

Optimizing the dynamic response of pressure reducing valves to transients in water networks

Khaled Zaki, Yehya Imam and Amgad El-Ansary

ABSTRACT

Pressure reducing valves (PRVs) are typically used to regulate excessive pressure in water distribution networks. During transient events, the dynamic response of PRVs may adversely affect pressure fluctuations in distribution networks. In this study, the dynamic response of PRVs was analyzed by developing a numerical model that coupled an existing water-hammer model and a two-parameter dynamic PRV model. PRV parameters were calibrated, and the model was validated using previous experimental observations. The model was then used to study the effect of PRV dynamics during transient events in a distribution network. To optimize the rate of PRV opening and closure and control its dynamic response, the model was interfaced with an optimization algorithm based on shuffled complex evolution. The applied objective function gave PRV parameters that accelerated damping of the transient pressure waves and minimized the root-mean-square deviation from post-transient steady pressure at all nodes in the network. The results of this study indicate the importance of accounting for PRV response when simulating transients in water distribution networks. This study also highlights the need for PRV manufacturers to include in their product catalogs dynamic PRV parameters for use in transient analysis.

Key words | dynamic response, hydraulic transients, optimization, pressure reducing valve, water hammer

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INTRODUCTION

Pressure reducing valves (PRVs) are frequently used to protect piping systems against excessive pressures by keeping pressure downstream of the valves below a set value. PRV types include conventional pilot-operated PRVs and PRVs with proportional–integral–derivative (PID) controllers. A typical pilot-operated PRV consists of two main parts: the main valve assembly and the pilot valve assembly (Figure 1(a)). Most previous studies of pilot-operated PRVs focused on operation during quasi-steady conditions. The objective was to control excess pressure and reduce leakage in the network by optimizing PRV location (Hindi & Hamam 1991), setting (Jowitt & Xu 1990; Vairavamoorthy & Lumbers 1998), or both location and setting (Reis *et al.* 1997; Nicolini & Zovatto 2009). Fewer studies examined the dynamic

response of PRVs during transient events even though the interaction between the transient pressure waves and the PRV response may exacerbate pressures in pipelines and pipe networks.

Experimental studies of the dynamic response of PRVs were conducted by Prescott & Ulanicki (2003) and by Meniconi *et al.* (2015, 2017). Mathematical models were developed by Prescott & Ulanicki (2003, 2008) for simulating the response of pilot-operated and PID-controlled PRVs. A number of studies focused on the dynamic response of PID-controlled PRVs (Quadros & Murilo 2013; Janus & Ulanicki 2017), flow-modulated PRVs (Li *et al.* 2009), PRVs with adaptive controllers (Ramirez-Llanos & Quijano 2009), and automatic control valves (Brunone & Morelli 1999).

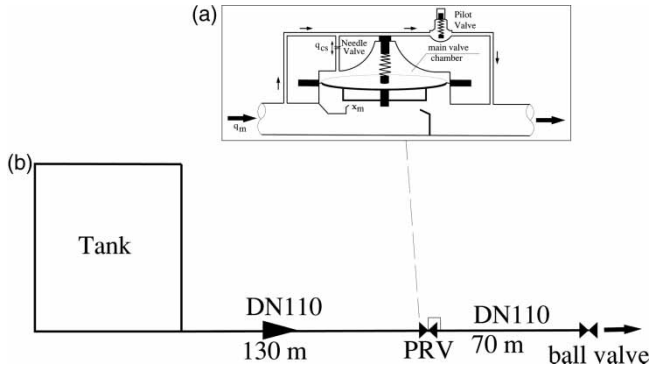


Figure 1 | (a) Schematic of PRV and (b) pipeline used in model validation (Meniconi et al. 2017).

Previous modeling studies primarily applied the two-parameter PRV model proposed by Prescott & Ulanicki (2003, 2008). To simplify transient analysis, these studies coupled the PRV response model with a rigid water-column model for pipes. Only Janus & Ulanicki (2017) coupled the PRV response model with a water-hammer model but for a simple pipeline. To our knowledge, no previous studies analyzed the dynamic response of PRVs in water distribution networks using coupled PRV-dynamic response and water-hammer models. Furthermore, while multiple studies addressed the optimization of PRVs with PID controllers (Prescott & Ulanicki 2008; Quadros & Murilo 2013), there seems to be a lack of studies that examine the optimization of the dynamic response of pilot-operated PRVs.

The main objectives of this study are to (1) illustrate the effect of the suboptimal dynamic response of pilot-operated PRVs during transients in water distribution networks and (2) optimize PRV parameters to minimize adverse effects of the PRV during transients. To achieve these objectives, a numerical model for analyzing the dynamic response of PRVs in networks was developed by coupling a pipe network transient model and the dynamic two-parameter PRV model proposed by Prescott & Ulanicki (2003, 2008). The coupled model is interfaced with an evolution optimization algorithm to determine optimal values for the two parameters in the dynamic PRV response model.

