A pressure relief valve (PRV) is installed for surge relief and pressure protection in a pipeline system. The valve, which is normally closed, is designed to open rapidly once its pressure setting is exceeded. A PRV's effectiveness depends on the properties of the system, the characteristics of the surge experienced, and the way in which the valve's attributes and settings are configured. This article illustrates the challenges inherent in PRV design and shows that an appropriately designed PRV can protect some systems from excessively high or low pressures and that inappropriate use can actually worsen a system's transient response. The general principles of PRV use and selection are presented along with a sensitivity analysis of PRV parameters. Although this understanding is essential to effective system design, a PRV is selected by evaluating PRV viability and cost-effectiveness in specific systems using numerical simulation.

Pressure-relief valve selection and transient pressure control

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Transient events, in particular rapid changes in flow rate, can cause serious problems in water distribution systems. High water hammer pressure can permanently deform or rupture a pipeline and its components; low pressures can collapse a pipeline, causing leaks, disrupting service, and contaminating pipelines.

Numerous transient control strategies have been developed, including changes within the distribution system (pipeline diameter, thickness, alignment, profile, and other hydraulic components), wave speed reduction, optimal operational procedures, and installation of dedicated devices such as automatic control valves, surge tanks, and air chambers (Karney & Simpson, 2007; Wylie et al, 1993). Automatic control valves, including pressure relief valves (PRVs), flow- or pressure-regulating valves, air valves, and check valves, are common and often cost-effective. Depending on the type, a valve is used to control transient conditions either by reducing the rate of net change in flow velocity in the pipeline or by discharging or admitting air into the pipeline. When triggered by pressure that is valued beyond a preset limit, a PRV opens to allow flow. The resultant outflow causes a pressure drop and thus has the potential to reduce the maximum pressure; inflow compensates for reduced water flow and can limit low pressures and even cavitation. A PRV must have a low physical inertia so that it can respond rapidly to the sensed pressure and open before the set point is greatly exceeded (Chaudhry, 1987). As the case studies presented in this article show, delays in valve opening can compromise protection of the distribution system.

TYPES OF PRVS AND THEIR APPLICATIONS

Depending on the application and the industry, various types of PRVs are used. A safety valve (also referred to as an overpressure pop-off valve), usually applied in steam or gas pipeline systems, is a spring- or weight-loaded valve that opens once pressure in the pipeline exceeds its set point and closes immediately when the pressure drops below the set point. Thus a safety valve is either fully open or fully closed. If not activated too frequently, a rupture disk can be used as an alternative to a safety valve. This type of valve is not a "true" valve but rather an opening in the pipe. The opening is covered by a diaphragm that ruptures and relieves pressure when the pressure set point is exceeded. One disadvantage of a rupture disk is that it continues to discharge until it is replaced.

In liquid applications, a PRV is usually mounted on the pressure side of a pump, hydro turbine, or main cutoff valve. It is typically a pilot-controlled throttling valve, opened or closed either hydraulically or by a servomotor, with opening and closing rates that can be individually set. It is distinct from a pressure-regulating valve, although both have pilot systems. In fact, a regulating or modulating valve typically uses a proportional integral derivative-type controller to accurately and continuously sustain a pressure set point in response to the sensed pressure or pressure difference. By contrast, a PRV is usually triggered by an event and, once triggered, follows a predefined opening and closing motion. More precisely, a PRV opens to release water when pipeline pressure at the valve inlet exceeds a high set point (referred to as SET1) and normal discharge of the valve is to a zone of lower pressure or to an open discharge area such as a pump-station wet well or adjacent storm sewer, pond, or stream. In addition, a PRV can open to admit water through a short bypass line when the valve downstream pressure in the main pipeline falls below a low-pressure set point (referred to as SET2). If the pressure of the water source linked with the PRV is higher than that in the pipeline downstream of the control valve, the PRV opens to supply fluid, thus compensating for the reduced flow and limiting the magnitude of the downsurge and the subsequent upsurge reflected from the downstream pipeline. A PRV set in this mode is commonly referred to as a pump- or valve-station bypass assembly.

PRVs have been used successfully under a wide range of hydraulic conditions and operating scenarios to reduce adverse transient pressure within a distribution system. They should not be used without properly assessing their ability to adequately protect the system. Because a PRV is a reactionary device, many hydraulic systems will not benefit from this type of valve. For example, if a PRV is used to relieve high pressure, the pressure relief will initially be local to the PRV itself, because its operation obviously depends on a local discharge of fluid. Protection of the pipeline as a whole will depend on a variety of factors that involve a complex interplay between the strength and source of the original surge condition, the way in which the valve action modifies the wave propagation, and the way in which these conditions interact with the distribution system's inherent strength. In some cases, a PRV may only provide quick, local protection, making other mitigation strategies more cost-effective. One misapplication is to use a PRV in the bypass mode to protect a pumped system with a rising main from an uncontrolled shutdown (power failure). Under these conditions, the available pressure on the suction side of the pump station may not allow sufficient flow to effectively limit the resultant downsurge. The first step in developing a positive transient control system using a PRV is to understand the valve's operation and limitations. A preliminary numerical evaluation provides a well-informed design engineer with insights into the suitability of a PRV to control surge pressures.

