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Optimizing pipeline systems with surge tanks using a dimensionless transient model

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ABSTRACT

The design factor of surge tank installation is a practical issue in the management of pressurized pipeline systems. To determine the general criteria for surge tank design in pipeline systems, dimensionless governing equations for unsteady flow and their solutions were developed for two widely used pipeline systems equipped with surge tanks. One is the reservoir pipeline surge tank valve and the other is the pipeline system with a pumping station and check valve protected by the surge tank. Two distinct time-domain responses, point- and line-integrated pressure, can be used as objective functions to optimize the surge tank area. The developed formulations were integrated into a metaheuristic engine, particle swarm optimization, to explore a general solution for a wide range of dimensionless resistances that comprehensively address various flow features into one dimensionless parameter. Depending on the dimensionless location of the surge tank, the optimum dimensionless surge tank areas were delineated for a range of dimensionless resistances for the two pipeline systems with and without a pumping station protected by a surge tank.

Key words: dimensionless frequency response, hydraulic transient, optimization, pipeline systems, pump, surge tank

HIGHLIGHTS

- Dimensionless solutions for pressure response were derived for pipeline systems with surge tanks.
- The dimensionless resistance represents flow rate, friction, diameter, length and wave speed.
- Both point- and line-integrated pressures were used as objective functions.
- The frequency domain models were integrated into particle swarm optimization.
- Dimensionless surge tank areas were delineated for dimensionless resistances.

INTRODUCTION

Water hammers in pipeline systems can be generated by sudden valve closures, pump stoppages, or instant check valve actions. When a pressure wave is generated by an abrupt change in flow velocity, it introduces either overpressure or pressure along the pipeline. Although a high pressure can burst a weakened part of the pipeline, a low pressure can generate column separation and cavitation, which usually substantially damage the pipeline system. To protect the pipeline structure from hydraulic transient events, surge protection devices, such as surge tanks, have been used in front of the control valve and pump station.

To analyze surge events in pipeline systems, the characteristic method has been used (Wylie & Streeter 1993; Karney & Simpson 2007; Wan & Zhang 2018) and the size and location of surge protection devices have been determined to relax sudden pressure variations, considering the cost of hydraulic structures (Di Santo *et al.* 2002; Jung & Karney 2009; Duan *et al.* 2010; Martino & Fontana 2012; Skulovich *et al.* 2015).

Transient generation and its propagation and reflection along pipeline systems introduce pressure oscillations, which can be expressed by the surface water variation of the surge tank (Guo *et al.* 2017). The length of the main pipeline and the location, cross-sectional area, and connector length of the surge tank in the pipeline system are important variables for determining the resonance characteristics of the pressure response. The cross-sectional area of a surge tank appears to be an important variable for moderating the oscillations in pipeline systems (Liu *et al.* 2023). The application of the impulse–response method demonstrated the potential of the frequency domain approach in the context of resonance characterization for the design of hydraulic structures using transient analysis (Kim 2010). Assuming that the layouts of pipeline systems with a surge tank are simple and similar to each other (e.g., reservoir pipeline surge tank valve), the pressure wave propagation pattern of the pipeline system can be generalized through the dimensionless development of governing equations and its optimum solution in the time-domain response (Kim & Choi 2022). Analytical developments for pipeline systems with and without pumping stations have provided distinct phase differences between the two systems depending on the transient generation location (Kim 2023).

A dimensionless analysis of the pressure response in pipeline systems equipped with surge tanks needs to be further explored in the context of a unified dimensionless viewpoint that can provide a robust basis for a comprehensive understanding of the system behavior and better management for various transient scenarios. The implementation of the pressure response feature in the practical flow regime can be successfully addressed by considering a wide range of dimensionless resistances in the optimum design of the system and modeling.

Therefore, this study explores a solution for optimum surge tank installation in a dimensionless space that can provide a general criterion for surge protection in pipeline systems, both with and without a pumping system. The objective function for parameter optimization can be either a point or a line-integrated response of the pressure at any designated point or part along the pipeline. Dimensionless developments for pipeline systems were integrated into a particle swarm optimization (PSO) scheme, which provides a comprehensive solution in a dimensionless space for the design of surge tank installations for two distinct pipeline systems.

