walls. With reference to PRDs, the Joukowsky Equation is explained simply: when a PRD cracks open and flow begins, it will cause the pressure at the inlet to drop in response – which is the basic operation of the PRD. Correspondingly, when the reclosing PRD re-seats, the flow is suddenly halted and results in a pressure rise – generating an acoustic pressure wave that travels throughout the piping network. This resulting pressure wave can also be of a large amplitude, depending on the relief rate and speed at which the reseating event occurs – inducing surge of its own.

2.2.2 Surge Intensity. Equation (2) is used to calculate the maximum possible pressure surge from a fast transient event such as a valve closure. This is done by setting the Δu to the steady-state velocity, assuming the valve closes instantly. This calculation is usually assumed to be conservative by engineers performing a surge analysis. However, it has been shown that surge pressures higher than the Joukowsky prediction are possible [16] and it is suggested to utillize a full unsteady system simulation to investigate surge events [17].

3. PHYSICAL MODELING

3.1 Forces Acting on a Relief Valve

PRDs typically consist of a plug that is depressed against the valve seat by a spring. Forces acting on this plug dictate the PRD state, opening/closing speed, and plug position - all of which characterize transient behavior for the PRD overall. Four generalized forces act vertically on the plug shown in Fig. 1:

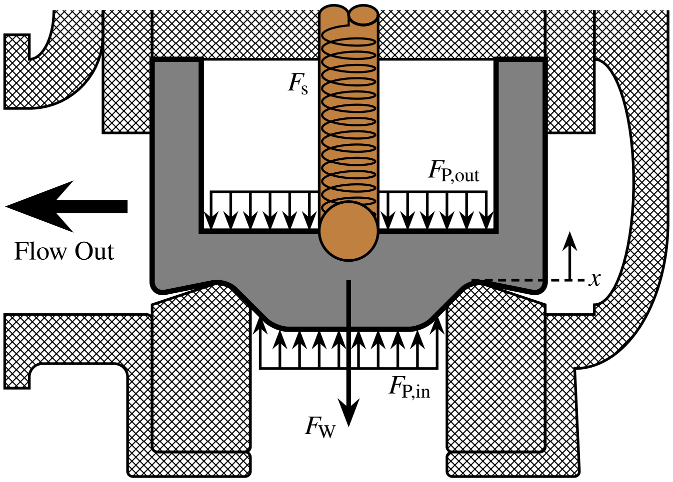

FIGURE 1: Generic PRV plug force diagram. Depicted forces are considered in reference to the vertical valve plug (gray) with mechanical contributions from an externally-acting spring (brown).

1. Force of the compressed spring pushing down on the plug.

$$F_s = k(x - x_0)$$

2. Force of the plug weight.

$$F_W = mg$$

3. Force applied by an inlet pressure on the cross-sectional area at the plug inlet - acting parallel to direction vector $\hat{\mathbf{i}}$, along x.

$$F_{P,in} = \int_{A_{in}} -p_{in} \left(\hat{\mathbf{i}} \cdot d\mathbf{S}\right)$$

4. Force applied by an outlet pressure on the cross-sectional area at the plug outlet - acting antiparallel to direction vector $\hat{\mathbf{i}}$, along x.

$$F_{P,out} = \int_{A_{out}} -p_{out} \left(\hat{\mathbf{i}} \cdot d\mathbf{S}\right)$$

Applying Newton's second law of motion:

$$\sum F_{plug} = F_{P,in} - F_{P,out} - F_s - F_W = m\ddot{x} \tag{3}$$

As the overpressure event begins, the inlet force exceeds the combined oppositional force of the spring, weight, and outlet pressure. The plug lifts upward and opens - relieving the overpressure. As the fluid is relieved and the overpressure event ends, the upstream pressure decreases - which causes the closing forces to exceed the opening force - thereby closing the plug.

Up to this point, the force balance in Eq. 3 is kept in a predominantly general form. It is meaningful to mention that this equation can be further simplified or complicated depending on the application. For instance, PRD lift performance curves are an industry-common means of characterizing PRD opening and closing behavior [3, 4, 10, 18]. These curves are usually provided by the PRD manufacturer and serve as a simpler alternative to solving Eq. 3 and correlating the plug position x to a relief rate. Alternatively, the force balance may be rewritten to incorporate multi-dimensional analyses - which allow the tracking of localized pressure differences in the nearby relieving fluid or vibrational analyses in the PRD mechanism itself [12, 19–21].