Once a decision has been made to use a PRV, it must be carefully and appropriately designed. There are four design considerations for a PRV. The first defines the valve's location. In a high-pressure relief mode of operation, the PRV should be positioned so that high pressure and flow can be diverted around pressure-sensitive areas and excess flow can be discharged appropriately. The remaining three design considerations relate to PRV characteristics and valve parameters, including the valve and port size (d), the high- or low-pressure set point (SET1 or SET2), and the opening and closure time periods (TV1 and TV2). Each valve parameter profoundly influences system performance. For instance, an oversized PRV will not be cost-effective, whereas an undersized valve cannot effectively alleviate excessive pressure surges. Using a fully dynamic transient model based on the method of characteristics, a simplified distribution system can be used to illustrate both the general principles of PRV design and the sensitivity of the response to control valve parameters.

PRV OPERATION IN PUMP SYSTEMS

To protect a distribution system from the unacceptable low pressure or excessive high pressure associated with a pump power failure, a PRV can sometimes be installed on a bypass line around a pump station. When power failure occurs at a pump motor, the reduced flow at the pump causes an imbalance in flow and a rapid reduction in pressure. The net effect is propagation of a rarefaction wave into the discharge pipeline. When the low-pressure wave reflects off a downstream boundary (e.g., water tank), the pressure is normalized to the free water surface level in the tank and thus reflected back into the system, establishing pressures that are sometimes higher than those originally experienced before flow was reduced. After this reflected positive wave has reached the pump and the pump check valve has closed, the check valve effectively becomes a "dead end," creating another reflection and magnification. In theory, the reflected wave doubles when it approaches a closed valve, producing a higher transient pressure. In a pumped system, a PRV will open at the initial low-pressure set point once power to the pump motor is cut off. The PRV, now open in anticipation of the returning positive wave, will provide a route to release the water from the system and prevent development of the high transient pressure condition. If the operating suction pressure is not positive in a pumped system, a partial or full vacuum pressure will develop at the PRV once the valve is opened. If a full vacuum pressure is developed, the severity of the transient pressure may be exacerbated because of cavity collapse. If a positive suction pressure is unavailable in a pump system, particular care (such as an air valve) might be needed in considering whether a PRV is an appropriate control device.

Unlike regular startup and shutdown, power failure is always sudden and unpredictable. In Figure 1, the main valve closure is equivalent to the reduction of pump flow caused by a power failure. This system, e.g., certain types of booster pumping stations, assumes a positive-suction operating head. As a result, the PRV in the bypass line opens rapidly to admit water into or release water from the pipeline back to the suction side of the pump. The PRV is then gradually closed to eventually shut down the system and bring it to rest; as we know a controlled, slow-closing valve has little effect on the transient condition. The pump check valve, which is typically installed at each pump, will close upon flow reversal. However, when the check valve is closed, the rotational moment of inertia that controls the rate of pump run-down during a power failure will effectively be eliminated (Ruus & Karney, 1997; Chaudhry, 1987). As a result, the energy dissipation required to slowly bring the system to rest and dampen the adverse transient pressure condition is left to the PRV bypass assembly.

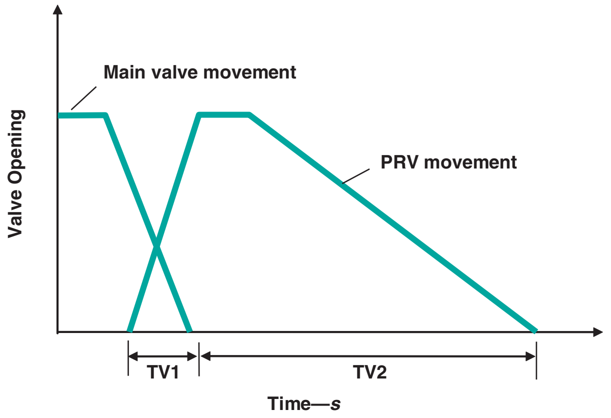
CASE STUDIES

The design of a PRV to control adverse transient pressure is system-specific and depends on the physical and hydraulic conditions in the system and the nature of the system's response to PRV operation during a transient event. Fully dynamic hydraulic transient modeling can be used to illustrate the hydraulic system's trends and tendencies and to estimate the system's transient performance with selection of various PRV parameters. To illustrate, a simple system with a PRV installed at both upstream and downstream locations is discussed here.