METHODS

Dimensionless governing equations

The pressure head and velocity variation in a pressurized pipeline system can be expressed by continuity and momentum conservation as functions of two independent variables for time (t) and distance (x), and two dependent variables for mean velocity (V) and pressure head (H) (Wyile & Streeter 1993),

$$\frac{\partial V}{\partial t} + g\frac{\partial H}{\partial x} + \frac{fV|V|}{2DA^2} = 0 \tag{1}$$

$$\frac{a^2}{g}\frac{\partial V}{\partial x} + \frac{\partial H}{\partial t} = 0 \tag{2}$$

where A is the cross-sectional area, a is the wave propagation speed, g is the gravitational acceleration, f is the Darcy–Weisbach friction factor and D is the diameter.

The mean flow rate Q can be defined by multiplying V and A and the independent dimensionless variables can be defined as follows: $\hat{t} = at/L$ and $\hat{x} = x/L$, where L is the length of the pipeline system. The dependent dimensionless variables can be defined as $\hat{H} = gAH/(4aQ_o)$ for the pressure head and $\hat{Q} = Q/Q_0$ for the flow rate:

The dimensionless continuity and momentum equations are derived from Equations (1) and (2) as follows (Kim 2023).

$$\frac{\partial \hat{Q}}{\partial \hat{t}} + \frac{\partial \hat{H}}{\partial \hat{x}} + \hat{R} = 0 \tag{3}$$

$$\frac{\partial \hat{H}}{\partial \hat{t}} + \frac{\partial \hat{Q}}{\partial \hat{x}} = 0 \tag{4}$$

where $\hat{R}$ is the dimensionless resistance, which can be estimated as $\hat{R} = \mathrm{fLQ_o}/(2\,\mathrm{DAa})$ for turbulent flow and $\hat{R} = 32\mathrm{L}\nu/(\mathrm{D}^2\mathrm{a})$ for laminar flow conditions, respectively.

Equations (3) and (4) indicate that the dimensionless variable $\hat{R}$ represents the impact of friction, diameter, wave speed, and mean flow rate in response to the dimensionless flow rate and pressure head.

Applying perturbation theory to the dimensionless pressure head and flow rate in Equations (3) and (4) yield the trigonometric relationship between the upstream and downstream dimensionless frequencies ($\hat{s}$) as

$$\widehat{H_D} = \widehat{H_U}\cosh\hat{\gamma}\hat{x} - \widehat{Z_c}\widehat{Q_U}\sinh\hat{\gamma}\hat{x} \tag{5}$$

$$\widehat{Q_D} = -\frac{\widehat{H_U}}{\widehat{Z_c}}\sinh\hat{\gamma}\hat{x} + \widehat{Q_U}\cosh\hat{\gamma}\hat{x} \tag{6}$$

where $\widehat{Z_c}$ is the dimensionless characteristic impedance of pipeline, and the dimensionless propagation constant, $\hat{\gamma}$, can be expressed as

$$\hat{\gamma} = \sqrt{\hat{s}(\hat{s} + \hat{R})} \tag{7}$$

where $\hat{s}$ is the dimensionless frequency.

Pipeline systems with surge tank with and without pumping stations

A surge tank is frequently located upstream of a downstream valve in a simple pipeline system, as shown in Figure 1. If the water level of the upstream reservoir is lower than that of the downstream reservoir, a pumping station and check valve are installed upstream of the pipeline system, as shown in Figure 2. A hydraulic transient can be introduced through the abrupt closure of the downstream valve (Figure 1) or sudden stopping of the upstream pump (Figure 2), which can provide a substantial pressure surge due to either overpressure or underpressure, which occasionally introduces cavitation.

The upstream length between the upstream reservoir and surge tank, L_U, can be converted into an upstream dimensionless length as $\widehat{L_U} = L_U/L$, and the dimensionless downstream length can be defined as $\widehat{L_D} = L_D/L$.

If the hydraulic transient is introduced from the downstream valve, a dimensionless impedance should develop from the upstream to the downstream direction. The dimensionless hydraulic impedance upstream of the joining point is expressed as follows:

$$\hat{Z}_{UJ} = -\widehat{Z_c} \tanh \hat{\gamma}\widehat{L_U} \tag{8}$$

If the transient pressure head from downstream introduces reversed flow into the upstream direction, the check valve at the outlet of the pump can be instantly closed to protect the pump; then, the upstream boundary condition is the no-flow condition, and the corresponding hydraulic impedance at the surge tank can be expressed as