This paper is structured as follows. The next section describes the developed numerical model, the objective functions that were applied in the optimization of PRV parameters and how the model was calibrated and validated.

Next, the paper presents the results of model validation, application, and parameter optimization. The last section discusses the effect of PRV parameters on its dynamic response and how PRV parameters should be determined to select PRVs with a suitable dynamic response.

METHODOLOGY

Mathematical model

The mathematical model that was used in this study had two components: a pipe network transient model and a dynamic PRV model. The transient model solved ordinary differential equations along forward and backward characteristic paths obtained by applying the method of characteristics to the full dynamic equations for pressurized pipe flow (Larock et al. 1999). The second component of the mathematical model was the two-parameter PRV model by Prescott & Ulanicki (2008). This model, referred to hereafter as the PU model (Prescott & Ulanicki model), is based on the commonly used valve equation (Larock et al. 1999; Chaudhry 2014):

$$q_m = c_v \sqrt{H_{in} - H_{out}} \quad (1)$$

where q_m is the flow through the PRV; H_{in} and H_{out} are the total heads at the inlet and the outlet of the PRV, respectively; and $c_v(x_m)$ is the main valve capacity coefficient which depends on PRV opening x_m (Prescott & Ulanicki 2008).

When the pressure downstream of the PRV exceeds a set value, the pilot valve closes to direct the flow into the main valve chamber, decreasing the main valve opening x_m to increase pressure losses and lower pressure downstream of the PRV. The rate of change of PRV opening was simulated in the PU model using the differential equation:

$$\frac{dx_m}{dt} = \frac{q_{cs}}{A_{cs}} \quad (2)$$

where q_{cs} is flow in or out of the main valve chamber and $A_{cs}(x_m)$ is the chamber horizontal area which depends on valve opening x_m (Prescott & Ulanicki 2008).

The PU model determines the flow q_{cs} in or out of the main valve chamber using the empirical formulas:

$$q_{cs} = \begin{cases} \alpha_{open}(H_{set} - H_{out}) & : \frac{dx_m}{dt} \geq 0 \\ \alpha_{close}(H_{set} - H_{out}) & : \frac{dx_m}{dt} < 0 \end{cases} \quad (3)$$

where H_{set} is the pressure head setting for the PRV, and the empirical coefficients α_{open} and α_{close} are PRV parameters that represent the lumped hydraulic response of PRV components. The two parameters α_{open} and α_{close} are needed to account for the difference in flow regulation by needle valve with flow direction into or out of the main valve chamber (Figure 1(a)).

Numerical implementation

The FORTRAN-based computer model of Larock et al. (1999) was extended to simulate transients in water distribution networks with PRVs. The developed model, referred to hereafter as TRANSNET II, requires the input of the following PRV data: location given by junction number, upstream pipe, and downstream pipe; initial upstream and downstream heads; initial valve opening; and pressure head setting.

TRANSNET II solves the ordinary differential equations that describe pipe transients and PRV dynamics using an explicit finite-difference discretization over $s - t$ grid where t is time and s is the distance along pipes (Larock et al. 1999). The time step Δt and the distance Δs between computational nodes along pipes were selected to satisfy the Courant condition (Wylie et al. 1993). At the PRV, TRANSNET II determined three unknowns at each time step, namely the inlet head H_{in} , the outlet head H_{out} , and the velocity V , assuming that pipes upstream and downstream of the PRV have the same diameter. The determination of velocity was done by combining the discretized equations for the forward characteristic path on the upstream side of the PRV and the backward characteristic path on the downstream side of the PRV with Equation (1) for the PRV to give,

$$V_{PRV}^{t+\Delta t} = \begin{cases} \frac{-C_1 + \sqrt{C_1^2 + 4C_2}}{2} & : C_1^2 + 4C_2 \geq 0 \\ \frac{C_1 - \sqrt{C_1^2 - 4C_2}}{2} & : C_1^2 + 4C_2 < 0 \end{cases} \quad (4)$$

where the second formula in Equation (4) is applicable when flow reverses. In Equation (4), $V_{PRV}^{t+\Delta t}$ is the mean velocity through the PRV at the time $t + \Delta t$ and the coefficients C_1 and C_2 are given by the following equations:

$$C_1 = 2 \frac{a}{g} \left(\frac{c_v}{A_k} \right)^2 \quad (5)$$

$$C_2 = \frac{a}{g} \cdot \left(\frac{c_v}{A_k} \right)^2 (C_3 + C_4)$$

where a is the transient wave celerity determined based on pipe elasticity and fluid compressibility (Larock et al. 1999); $g = 9.81 \text{ m/s}^2$ is gravitational acceleration, and the coefficients C_3 and C_4 are computed based on the velocity and head at previous time step upstream and downstream of the PRV, respectively.