Brief description of the system. Two reservoirs are linked by a uniform pipeline with length (L) = 500 m, diameter (D) = 1.0 m, friction factor (f) = 0.012, and wave speed (a) = 1,200 m/s (Figure 2). The water level is 15 m at the upstream reservoir and 12 m at the downstream reservoir. At each end of the pipeline there is a primary valve and a PRV; the PRV is situated on a short bypass line that connects either end of the pipeline to its associated reservoir. At initial steady state, both main valves are fully opened, both PRVs are fully closed, and flow in the pipeline is $Q_0 = 1.73\ \text{m}^3/\text{s}$.

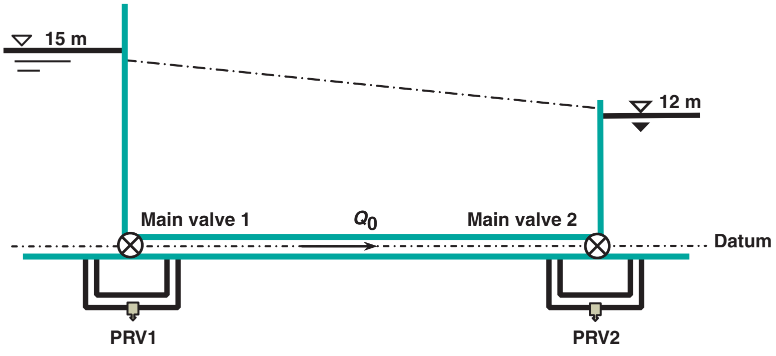
Case study 1: Upstream control. Main valve 1 at the upstream end is fully closed within 5 s, causing an incident rarefaction pressure wave in the pipeline. When the pressure at the outlet of PRV1 (i.e., the pressure at the outlet of main valve 1) falls below its set point (SET2), the PRV opens to admit water into the pipeline and avoid downsurge at the outlet of main valve 1. This reduces the subsequent upsurge reflected from the downstream reservoir during the transient event.

FIGURE 1 Operation of main valve and PRV



PRV—pressure-relief valve, TV1—opening time period, TV2—closing time period

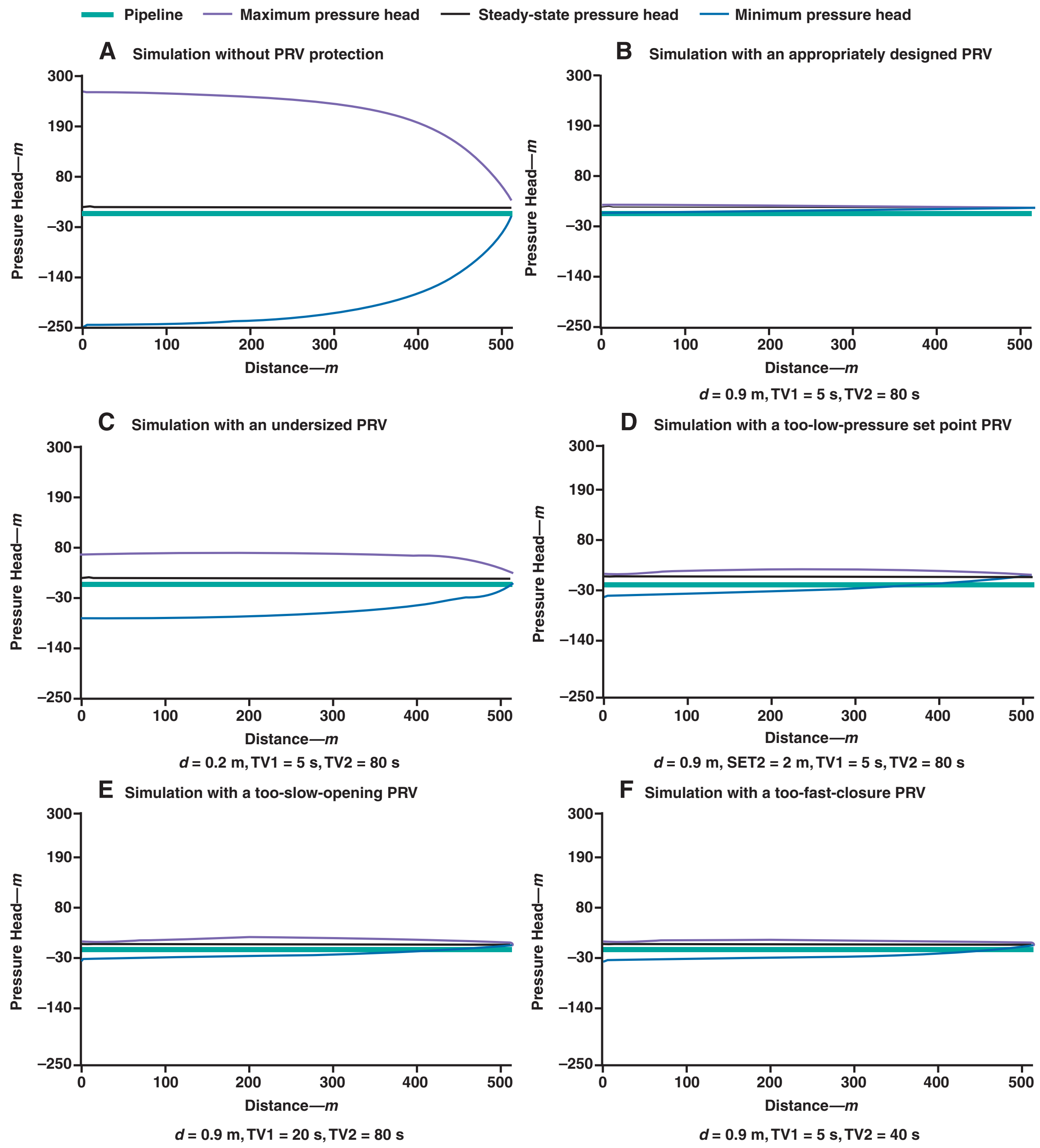
FIGURE 2 PRV installations in a simple pipeline system