Equation 3 is simplified for the purposes of detailing differences between commonly used PRD types. A purely one-dimensional simplification has been made and the effect of differences in local pressure is ignored, resulting in the following reduced force balance:

$$p_{\text{in}}A_{\text{in}} - p_{\text{out}}A_{\text{out}} - k(x - x_0) - mg = m\ddot{x} \tag{4}$$

This generalized expression is the starting point for the characterization of varying PRD effects, as detailed further below. Note that in this general form, no assumptions have been made about the variability of pressure or relevant plug area with regards to time.

3.2 Balanced Model

Generic PRDs are often represented by Eq. 4. Two classifications - unbalanced and balanced PRDs - are often considered with regards to this equation. The differences between these two models are in the handling of the p_{out} term - such that the plug outlet-side pressure is sourced differently. PRDs with a plug downstream force dependent on a variable outlet pressure are referred to as unbalanced. An example is shown in Eq. 4, where the plug outlet-side pressure corresponds to a fluctuating pressure at the PRD outlet $p_{\text{out}} = p_{\text{e,PRD}}$.

When the PRD does not discharge directly to a constant pressure, the PRD outlet pressure fluctuates with flow through the device - instigating possibly erratic behavior in unbalanced PRDs. Balanced PRDs mitigate this effect by isolating the plug outlet from the PRD outlet, such that the plug outlet is subjected to a known constant pressure $p_{\text{c, out}}$ instead - such as an ambient pressure, as shown in Eq. 5.

$$p_{\text{in}}A_{\text{in}} - p_{\text{c, out}}A_{\text{out}} - k(x - x_0) - mg = m\ddot{x} \tag{5}$$

3.3 Remote Sensing Model

Remote sensing PRDs are pilot-operated devices - which maintain a high closing force at the plug outlet, such that the outlet-side pressure is typically maintained at the PRD inlet pressure via a control pilot.

$$p_{\text{in}}\left(A_{\text{in}} - A_{\text{out}}\right) - k(x - x_0) - mg = m\ddot{x} \tag{6}$$

The plug outlet area that experiences this closing pressure effect is typically larger than the area at the plug inlet while the PRD is closed. In this state, the outlet plug force exceeds the inlet plug force - keeping the plug sealed.

High pressure is maintained at the plug outlet by a small line between the plug outlet chamber and PRD inlet. There is a pilot valve on this line normally open to the PRD inlet and chamber, but closed to the atmosphere. As the pilot triggers to open (at the PRD set pressure), it isolates the chamber from the inlet pressure and vents the chamber's pressure to a constant pressure source (such as the atmosphere) rapidly, equilibrating the plug outlet pressure to that pressure source, such as in Eq. 5, allowing the plug to displace more easily and unseat.

For remote sensing devices, the pilot valve has a sensing line connected to a location elsewhere in the system. When pressure at that location exceeds a target setpoint, the pilot switches position and vents the chamber. In this state, the PRD inlet is able to unseat the plug more easily - because the outlet chamber is no longer pressurized. When the pressure at the remote location recedes below the setpoint, the pilot valve switches to normal operating position. In normal operating position, the pilot line pressurizes the chamber with the pressure at the PRD inlet once again - preparing the PRD for another overpressure event. This repressurization is often limited by an orifice in the line between the chamber and PRD inlet, to control the closing mechanism for the PRD - mitigating slam or the possibility of an unintended surge.

The opening and closing rate of a remote sensing device depends on spring stiffness and ventilation/repressurization rate of the chamber. While it is possible for a remote sensing PRD to remain sealed by the spring alone despite a depressurized PRD outlet chamber, the opening and closing mechanism is much more sensitive to pilot valve position, which is dictated by remote pressure.

3.4 Surge Anticipation Model

Surge anticipation relief valves are a special type of remote-sensing pilot-operated PRDs. They attempt to anticipate high pressure waves originating from a reflected low pressure wave, originating from a driving event such as a pump trip or opening valve elsewhere in the system. Unlike remote sensing devices, surge anticipation relief valves operate in response to both high and low target pressure setpoints, and the remote sensing location is near or at the source of the low pressure wave.