After calculation of velocity $V_{PRV}^{t+\Delta t}$, the inlet and outlet heads at the PRV were calculated using the following equations:

$$H_{in}^{t+\Delta t} = (C_3 - V_{PRV}^{t+\Delta t}) / \left(\frac{g}{a} \right) \quad (6)$$

$$H_{out}^{t+\Delta t} = (V_{PRV}^{t+\Delta t} - C_4) / \left(\frac{g}{a} \right) \quad (7)$$

The PRV opening at a subsequent time step $t + \Delta t$ was obtained using the discretized form of Equation (2):

$$x_m^{t+\Delta t} = x_m^t + \Delta t \frac{q_{cs}(x_m^t)}{A_{cs}(x_m^t)} \quad (8)$$

where the flow q_{cs} into or out of the valve chamber is computed using Equation (3) depending on whether the PRV was opening ($H_{out}^t < H_{set}$) or closing ($H_{out}^t > H_{set}$). For the application of Equations (5) and (8); variation of C_v and A_{cs} with valve opening x_m was described using the empirical relationships given by Prescott & Ulanicki (2008).

PRV parameter optimization

The selection of optimal values for the PU model parameters α_{open} and α_{close} was done using the shuffled complex evolution (SCE) optimization algorithm (Duan et al. 1992).

Two objective functions were tested. The first objective function OF1 minimized the average root-mean-square deviations (RMSDs) of simulated hydraulic grade levels from post-transient steady hydraulic grade levels. This average RMSD was computed based on RMSD at all nodes in the network. For node i on pipe k , the RMSD was calculated using the following equation:

$$\text{RMSD}_{k,i} = \sqrt{\frac{\sum_{j=1}^n (H_{\text{st}} - H_c^j)^2}{n}} \quad (9)$$

where H_c^j is the simulated head at node i on pipe k at time step j , H_{st} is post-transient head at node i ($H_{\text{st}} = H_s$ downstream of the PRV), and $n = \frac{T}{\Delta t}$ is the number of time steps Δt in the total simulation duration T .

The second objective function OF2 minimized the RMSD of simulated hydraulic grade levels immediately downstream of the PRV from the PRV set value H_s as done in previous studies (Prescott & Ulanicki 2008) that focused on optimizing the dynamic response of PID-controlled PRVs (Prescott & Ulanicki 2008).

MODEL CALIBRATION AND VALIDATION

The TRANSNET II model was calibrated and validated using experimental observations from Meniconi *et al.* (2017). The calibration and validation simulations consisted of HDPE pipeline supplied from a pressurized tank with a head ranging from 22 m to 55 m. The pipeline had a nominal diameter of 110 mm and a total length of 200 m. Transient wave celerity in the pipeline was ~ 370 m/s. A PRV was located 130 m downstream of the tank and had a pressure head setting of 26 m. A ball valve was located at the downstream end of the pipeline to control pipe flow (Figure 1(b)). For the calibration and validation simulations, a time step of 0.1 s was used in simulating transient events for a duration of 15 s after the start of the event. Simulation results were compared to observed pressure upstream and downstream of the PRV.

Simulation of sudden complete closure of the downstream ball valve was used to calibrate α_{close} for the

PRV. Experimental observations by Meniconi *et al.* (2017) indicated that, with ball valve closure, an initial flow of 2.5 L/s in the pipeline was stopped abruptly, increasing pressure upstream of the ball valve. A positive pressure wave propagated in the upstream direction towards the PRV, sharply increasing pressure head from 27.3 m to 59.8 m downstream of the PRV and from 49 m to 57.9 m upstream of the PRV (Figure 2(a) and 2(b)). The PRV closed gradually to decrease the downstream pressure head which oscillated with diminishing amplitude until approaching a steady head. This steady value was similar to the upstream head as the PRV did not completely close when there was no flow in the pipeline. Calibration of the model for the sudden closure of the ball valve gave a value of 2×10^{-5} m²/s for α_{close} . With this calibrated value, the model reasonably reproduced the observed pressure heads; the Nash–Sutcliffe model efficiency coefficient (NSE) was 0.92 for head downstream of the PRV and 0.90 for head upstream of the PRV.

Simulation of a sudden opening of the downstream ball valve was used to calibrate α_{open} for the PRV (Figure 2(c) and 2(d)). Starting with no flow in the pipeline and a pressure head of 51.0 m upstream and downstream of the PRV, the downstream valve was suddenly opened to discharge a flow of 2.41 L/s. Experimental observations by Meniconi *et al.* (2017) indicated that a negative pressure wave propagated towards the PRV causing a sharp decrease in pressure head to 7.5 m and 45.0 m downstream and upstream of the PRV, respectively. In response, the PRV opened gradually, decreasing head losses and increasing downstream pressure until it approached a steady value after about 5 s. Calibration of the model for sudden opening of the ball valve gave a value of 3.5×10^{-7} m²/s for α_{open} . Similar to sudden valve closure, an agreement between model results and observations for sudden valve opening was reasonable; the NSE coefficient was 0.97 for head downstream of the PRV and 0.85 for head upstream of the PRV.