PRV—pressure-relief valve, Q_0—initial steady state flow in the pipe

Comparison for different upstream PRV parameters. The transient pressures in the pipeline are compared in Figure 3 for the following systems: one without PRV protection, one with an appropriately designed PRV, and four with poorly designed PRVs. Without PRV protection (Figure 3, part A), rapid closure of the main valve would result in approximately 260 m of maximum pressure head and –240 m of minimum pressure head in the system. The maximum head of 260 m is extremely high, and this may cause pipe rupture. The negative pressure head (–240 m) is a numerical value from the simulation model and does not factor in vaporization and cavitation. However, the modeled –240-m rarefaction wave is completely unacceptable because of the high probability of cavitation and subsequent cavity

FIGURE 3 System transient performance varying with upstream PRV design



A Simulation without PRV protection

B Simulation with an appropriately designed PRV

d = 0.9 m, TV1 = 5 s, TV2 = 80 s

C Simulation with an undersized PRV

d = 0.2 m, TV1 = 5 s, TV2 = 80 s

D Simulation with a too-low-pressure set point PRV

d = 0.9 m, SET2 = 2 m, TV1 = 5 s, TV2 = 80 s

E Simulation with a too-slow-opening PRV

d = 0.9 m, TV1 = 20 s, TV2 = 80 s

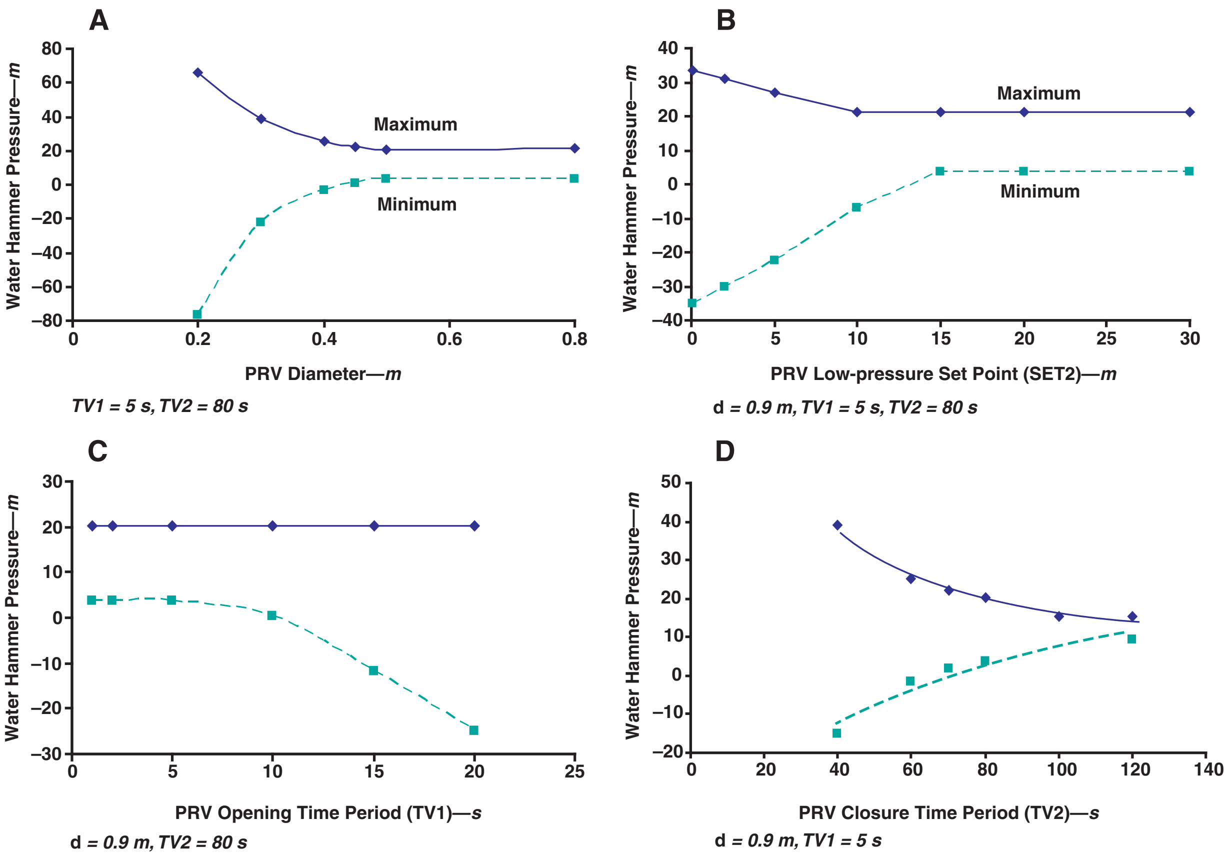
F Simulation with a too-fast-closure PRV

d = 0.9 m, TV1 = 5 s, TV2 = 40 s

d—valve and port size, PRV—pressure-relief valve, SET2—low-pressure set point, TV1—opening time period, TV2—closing time period

Default SET2 is equivalent to SET2 ≥ 15 m, i.e., the PRV is activated instantly when main valve 1 closes.

FIGURE 4 Sensitivity analysis of upstream PRV parameters



d—valve and port size, PRV—pressure-relief valve, TV1—opening time period, TV2—closing time period