$$\hat{Z}_{UJ} = -\widehat{Z_c} \coth \hat{\gamma}\widehat{L_U} \tag{9}$$

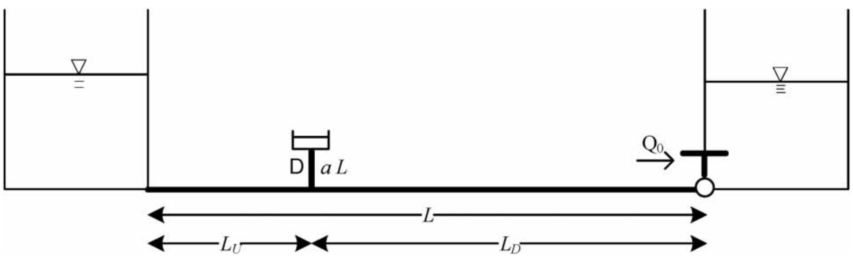

Figure 1 | Schematic of a reservoir pipeline surge tank pipeline valve (R-P-ST-P-V) system.

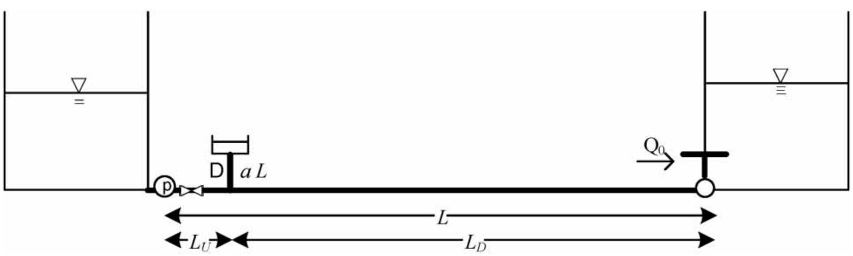

Figure 2 | Schematic of a reservoir pumping station check valve surge tank pipeline valve (R-PS-CV-ST-P-V) system.

The dimensionless hydraulic impedance at the surge tank can be approximated by considering the flow rate fluctuation and pressure as follows: $q' = -A_S dh'/dt$, where A_S is the surge tank area. The disturbance of the pressure head (h') can be approximated as $h' = H_S e^{st}$, where H_S is the steady pressure head in the surge tank, and s is the frequency.

If the dimensionless fluctuations can be defined as follows; $\widehat{h'} = gAh'/(aQ_o)$ and $\widehat{q'} = q'Q_o$, the dimensionless pressure head variation at the entrance of the surge tank can be expressed as,

$$\widehat{h'} = \widehat{H_S} e^{i\hat{s}\hat{t}} \tag{10}$$

where $\widehat{H_S} = \dfrac{gAH_S}{aQ_o}$

The dimensionless flowrate fluctuation at the entrance of the surge tank can be expressed as,

$$\widehat{q'} = \widehat{Q_S} e^{i\hat{s}\hat{t}} \tag{11}$$

where $\widehat{Q_S} = -\dfrac{A_S aH_S}{LQ_o} i\hat{s}$

The hydraulic impedance at the surge tank is expressed as $\widehat{Z_s} = \widehat{H_s}/\widehat{Q_s}$ and the hydraulic impedance at the downstream connector is evaluated as follows:

$$\widehat{Z_{Dc}} = \frac{\widehat{Z_s} - \widehat{Z_{cc}} \tanh \hat{\gamma}\widehat{L_c}}{1 - \widehat{Z_s}/\widehat{Z_{cc}} \tanh \hat{\gamma}\widehat{L_c}} \tag{12}$$

where $\widehat{Z_{cc}}$ is the dimensionless characteristic impedance and $\widehat{L_c}$ is dimensionless length of the connector, respectively.

The dimensionless hydraulic impedance of the main pipeline downstream of the surge tank connector is expressed as

$$\widehat{Z_{DJ}} = \frac{-\widehat{Z_c} \tanh \hat{\gamma}\widehat{L_U}}{1 - \widehat{Z_c} \tanh \hat{\gamma}\widehat{L_U}/\widehat{Z_{Dc}}} \tag{13}$$

The dimensionless hydraulic impedance downstream of the surge tank connection from the sudden pump stoppage can be expressed as

$$\widehat{Z_{DJ}} = \frac{-\widehat{Z_c} \coth \hat{\gamma}\widehat{L_U}}{1 - \widehat{Z_c} \coth \hat{\gamma}\widehat{L_U}/\widehat{Z_{Dc}}} \tag{14}$$