A typical low pressure surge event is mitigated via a surge anticipation valve with the following steps:

1. Downsurge (from a pump trip, cracked valve, etc.) reduces pressure at remote location below low pressure setpoint
2. Low pressure control pilot ventilates PRD outlet chamber - preparing PRD for an incoming high pressure wave
3. Downsurge reflects elsewhere in system - creating an upsurge traveling in direction of primed PRD
4. Upsurge raises pressure at remote location above high pressure setpoint and raises PRD inlet pressure above PRD cracking setpoint - opening PRD and relieving fluid
5. PRD relieves fluid until pressure at remote location recedes below high pressure setpoint -or- PRD inlet pressure recedes below reseating pressure setpoint, at which point the plug reseats

Surge anticipation valve repressurization is similarly limited by an inline orifice between chamber and relief valve inlet, so that relief valve slam is mitigated - however, it reduces the effectiveness of a surge anticipation valve to respond to consecutive surge events. In most cases, surge anticipation valves also maintain the capability to crack once the remote sensing pressure rises above the high pressure setpoint - regardless of the status of the low pressure remote pilot, allowing surge anticipation valves to behave as a standard remote sensing pilot-operated PRD. In either the surge anticipation or surge response operation, the high pressure pilot controls the repressurization of the outlet PRD chamber.

4. COMPUTATIONAL MODELING

4.1 Method of Characteristics

The Method of Characteristics (MOC) is the premier method for modeling one-dimensional acoustic transients in liquid-full piping networks. This method is well documented in many references [17, 22], and will not be further discussed beyond the implications as they pertain to modeling systems with PRDs.

Derived from the fundamental equations of unsteady fluid dynamics, water hammer is representable with system of non-linear hyperbolic partial differential equations. The MOC simplifies these into ordinary differential equations, with a solution along wave paths. Making a liquid-flow assumption, these ordinary differential equations result in simple algebraic equations to relate flow and pressure along wave paths of a fixed wavespeed.

$$p = C^+ - B^+\dot{m} \qquad\qquad p = C^- + B^-\dot{m} \tag{7}$$

Equations (7) are linear and evolve the solution space with time by calculating $C^\pm$ and $B^\pm$ from the pressure and flow solution at previous points in time.

As a transient hydraulic event occurs such as a PRD cracking open, acoustic waves propagate away from the PRD inlet into the upstream piping system at the wavespeed. As these waves travel, the PRD inlet experiences a change in the pressure that remains until the waves reflect at a boundary and return to the inlet, renormalizing the pressure at the location. The amount of time for this to occur is called the communication time. If the time for the event to occur is less than the communication time, the resulting pressure surge can be approximated with the full Joukowsky pressure surge [15, 17].

4.2 Component modeling using MOC

The MOC specifies the interior piping network solution only – however, transients are initiated by connected components at the inlet or outlet of a pipe. For instance, a PRD is representable as such a component – and will impart a transient response on connected piping. For simple components with an upstream and downstream connected pipe, the incoming mass flowrate equates to the outgoing mass flowrate. Considering this using the compatibility equations shown in Eq. (7) results in a relationship for the mass flowrate to the pressure differential across the component.

$$\Delta p = (C^- - C^+) + (B^- + B^+)\dot{m} \tag{8}$$

Equation (8) can be applied to any simple component. For a valve, the left side of the equation is replaceable with an appropriate pressure drop model, depending on the behavior of the PRD. Frequently in liquid full systems, simplified loss components are assumed to fit to a generic quadratic resistance loss model [6, 14, 17, 23]. When this kind of loss model is coupled with Eq. (8), $\dot{m}_{\text{PRD}}$ can be solved for quadratically.

$$\dot{m}_{\text{PRD}} = \mp\frac{(B^+ - B^-)}{2R_{\text{PRD}}} \pm \sqrt{\left(\frac{B^+ + B^-}{2R_{\text{PRD}}}\right)^2 + \frac{(C^+ - C^-)}{R_{\text{PRD}}}} \tag{9}$$

Within the scope of Eq. (9), the values of R_{PRD}, $C^\pm$, and $B^\pm$ are all computed from the pipe solution and valve at the previous timestep. Note the plus-minus signage in the Eq. 9, indicating multiple mathematical solutions for the mass flowrate. However, one solution ($-,+$ configuration) is physically realistic only for flow exiting the valve - while the other ($+,-$ configuration) is realistic only for flow entering from the valve. With the resulting value for $\dot{m}_{\text{PRD}}$, Eq. (7) can be used to determine the inlet and outlet pressure of the PRD at that timestep. This cycle sets and computes the boundary conditions for the MOC pipe solution, until a final time is reached.