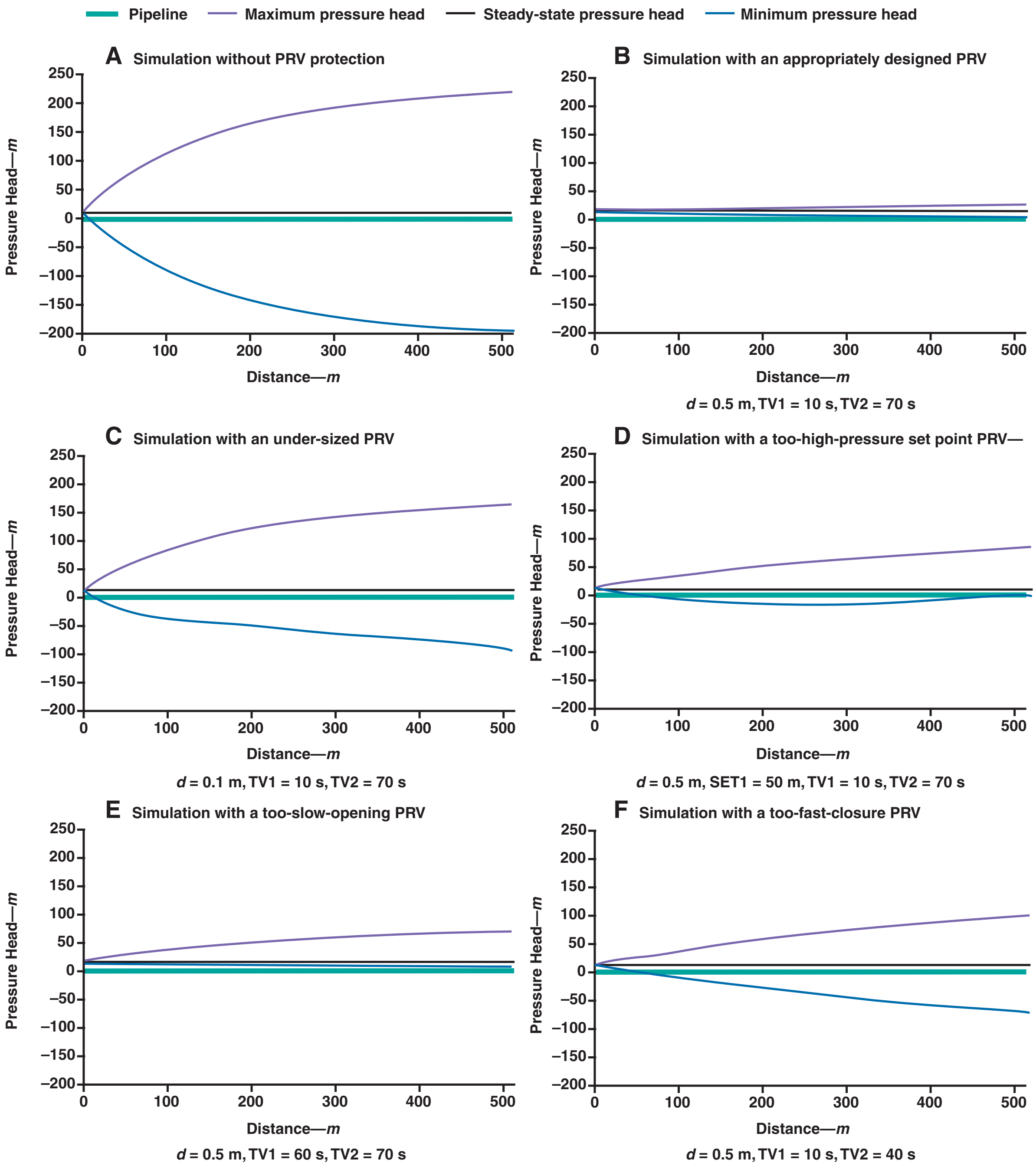
collapse. Cavitation will lead to vapor cavity formation and subsequent cavity collapse (the so-called column rejoinder effect), which can cause extremely high pressures. The large negative pressures indicate that the response is unacceptable when the PRV is not operated, and thus a protection from transient pressure is necessary for this system. As shown in Figure 3, part B, operation of an appropriately designed PRV will limit maximum and minimum transient pressure heads along the pipeline to be in the range of 3.6 to 22 m. However, inappropriate selection of PRV parameters, such as an undersized PRV, a pressure set point for SET2 that is too low, opening of a PRV that is too slow, and closure of a PRV that is too fast, would result in poor performance and unacceptable transient pressures in the pipeline (Figure 3, parts C–F). Yet, Figure 3 shows that even a poorly designed PRV provides some protection and is certainly preferable to avoiding the PRV completely.

Sensitivity analysis of upstream PRV parameters. Proper selection of a PRV's control parameters is important to transient control, particularly because these parameters are inevitably uncertain. For example, activation of a PRV depends on the pressure it senses, which in turn depends on exactly how and where the pressure is sensed and how this sensed pressure is itself changed by both the ongoing transient in the system and action of the control valve. Sensitivity analyses would reveal how the system's transient performance changes with variation of each PRV parameter, and this could aid in identifying rules for PRV design. Therefore, the sensitivities of each PRV1 parameter (*d*, SET2, TV1, TV2) were analyzed and are shown in Figure 4.