Validation of the TRANSNET II model was performed by applying the model with the calibrated α_{open} and α_{close} parameters to simulate another experiment by Meniconi *et al.* (2017). In this experiment, the transient event was slow valve closure which generated a positive pressure

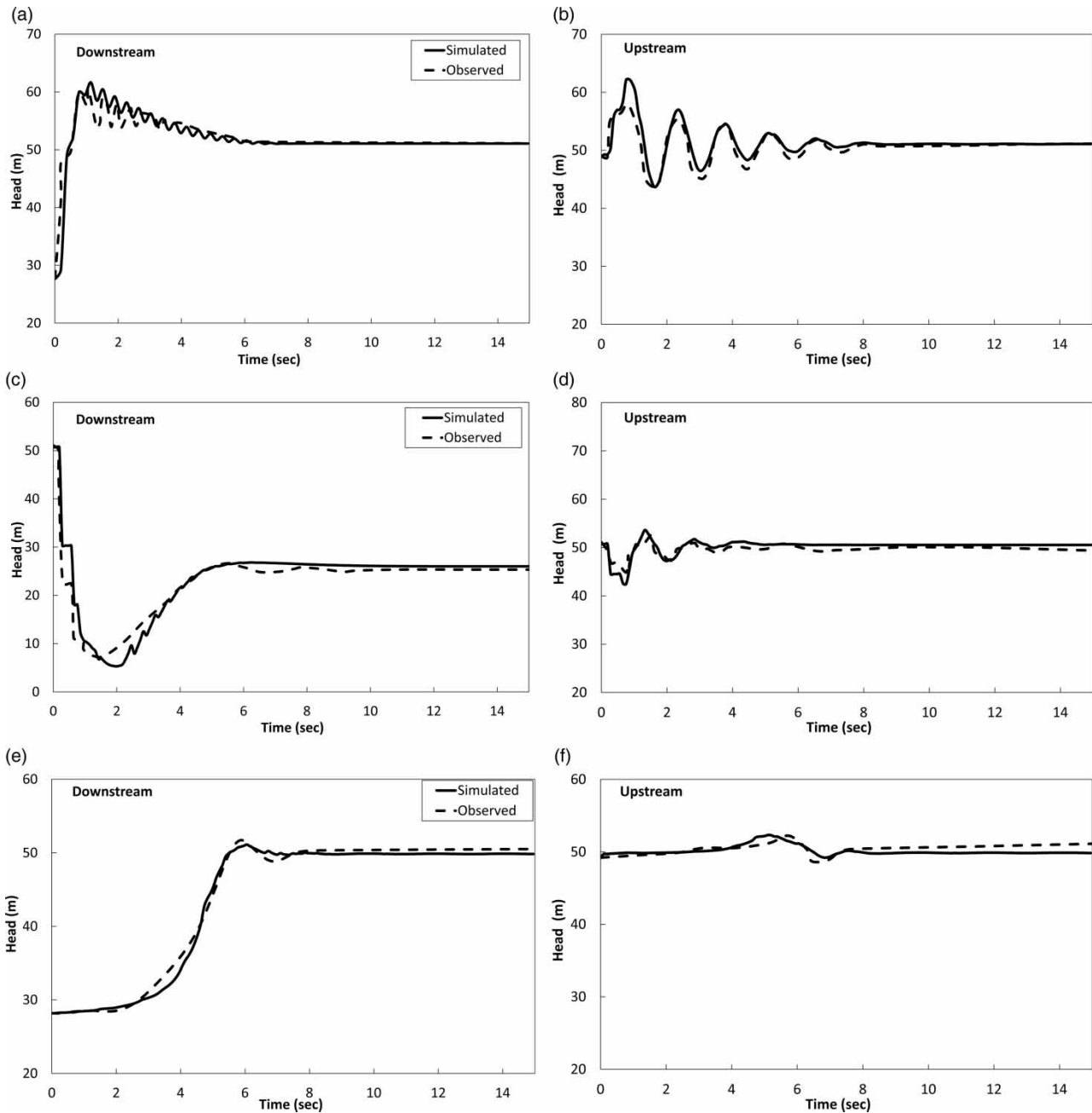


Figure 2 | Simulated and observed pressure head downstream and upstream of the PRV. Pressure heads are for (a), (b) complete sudden closure, (c), (d) sudden opening, and (e), (f) slow closure of the downstream ball valve. The observed head is from Meniconi et al. (2017).

wave that propagated towards the PRV and gradually increased its downstream head from 27.3 m to 51.7 m (Figure 2(e) and 2(f)). Simulated and observed results were in good agreement; the NSE coefficient was 0.99

for head downstream of the PRV and 0.98 for head upstream of the PRV. These NSE values are close to 1.0, indicating that the model gives reliable predictions of the dynamic response of PRVs during transient events.