4.3 Special PRD considerations with the MOC

Modelling PRDs one-dimensionally with Eq. (9) requires a connecting pipe at the inlet and outlet, where the relieved fluid is computationally tracked as it passes into the outlet pipe. Alternatively, a PRD that relieves to some exit condition does not track the outlet pipe, meaning there are no wave characteristics to utilize on the downstream side. Instead, the pressure downstream of the PRD should be known (or calculable) and Eq. (9) reduces to reflect that, such that $B^- \rightarrow 0$ and $C^- \rightarrow p_{\text{out}}$.

The final computational configuration considered for a PRD is to model it as an inline exit PRD, such that the PRD has a connected inlet pipe, outlet pipe, and third flow path to a defined exit condition. In this configuration, the PRD pressure upstream of the inline exit p_{PRD} is calculable by summing the mass flow rates at the PRD and combining them with Eq. (7) before applying a resistive pressure loss model.

$$p_{\text{PRD}} = \frac{\frac{C^+}{B^+} + \frac{C^-}{B^-} - \dot{m}_{\text{exit}}}{\frac{1}{B^+} + \frac{1}{B^-}} \rightarrow \Delta p = p_{\text{PRD}} - p_{\text{exit}} \tag{10}$$

Following simplifications, Eq. (10) will result in a quadratic equation which can be solved for $\dot{m}_{\text{exit}}$ in a similar fashion to Eq. (9).

4.4 PRD resistance modeling

A relationship for the PRD flow resistance R_{PRD} is required for an MOC simulation. This resistance is often a function of plug position and geometric characteristics of the PRD – in which the former of these two parameters is transient in nature and is actuated by the system pressure. This relationship might be approximated with information provided by the PRD manufacturer - such as a PRD performance curve or lift curve - or it may be computationally modeled directly.

If approximated, the effective coefficient of discharge for a selected PRD may be assumed to vary linearly over the designed-for opening time, which should be provided by a manufacturer. While the real resistance profile will be nonlinear, this approximation will characterize the response better than an instantaneous opening assumption.

Alternatively, if the specific geometric properties for the PRD are known, then a physical model is determinable from a force-balance model of the plug. This type of model is frequently used for cases investigating reclosing PRD instabilities in the form of valve chatter or flutter [6, 12, 13, 24]. Utilizing this force-balance model will involve solving for the relationship presented in Eq. (3) for the plug position with respect to time. From this, valve

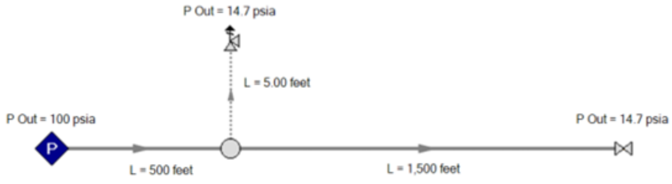

FIGURE 2: System with a conventional PRD

flow resistance is determined for a given plug position - and then an expression for the resistive pressure drop can be used in Eq. (10) to relate the pressure and flow rate at that timestep, and then solve quadratically for the mass flowrate - similarly to Eq. 9.

For cases where a representation of the system is not desired, three-dimensional CFD software is desirable to represent this force-balance model [12, 20]. However, use of a computationally expensive software is less desirable for generalized and larger piping systems that would be impacted by surge. Traditionally, CFD software such as this would have more pertinence toward investigating phenomena within a short distance to the PRD, such as the dynamic vibrational analyses of the PRD actuation. As a result, use of this force-balance method and higher-dimensional software will be omitted from the remainder of this paper – and the coefficient of discharge method will be used to approximate transient resistance at the PRD.

5. SIMULATIONS

The impact of an acoustic surge on various states of PRD operation is investigated using AFT Impulse 10 [25] and following the MOC as discussed previously. For each time step of the simulation, the state of the PRD in question is determined relative to the inlet static pressure in the upstream connecting pipe. When inlet pressure exceeds the pressure setpoint, the PRD cracks open and relieves flow. A variety of scenarios are discussed pertaining to conventional PRDs and surge-designed PRDs, and their behavior in response to surge. For the following scenarios, cavitation effects are ignored.