Figure 4, part A, illustrates that an increase in valve size would improve transient performance but only to a certain limit; an increase in valve size beyond 0.5 m would not efficiently improve transient performance in this case study. The authors' design and field experience indicate that PRV diameters usually range from one twentieth to one third of the main pipe diameter, with most values near the middle of this range. The logic for achieving this type of range is evident in Figure 4, part A, although not exactly followed. The slight discrepancy that appears can be explained as follows: in this case study, only 3 m of pressure head existed along a 500-m length of pipe; thus, the velocity in this system is very slow. This implies that in order to discharge a certain amount of water, a larger PRV is needed. The ultimate choice of a PRV size is usually a compromise between cost, which increases rapidly with increase in diameter, and hydraulic control and protection, which usually provide diminishing returns with PRV diameter.

Figure 4, part B, illustrates that the variation in transient pressures diminishes with an increase in the low-pressure set point (SET2). An issue is how quickly the bypass or PRV will open immediately after the transient down-pressure wave is sensed in association with the motion of the primary valve. Because of the system configuration presented in this case study, there is no improvement in response when SET2 is beyond 15 m, because the valve stays open once the set point is higher than the upstream reservoir pressure. In general, the lower or more sensitive the threshold pressure for PRV activation, the bet-

FIGURE 5 System transient performance varying with downstream PRV design



PRV—pressure-relief valve, SET1—high-pressure set point, TV1—opening time period, TV2—closing time period

Default SET1 is equivalent to SET1 ≤ 15 m, i.e., the PRV is activated instantly when main valve 2 closes.