MODEL APPLICATION TO A WATER DISTRIBUTION NETWORK

Effect of PRV parameters on response to transients

To examine the effect of α_{open} and α_{close} on PRV response during transient events, the TRANSNET II model was applied to a hypothetical water distribution network with a single PRV (Figure 3). The network consisted of 10 pipes with a Hazen–Williams coefficient of 130 and a transient wave celerity $a = 400$ m/s. The network supplied two zones: zone A (junctions 4–8) and zone B (lump summed at junction 10). Elevations in zone A ranged between 10 m and 20 m above datum which is lower than the supply node (junction 1), while elevations in zone B ranged between 20 m and 30 m. The PRV was placed at junction 3 to control pressure in zone A during normal operations by reducing the total head from 96.9 m upstream of the PRV to a set head of 72.6 m downstream of the PRV.

Initially, the total demand for zones A and B was 30 L/s. The network was subjected to a transient event due to sudden demand change. The sudden change simulated an industrial user requiring an abrupt increase in demand from 0 L/s to 7.5 L/s at junction 5. Two sets of scenarios were simulated to analyze the effect of α_{open} and α_{close} on the dynamic response of the PRV and pressure in the network.

To simplify the analysis, the first set consisted of three scenarios S1, S2, and S3 with equal values of α_{open} and α_{close} for each scenario. The values for α_{open} and α_{close} differed between scenarios by up to two orders of magnitude as follows: $\alpha_{\text{open}} = \alpha_{\text{close}} = 10^{-7}$ m²/s for scenario S1, $\alpha_{\text{open}} = \alpha_{\text{close}} = 10^{-6}$ m²/s for scenario S2, and $\alpha_{\text{open}} = \alpha_{\text{close}} = 10^{-5}$ m²/s for scenario S3.

The second set consisted of two scenarios S4 and S5 with unequal α_{open} and α_{close} for each scenario. For scenario S4, $\alpha_{\text{open}} = 10^{-7}$ m²/s and $\alpha_{\text{close}} = 10^{-5}$ m²/s. For scenario S5, $\alpha_{\text{open}} = 10^{-5}$ m²/s and $\alpha_{\text{close}} = 10^{-7}$ m²/s. The scenarios with unequal values for α_{open} and α_{close} are more realistic than the scenarios with equal values; the action of the needle valve controlling flow into and out of the chamber of the main valve of the PRV depends on flow direction (i.e., whether the valve is opening or closing) (Prescott & Ulanicki 2003). For all scenarios S1–S6, a time step of 0.025 s was used in simulating the transient event for the duration of 60 s.

In all scenarios S1–S5, two negative pressure waves were induced by the sudden increase in demand at junction 5. The first negative pressure wave propagated directly from junction 5 towards junction 4 and the PRV, leading to a decrease in head downstream of the PRV. The other negative pressure wave propagated along the longer path from junction 5 to 4 through junctions 6 to 8, which further decreased the head downstream of the PRV (Figure 4(a) and 4(d)).

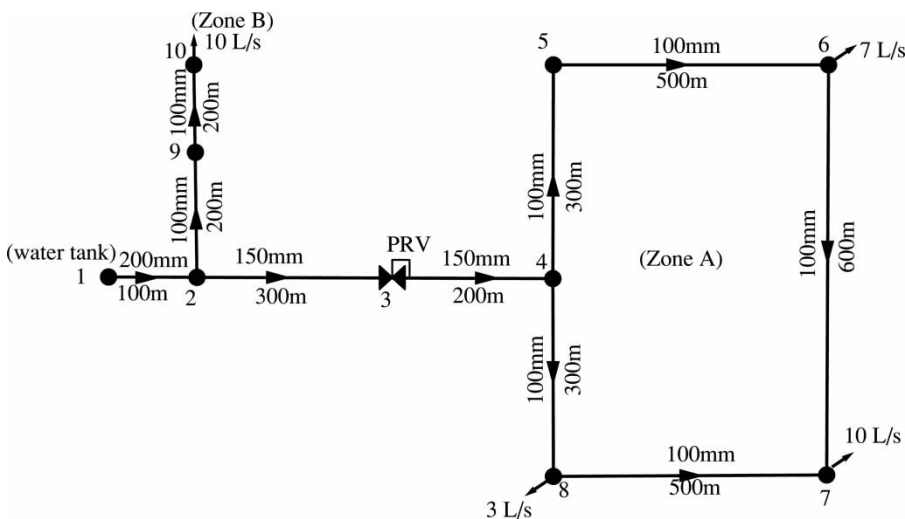


Figure 3 | Layout of hypothetical network. Numbers given on pipes denote diameter (mm) and length (m). Arrows denote demand at junctions.