5.1 Conventional PRD instability in response to surge

A simple PRD system is considered in Fig. 2. Water (ρ = 998.6 kg m $^{-3}$) flows at an upstream specified static pressure p = 698.5 kPa (100 psia) through 10.23 cm (4 in) diameter pipeline of L = 609.6 m (2000 ft) with wavespeed a = 1219 m s $^{-1}$ (4000 ft s^{-1}) and downstream exit valve discharging to atmospheric conditions. The exit valve closes linearly over Δt_{close} = 0.1 seconds, which instigates an upsurge traveling up the pipeline. An exit relief valve (discharging to atmospheric conditions) is placed 152.4 m (500 ft) into the pipeline, with an inlet connection 1.52 m (5 ft) long. The relief valve is sized (K = 0.656, A_{orifice} = 20.8 cm^2) to relieve a pump deadhead event when the exit valve at the end of the pipeline remains closed for a substantial period. For the relief valve, the pressure set point p_{set} = 792.9 kPa (115 psia) and reseating pressure p_{reseat} = 758.4 kPa (110 psia) with a 72.4 kPa (10.5 psia) overpressure and a linear opening profile that takes 1 second to fully open or close.

One manner for PRD instability (valve chatter) to occur is when a relief valve cracks, and an inlet pressure loss results in PRD inlet pressure dropping below the reseating pressure [4]. With inlet pressure below reseating pressure, the PRD moves to shut the valve – instigating a pressure rise over the pressure setpoint and causing an instability cycle. For this simulation, a large entrance loss factor is applied to the branch junction upstream of the relief valve (see Fig. 2) to force this instability – which can be seen in Fig. 3.

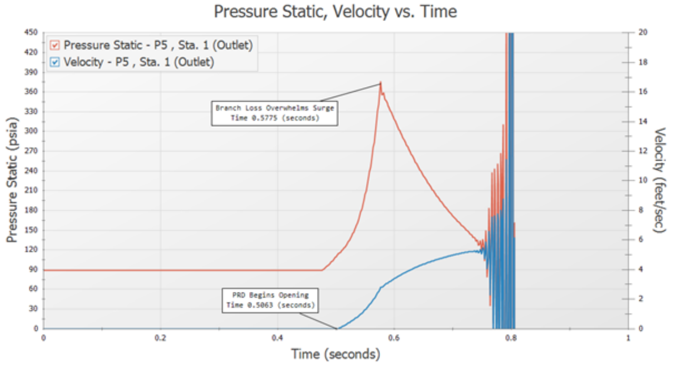

FIGURE 3: Demonstration of the PRD instability at the PRD inlet, comparing the static pressure (orange) and velocity (blue) at the valve inlet with the timing of the valve opening and process into the instability indicated.

The surge wave reaches the relief valve just before 0.5 seconds into the simulation, and it cracks the valve slightly after 0.5 seconds. As the valve opens and flow rate through the relief valve rises, the effectual frictional loss through the branch increases until it outweighs the surge pressure at the PRD inlet. Eventually, this causes the inlet pressure to fall below the reseating pressure and begin the instability behavior, which would be equivalent to a relief valve chatter. Because the PRD plug is not modeled with a force balance, this instability replicates unphysical pressure and velocity rapidly until the model cannot numerically recover.

Like other sources indicate [6, 12, 13], this instability appears to be influenced by the system configuration with respect to pipe length. If the relief valve branch is moved to either 30.48 m (100 ft) from the source pressure junction or the closing exit valve, the instability is no longer visible. While this example is certainly contrived, it is not difficult to translate this example to a real system. In a case where large amounts of resistive loss could significantly decrease the PRD inlet pressure, the resulting chatter can be devastating for both system and PRD alike.

5.2 Conventional PRDs sized for surge mitigation

Multiple sources and standards reflect that use of PRDs should be limited to alleviating traditional overpressure scenarios, and specifically PRDs should not be used for surge mitigation [8–10]. However, the authors believe it is valuable to demonstrate that while conventional PRDs can be sized to mitigate surge effectively, it is inconvenient to do so.