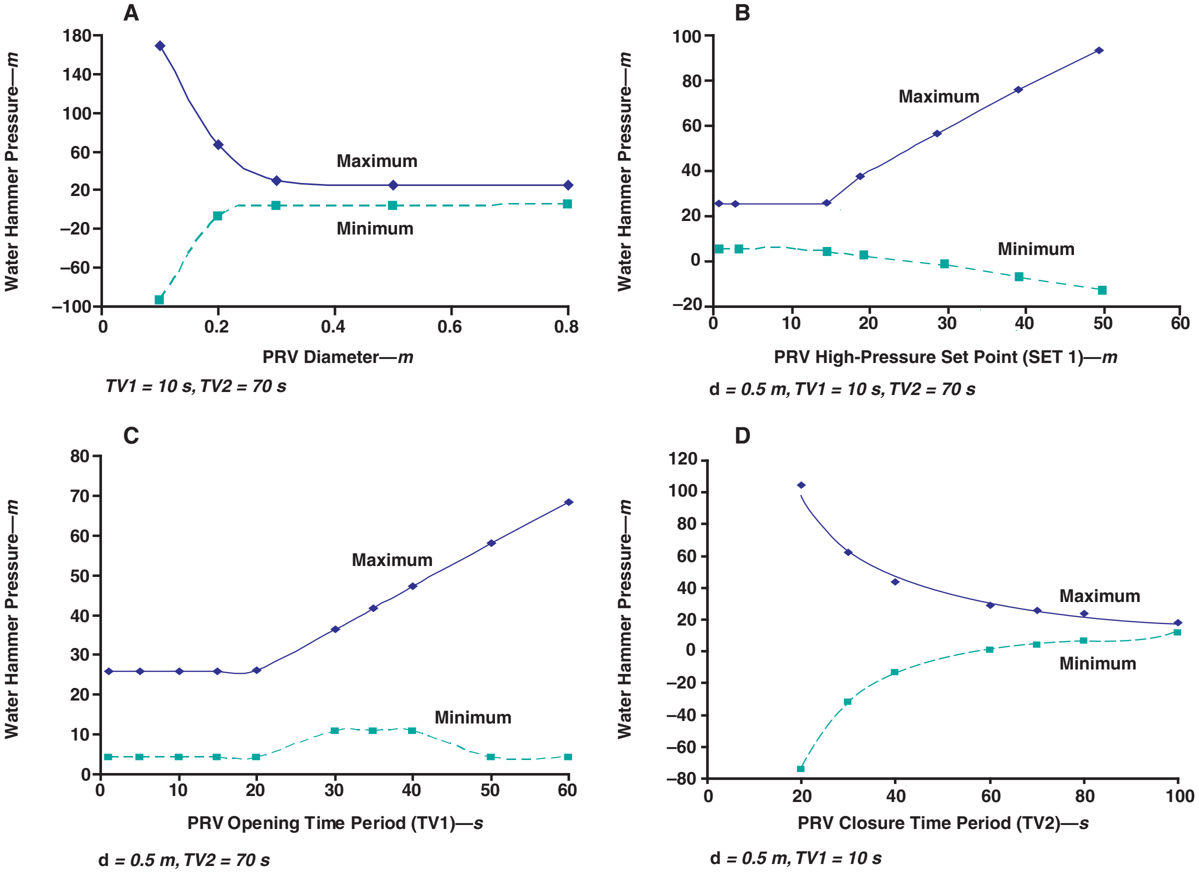
ter the transient protection, because the valve will begin its response earlier. However, there is an obvious trade-off, because a valve that activates quickly is much more prone to activate not only for important design events but also for normal or routine transient events that pose no threat to the system. A valve that opens prematurely not only requires more frequent routine maintenance but, depending on system configuration, can waste both energy and fluid from the system.

Figure 4, part C, shows that variation of opening time period (TV1) does not affect the maximum transient pressure in this case study; in general, the shorter the opening time (TV1), the less severe the resulting negative pressure. When TV1 is shorter than 5 s, a reduction in TV1 no longer changes the minimum transient pressure. When TV1 is longer than 10 s, the negative pressure would occur in the pipeline and rapidly becomes more severe with increasing TV1. In this case study, the appropriate opening time for the PRV should be within 5–10 s when both ease of PRV operation and prevention of negative pressures in the pipeline are considered. As mentioned here and discussed by Chaudhry (1987), a low valve inertia or a highly responsive control system is required for a PRV to achieve a response and activation. These components can increase cost and/or maintenance requirements of the valve. However, the timing of PRV operation and the system's transient response are unique to each hydraulic system and essentially balance the needs and costs of the control valve, the configuration of the system, and the nature of the disturbance that actually generates the transient response.