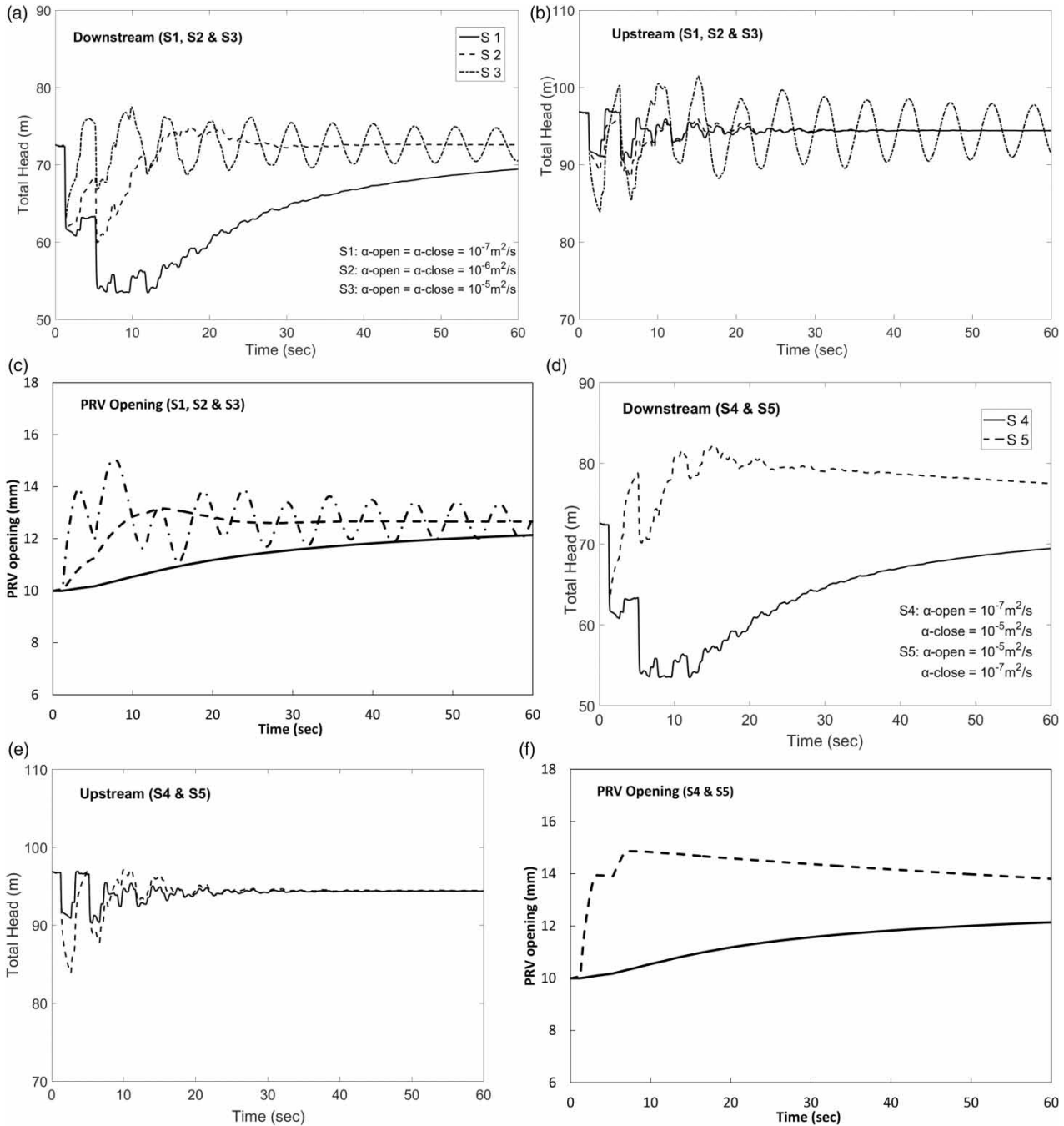


Figure 4 | (a), (d) Head downstream of the PRV, (b), (e) head upstream of the PRV, and (c), (f) PRV opening for the hypothetical pipe network of Figure 3.

The PRV parameters α_{open} and α_{close} greatly affected the rate at which head upstream and downstream of the PRV approached new steady-state conditions after transient events. In scenario S1 with small values of $\alpha_{\text{open}} = \alpha_{\text{close}} = 10^{-7} \text{ m}^2/\text{s}$, the PRV response was slow.

The head downstream of the PRV rapidly decreased from 72.6 m to 61.0 m, decreased again to 53.8 m at time 9 s, and then slowly approached to a steady value over an extended period of 60 s. The head upstream of the PRV decreased from 96.9 m to 91.5 m, then oscillated with a

diminishing amplitude that was damped within 30 s (Figure 4(a)–4(c)). In scenario S2, higher values of the PRV parameters $\alpha_{\text{open}} = \alpha_{\text{close}} = 10^{-6} \text{ m}^2/\text{s}$ led to a more rapid PRV response compared to scenario S1. The head downstream of the PRV decreased in scenario S2 to 62.0 m then to 60.0 m. The head then approached a steady value over a period of 30 s which is shorter than scenario S1. Upstream of the PRV in scenario S2, the head decreased to 88.6 m lower by 3% than head in scenario S1 (Figure 4(a)–4(c)).