This simulation case uses a similar model to Fig. 2, but with the following notable changes. The branched exit relief valve is replaced by an inline exit relief valve and the specified static pressure is raised to p = 2068 kPa (300 psia). The PRD is set such that p_{set} = p_{reseat} = 2068 kPa (300 psia) with a 207 kPa

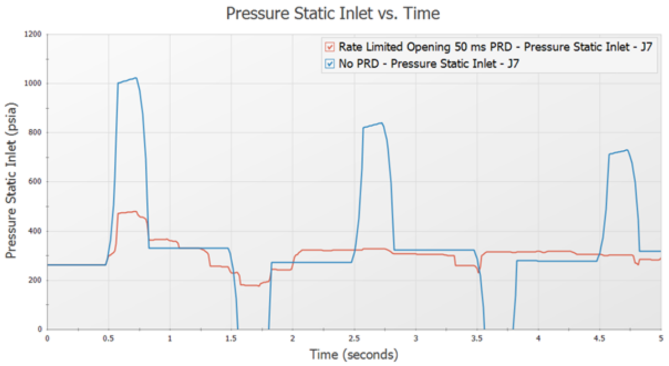

FIGURE 4: Comparison case of a PRD sized to mitigate the full surge wave in question (blue) with a 50 ms opening time PRD (red)

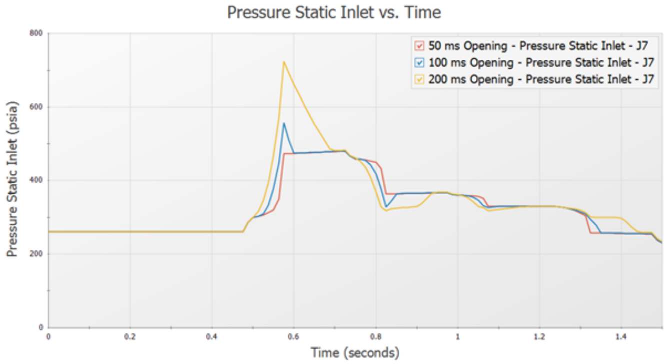

FIGURE 5: Comparison of opening duration for a conventional PRD sized for surge mitigation traced at the PRD upstream; the 50 ms opening duration simulation (red) exhibits peak shaving characteristics in comparison to the 100 ms duration simulation (blue) and 200 ms duration simulation (yellow)

(30 psia) overpressure and a linear opening and closing profile. The relief valve fully opens over 50 ms and closes effectively instantaneously.

For comparison, a case with no functioning PRD was also modeled to see the full impact of the pressure surge on the system unmitigated, which is compared against the 50 ms opening PRD. This comparison is shown in Fig. 4.

The PRD is opened just long enough to propagate a downsurge into the upstream pipe, which will counter the effects of the surge wave from the valve closure that occurs downstream of the PRD. This would behave as surge mitigation and system protection for all system components upstream of the PRD and would be extremely effective mitigation.

However, this surge mitigation is unrealistic – because it requires a PRD perfectly sized to counteract the surge wave. In a more complex system, the surge wave is not guaranteed to match the Joukowsky pressure rise [16], making the surge magnitude more difficult to predict - thus making it more difficult to size the relief valve reliably. Additionally, this requires a very fast opening PRD at 50 ms to full open. To visualize the effect of slightly slower opening PRDs, the case of a 100 ms and 200 ms opening duration are also simulated and shown in Fig. 5.

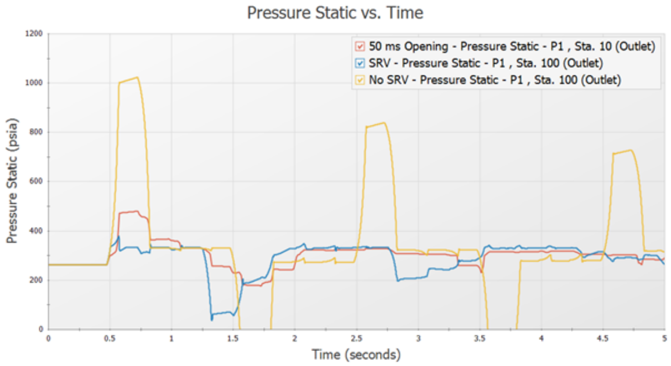

FIGURE 6: Transient static pressure tracing upstream of the PRD, where the surge relief valve simulation (blue) is compared to the unmitigated surge simulation (yellow) and the conventional surge-mitigating PRD with a 50 ms fully opening duration simulation (red)

Figure 5 demonstrates the phenomenon of *peak shaving* at the onset of the upsurge to the PRD inlet. Though unrealistic, this simulation indicates that a faster actuating PRD is better at mitigating surge – provided that the PRD is sized to mitigate the surge event in question.