As shown in Figure 4, part D, slowing of PRV closure (i.e., increasing TV2) results in smaller variations in transient pressures, which benefits hydraulic control but diverts more water during PRV operation. In addition, when TV2 is shorter than 60 s, the range of maximum and minimum pressures becomes more sensitive to the variation of TV2. In this case study, 60–80 s is suggested for the PRV closure time period.

Case study 2: Downstream control. In this case study, main valve 2 at the downstream end is fully closed in 5 s, causing an incident upsurge in the pipeline. When the pressure at the inlet of PRV2 (i.e., the pressure at the inlet of main valve 2) exceeds its set point (SET1), the PRV opens to discharge water into the downstream reservoir to mediate the pressure rise in the upstream pipeline.

FIGURE 6 Sensitivity analysis of downstream PRV parameters



TV1 = 10 s, TV2 = 70 s

d = 0.5 m, TV1 = 10 s, TV2 = 70 s

d = 0.5 m, TV2 = 70 s

d = 0.5 m, TV1 = 10 s

PRV—pressure-relief valve, TV1—opening time period, TV2—closing time period

Comparison for different downstream PRV parameters. If there is no PRV protection, rapid closure of main valve 2 results in 232 m of maximum pressure and –200 m of minimum pressure (see previous text regarding pressure in excess of full vacuum condition) in the system (Figure 5). Operation of an appropriately designed PRV will reduce the envelope of maximum and minimum transient pressure to 4.2 m and 25.8 m, respectively. The undersized PRV or the inappropriate setting of the PRV set point or valve timing would result in unacceptable hydraulic transient conditions (Figure 5, parts C–F).

Sensitivity analysis of downstream PRV parameters. The sensitivities of each PRV2 parameter (*d*, SET1, TV1, TV2) were analyzed and are shown in Figure 6; the results are similar to those from the previous case study. Figure 6, part A, illustrates that the most economically efficient and hydraulically effective diameter for the PRV is approximately 0.2–0.3 m, which is well within the range of one fifth to one third of the main pipe diameter.

Figure 6, part B, shows that the range of transient pressures becomes narrower as the high-pressure set point (SET1) is reduced. However, there is little improvement in transient control when SET1 is set lower than 15 m, which is the water level in the upstream reservoir. In addition, a negative or partial vacuum pressure resulting from the boundary reflection will become more severe if SET1 is set higher than 32 m. In this case study, a proper SET1 value of 15–32 m should be selected.

Figure 6, part C, shows that a reduction in PRV opening time (TV1) will reduce the maximum transient pressure in the system, though only slightly affecting the minimum transient pressure in the pipeline. A reduction in TV1 to < 20 s does not change the transient response any further. In this case study, results indicate that the system is rather insensitive to the selection of TV1 as long as TV1 is not extremely long (e.g., longer than 60 s).

Figure 6, part D, shows that a slow PRV2 closure would improve transient pressure performance. In this case study, 60 s or longer is required for TV2 to prevent the negative pressure from occurring in the pipeline. The trade-off is that a slower closing time will result in more water being diverted out of the system during PRV operation.

CONCLUSIONS

The objective of PRV design is to transform the existing hydraulic system into a new hydraulic system with a more acceptable transient response. In evaluating a PRV, the first step is to qualitatively evaluate the PRV's viability as an appropriate protection device. The ability to qualitatively assess a PRV's viability requires a comprehensive understanding of how a PRV contributes to transient mitigation. A PRV is a reactionary device that establishes a pathway to either introduce or relieve energy from the hydraulic system. Many designs have failed because a PRV was not applied correctly. However, if a PRV is found to be a viable surge-control alternative, a series of interdependent design parameters must be considered in PRV design. The basic principles in designing a PRV and its associated parameters have been described in this article and are summarized as follows:

- An undersized PRV would be insufficient to protect a distribution system from extreme transient pressures. However, there is no point in oversizing a PRV because, beyond a certain point, there is little further improvement in its water hammer performance, even though its cost continues to increase.
- If the pressure set point is too extreme (i.e., too low for the low-pressure set point or too high for the high-pressure set point), the PRV will not adequately provide transient pressure control.
- If the PRV either opens too slowly or closes too quickly, it could cause dangerous occurrences of water hammer. In general, however, a PRV helps to alleviate extreme water hammer pressures.

Although the case studies presented in this article showed common principles to follow when selecting a PRV, the detailed values of each parameter will be different from case to case. For instance, TV1 is required for 5 to 10 s in the upstream PRV, while it could be as long as 20 s in the downstream PRV. Therefore, to make wise and informative choices for PRV parameters, a fully dynamic hydraulic simulation should be performed for each distribution system.

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