In scenario S3, the head downstream of the PRV decreased to 63.5 m, then increased rapidly to 76.0 m before decreasing again to 66.8 m. For this scenario, the high values of α_{open} and α_{close} made the valve more sensitive and faster in opening and closing which triggered oscillations that persisted for an extended period. Upstream of the PRV in scenario S3, the head decreased to 84.0 m lower by 8% than head in scenario S1, then oscillated with diminishing amplitude but with a range larger than scenarios S1 and S2 (Figure 4(a)–4(c)).

In scenario S4, the head downstream of the PRV decreased to 61.0 m then to 53.8 m (Figure 4(d)–4(f)). The small value of $\alpha_{\text{open}} = 10^{-7} \text{ m}^2/\text{s}$ slowed down the valve opening; the valve continued to open approaching steady state over an extended period of more than 60 s. Throughout this period, only the parameter α_{open} controlled the PRV response and the simulated pressures in scenario 4 were identical to pressures simulated in scenario 1 even though α_{close} was different (Figure 4(a) and 4(d)).

In scenario S5 where the value of $\alpha_{\text{open}} = 10^{-5} \text{ m}^2/\text{s}$ was higher than $\alpha_{\text{close}} = 10^{-7} \text{ m}^2/\text{s}$, the PRV was more sensitive and faster in opening than in closing. The head downstream of the PRV decreased to 63.5 m similar to scenario S3 and then increased rapidly to 78.8 m due to the high value of α_{open} and fast valve opening. A subsequent decrease in pressure to 70.2 m, below the PRV set point, led to fast valve opening and overshooting to 80.6 m beyond the set point. The PRV then started to close slowly approaching steady state as a result of the small value of α_{close} (Figure 4(d)–4(f)).

The analysis above clearly shows that the values of α_{open} and α_{close} affect the maximum pressure, minimum pressure, and wave damping that occur in pipe systems during transient events. These results indicate the importance of

examining PRV-dynamic response during transients and identifying the optimal PRV parameters that improve its dynamic response.

Optimal PRV parameters

The application of the SCE optimization algorithm to the network described above gave optimal values of α_{open} and α_{close} that differed with the applied objective function. Using the objective function OF1, the optimal values were $\alpha_{\text{open}} = 5.9 \times 10^{-6} \text{ m}^2/\text{s}$ and $\alpha_{\text{close}} = 6.4 \times 10^{-6} \text{ m}^2/\text{s}$. In contrast, optimal values for OF2 were two orders of magnitude higher, $\alpha_{\text{open}} = 5.9 \times 10^{-4} \text{ m}^2/\text{s}$ and $\alpha_{\text{close}} = 8.2 \times 10^{-4} \text{ m}^2/\text{s}$. A comparison of the maximum and minimum head that occurred during the transient event with both sets of PRV parameters was carried out along path 1 (nodes 1–8) and path 2 (nodes 1, 2, 9, and 10) to clarify the effect of objective function on optimization results. For path 1, using OF1 reduced the maximum head immediately upstream of the PRV from 111.0 m when using OF2 to 99.0 m (Figure 5(a)). This difference of 12 m was the highest difference in head simulated by using optimal PRV parameters from the two objective functions. Downstream of the PRV, the highest difference in the maximum head was 4 m and occurred at location 2,000 m along path 1 about 1,600 m downstream of the PRV. At this location, the maximum head was 59.0 m by using OF2 and 63.0 m by using OF1 (Figure 5(a)). Similar to maximum pressure, the highest difference in minimum pressure along path 1 occurred immediately upstream of the PRV. The minimum head at this location was 74.4 m for OF2 and 86.2 m for OF1 (Figure 5(b)).

For path 2 (nodes 1, 2, 9, and 10), the advantage of using OF1 is clear by reducing the highest maximum head from 108.0 m to 101.0 m and increasing the lowest minimum head from 88.7 m to 93.3 m (Figure 5(c) and 5(d)).

The RMSD immediately downstream of the PRV was 6.2 m when using OF1, higher than the RMSD of 2.7 m for OF2. In contrast, the RMSD immediately upstream of the PRV was 6.7 m for OF1, smaller than the RMSD of 18.3 m for OF2. Overall, the average RMSD for the network was slightly smaller for OF1 (6.8 m) compared to RMSD for OF2 (6.9 m). The main advantage in using OF1 is considering the entire network in the optimization and not focusing on downstream of the PRV alone as this may lead to