5.3 Surge-mitigating PRDs

For a PRD to be an effective surge mitigation device, it should actuate quickly and to an appropriate relief rate regardless of the surge origination and magnitude. Ideally, a PRD for surge-mitigation should be placed near the surge source to mitigate the surge wave as quickly as possible before it causes damage to nearby components.

5.3.1 Surge Relief Valve. The surge relief valve is a unique type of PRD that is better understood as a fast-acting pressure sustaining control valve. While a conventional PRD relieves fluid at a pressure setpoint, a surge relief valve attempts to force the inlet pressure at the surge relief valve to the pressure setpoint, if the inlet pressure exceeds that setpoint during dynamic behavior.

This simulation case uses the similar model as the previous example but replaces the inline relief valve with an exit pressure sustaining control valve discharging to atmosphere. The pressure sustaining control valve setpoint is set to a static pressure p_{set} = 2275 kPa (330 psia), given a valve flow coefficient of $K_v = 86.5$ ($C_v = 100$) when fully open, and a linear profile that opens in 50 ms and closes over 2 seconds.

The surge relief valve simulation is compared to the cases of no surge mitigation and the 50 ms opening conventional relief valve previously discussed. This comparison is visualized with the pressure at the outlet of the L = 152.4 m (500 ft) pipe, upstream of the associated PRD or branch (depending on the example) in Fig. 6.

As seen, the behavior of a surge relief valve outshines that of the surge-mitigating conventional PRD. The transient response is very fast and very effective for mitigating surge. The valve attempts to eliminate passing upsurge from a surge event and prevent the pressure from exceeding the pressure setpoint at the control valve.

It should be noted that this surge relief valve, as shown in Fig. 6, will struggle to handle passing downsurges in the system unless the rate of closure is increased for the surge relief valve. However, fast actuating opening and closing times may overconstrain the system, and introduce numerical artifacts that indicate the system is overcontrolled – which may take the form of instabilities.

6. SYSTEM DYNAMICS

6.1 Configurations Vulnerable to Surge

Surge vulnerability is evident in system configurations where the duration of a valve closure is shorter than the communication time, leading to the development of full Joukowsky pressure rise. Some systems with long-duration valve closures are also at risk if the valve's characteristic only controls flow during the final closure. This is a common occurrence in longer systems with closures of full port valves, like gate or ball valves. Furthermore, systems with higher operating velocities will see higher proportional pressure rise as a result of upsurge from a surge source, such as a valve closure. Long pipelines are prone to experiencing severe pressure rise before pressure waves can be adequately dampened by reflections.

6.2 Mitigation

Outside of using surge relief valves for surge mitigation, various components to assist with surge mitigation can be used. Some such components include surge tanks or gas accumulators sized to dampen surge waves in the system, sometimes vacuum breaker or air valves, or even going so far as to modify the system piping. Alternatively, operational changes can be made to reduce the system impact of surge. Such changes include slowing controlled transient components (such as valve closures) as much as possible, avoiding pump tripping or transient changes to pump operating position, or avoiding problematic component behavior such as check valve slam, chatter, or instances of operational system cavitation. It should be noted, there is no one-size-fits-all solution to surge mitigation - and the characteristics of the system alongside a dynamic simulation of the system at hand should be considered to determine the best means for avoiding and mitigating surge.

Within the scope of surge relief valves, mitigation of surge involves strategically placing specialized surge relief valves near point of origin for a surge event. The most effective location for the surge relief valve is dependent on the characteristics of the surge event and the connecting system. For instantaneous events, the mitigating valve should be placed near the transient source to relieve the full Joukowsky pressure rise as soon after the initiation of the surge event as possible. The intent is to prevent the pressure rise from propagating throughout the entire system and causing damage. For cases where surge pressure rise occurs over longer duration events, the relief valve may be situated further away. However, it is crucial to evaluate transient behavior of the surge wave and ensure its duration is longer than the communication time between the source of the surge and the relief valve.

Preventing an instantaneous event requires positioning the surge relief valve closer to the origin than a system boundary, where surge waves might reflect. Additionally, controlling the closure of the surge relief valve is essential to prevent rapid closure and the initiation of a secondary surge event, potentially more severe than the original surge event.

7. DESIGN BASICS

Effective surge mitigation requires a special surge relief valve designed to respond to demanding conditions that originate from acoustic surge waves. Conventional PRDs, such as direct spring-loaded relief valves or rupture disks, are considered unacceptable devices for surge applications.

An effective surge relief valve is reliable with a fast actuation time, high capacity and high set point accuracy. Preferably the valve has a controllable, proportional operation (controlled opening and closure) instead of binarily open or closed operation. An effective surge relief valve should excel at both instances of *peak shaving* surge waves and diverting flow from surge events.

The requirements for a safe and reliable surge relief system are the following:

- Ultrafast surge relief valve reaction, but moreover reaction on the amount of flow/pressure generated by the surge with no fixed response time.
- Suitable for all types of fluids, including dirty or highly viscous process liquids.
- The valve maintains a very accurate, stable and reliable pressure set point.
- The valve opening is fast but controlled, following the pressure rise until required capacity is reached.
- Valve closure is controlled and appropriately fast for the system, in order to avoid secondary surges while still controlling system downsurge.
- Valve should have a reliably tight seat when closed to avoid fluid leakage and unintentional pressure relief.
- Because the valve is an overpressure protection device, it is considered effective if its reliability can be proven, preferably with 3rd party assessed field failure rates, data, and certification.

The discharge side of the surge relief valve (downstream side) shall preferably be atmospheric pressure. When the valve begins relieving and opens, the system downstream of the surge relief valve should have sufficient volume so that the discharge side pressure does not rise. This is important for all surge relief designs, as variable surge relief valve backpressure can reduce the effectiveness of surge mitigation, reducing the reliability of a surge relief valve.

8. SPECIALIZED VALVES

Surge relief valves are designed to mitigate surge and protect connected piping and components from surge overpressure. This requires specialized valves suitable to handle the requirements discussed previously without compromising the reliability for surge mitigation to be effectively accomplished. This type of selection is important, as conventional PRDs fail the aforementioned requirements on numerous categories - so many specialized modifications must be made to existing PRDs to allow them to handle surge pressures.

8.1 Valve Types

There are several types of surge relief valves designs. They can be angle style, Y-body or axial design. They can be pilot operated or gas (nitrogen) operated. The advantages of a pilot operated surge relief valve is that these are completely self-contained and do not require any external pressure source, power or controls. These valves are operated by using the liquid pressure in the pipeline.

It is a common misconception that all pilot operated valves are too slow to be used for surge mitigation via peak shaving. While they appear to be rare, there are several valve manufacturers that design for and create pilot-operated surge relief valves. From the authors' research, these types of valves are sometimes referred to as pilot-operated surge control valves in addition to surge relief valves. However, the other predominant type of surge valve is the surge anticipating valve, which may also be referred to as a surge relief valve or surge control valve depending on the manufacturer. Clarifying the valve design and operation with a manufacturer is vital to ensure surge can be mitigated in a system appropriately.

8.2 Choosing the right valve

Typical size range for surge relief valves spans from 2 in to 12 in. Some manufacturers have larger surge relief valve sizes available, even up to 24 in. Large systems with high flow rates require large relief capacities. Although a single large relief valve could be selected, it is often a better option to have several smaller size valves in parallel. Some of the advantages are that a smaller valve will react faster and open faster than a large valve. Additionally, multiple parallel valves provides redundancies; if one valve should fail, the other valves will have sufficient capacity to avoid overpressure in case.

9. CONCLUSION

Great care should be taken in addressing concerns of surge or other unsteady phenomena in a PRD-protected system. Conventional relief devices are deemed insufficient for the task of surge mitigation, despite wide usage in both liquid and gas applications for other overpressure events - and should be considered carefully when a PRD-protected system is surge vulnerable. Where there is no guarantee that conventional PRDs will automatically experience transient issues, they are often overlooked by system engineers and relief valve engineers alike in their propensity to cause issues when exposed to surge phenomena. It is the authors' goal to improve understanding about relief device behavior in surge, so as to help engineers avoid these issues.

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