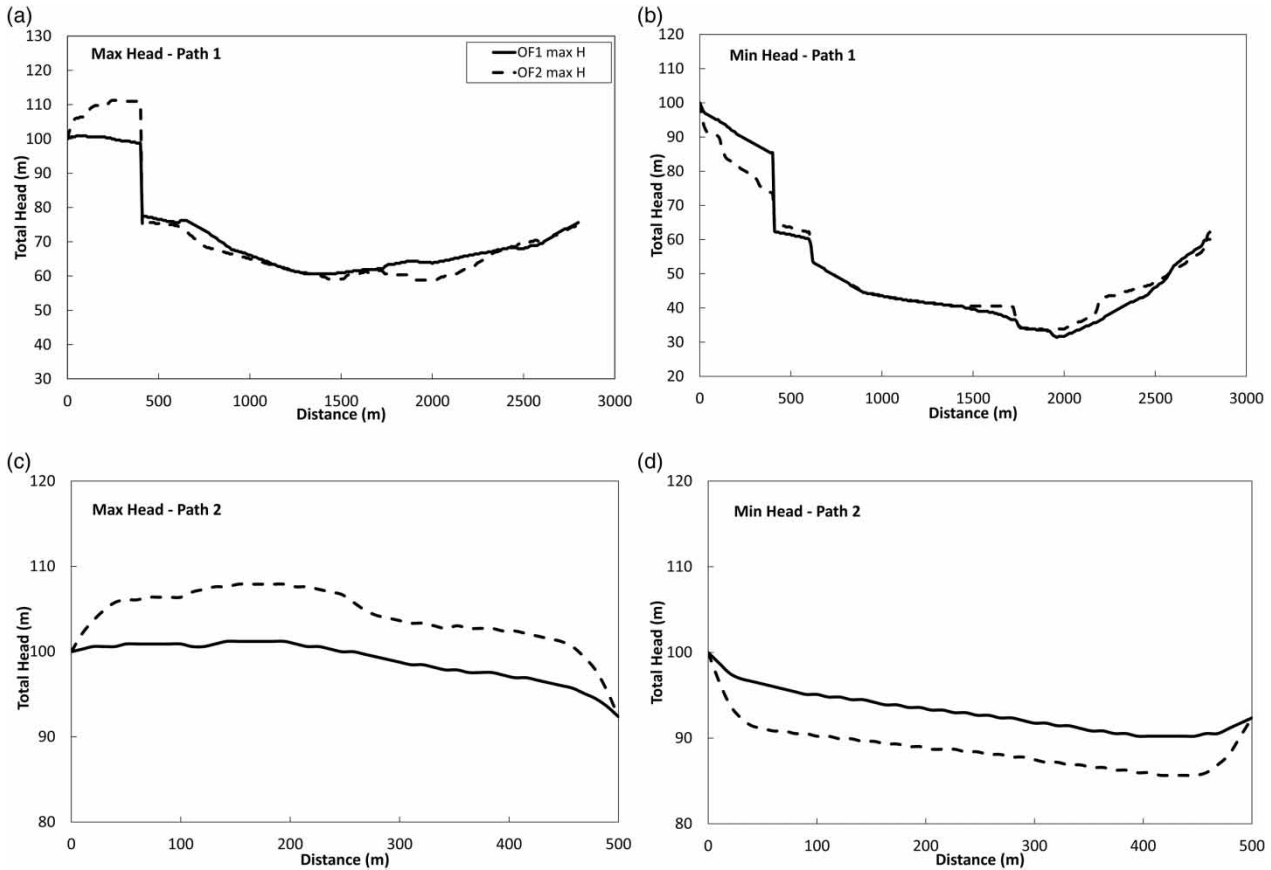


Figure 5 | (a), (c) Maximum and (b), (d) minimum simulated head along paths 1 and 2 of the pipe network of Figure 1(b). Head shown is for optimal PRV parameters based on objective functions OF1 and OF2.

unacceptable pressure heads upstream of the PRV. Constraints or requirements at specific nodes in the network may be accommodated by adjusting OF1. The adjustment includes increasing the weight for the RMSD of the target nodes when calculating the average RMSD.

CONCLUSIONS

The dynamic response of PRVs during transient events is challenging to simulate as it is based on PRV properties and the interaction between the PRV and the network. We developed a model to simulate the interaction between PRVs and water networks during transient events through coupling the TRANSNET water-hammer model (Larock *et al.* 1999) and the two-parameter PRV model proposed by Prescott & Ulanicki (2008). The PRV parameters α_{open}

and α_{close} were calibrated and validated using the experimental observations by Meniconi *et al.* (2017). Nash–Sutcliffe model efficiency coefficient for the developed model was close to unity, indicating that the model gives reliable predictions of the dynamic response of PRVs during transient events.

Five scenarios were simulated for a hypothetical network with different values of α_{open} and α_{close} to examine how PRV parameters affect maximum pressure, minimum pressure, and wave damping that occurs in pipe systems during transient events. The model was then interfaced with SCE algorithm to optimize the PRV parameters and improve the dynamic response of PRVs during transient events. Model application to the hypothetical network with an objective function that considers pressure heads at all network nodes reduced the highest maximum head upstream of the PRV by 7% and increased the lowest

minimum head upstream of the PRV by 5%. To facilitate the application of optimization results and selection of PRVs with the optimal dynamic response, it is recommended that PRV manufacturers experimentally determine the PRV parameters and include these parameters in PRV catalogs.

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