Dimensionless hydraulic impedance at downstream valve can be derived as follows:

$$\widehat{Z_{DV}} = \frac{\widehat{Z_{DJ}} - \widehat{Z_c} \tanh \hat{\gamma}\widehat{L_D}}{1 - \widehat{Z_{DJ}}/\widehat{Z_c} \tanh \hat{\gamma}\widehat{L_D}} \tag{15}$$

The dimensionless pressure head response due to the downstream flow rate variation at a point between the downstream valve and the connecting point for the surge tank can be developed as follows:

$$\frac{1}{2}(\widehat{Z_{DV}} + \widehat{Z_c})e^{\hat{\gamma}\widehat{x_D}} + \frac{1}{2}(\widehat{Z_{DV}} - \widehat{Z_c})e^{-\hat{\gamma}\widehat{x_D}} \tag{16}$$

where $\widehat{x_D}$ is the dimensionless distance from the downstream valve to the upstream point.

The dimensionless pressure head response owing to the downstream flow rate variation at a point between the connecting point and the upstream reservoir can be developed as follows:

$$\frac{1}{2}(\widehat{Z_{Uc}} + \widehat{Z_c})e^{\hat{\gamma}\widehat{x_U}} + \frac{1}{2}(\widehat{Z_{Uc}} - \widehat{Z_c})e^{-\hat{\gamma}\widehat{x_U}} \tag{17}$$

where $\widehat{x_U}$ is the dimensionless distance from the connecting point in the upstream direction, and $\widehat{Z_{Uc}}$ is the dimensionless hydraulic impedance at the upstream location of the surge tank connection point.

The dimensionless pressure head response owing to the pressure change in the pump between the pump and surge tank connecting point can be expressed as

$$\frac{1}{2}(1-\widehat{Z_c}/\widehat{Z_p})e^{\hat{\gamma}\widehat{x_u}}+\frac{1}{2}(1+\widehat{Z_c}/\widehat{Z_p})e^{-\hat{\gamma}\widehat{x_u}} \tag{18}$$

where $\widehat{Z_p}$ is the dimensionless hydraulic impedance at the pump and $\widehat{x_u}$ is the dimensionless distance from the upstream to the downstream connecting point.

The dimensionless pressure head response owing to the pressure change in the pump between the connecting point and downstream valve can be expressed as

$$\frac{1}{2}(1-\widehat{Z_c}/\widehat{Z_{cd}})e^{\hat{\gamma}\widehat{x_d}}+\frac{1}{2}(1+\widehat{Z_c}/\widehat{Z_{cd}})e^{-\hat{\gamma}\widehat{x_d}} \tag{19}$$

where $\widehat{Z_{cd}}$ is the dimensionless hydraulic impedance downstream of the connecting point, $\widehat{x_d}$ is the dimensionless distance from the connecting point downstream.

The line-integrated pressure response between the connecting point and the downstream valve in Figure 1 can be expressed as

$$\frac{1}{2\hat{\gamma}}(\widehat{Z_D}+\widehat{Z_c})e^{\hat{\gamma}\widehat{L_D}}+\frac{1}{2\hat{\gamma}}(\widehat{Z_D}-\widehat{Z_c})e^{-\hat{\gamma}\widehat{L_D}}-\widehat{Z_c}/\hat{\gamma} \tag{20}$$

The line-integrated pressure response between the upstream reservoir and the connecting point owing to Figure 1 can be expressed as

$$\frac{1}{2\hat{\gamma}}(\widehat{Z_U}+\widehat{Z_c})e^{\hat{\gamma}\widehat{L_U}}+\frac{1}{2\hat{\gamma}}(\widehat{Z_U}-\widehat{Z_c})e^{-\hat{\gamma}\widehat{L_U}}-\widehat{Z_c}/\hat{\gamma} \tag{21}$$

The line-integrated pressure response between the upstream pump and the connecting point due to the pump stopping in Figure 2 can be expressed as

$$\frac{1}{2\hat{\gamma}}(1-\widehat{Z_c}/\widehat{Z_p})e^{\hat{\gamma}\widehat{L_U}}+\frac{1}{2\hat{\gamma}}(1-\widehat{Z_c}/\widehat{Z_p})e^{-\hat{\gamma}\widehat{L_U}}+\widehat{Z_c}/(\widehat{Z_p}\hat{\gamma}) \tag{22}$$

The line-integrated pressure response between the connecting point and the downstream valve owing to pump stopping in Figure 2 can be expressed as

$$\frac{1}{2\hat{\gamma}}(1-\widehat{Z_c}/\widehat{Z_{cd}})e^{\hat{\gamma}\widehat{L_D}}+\frac{1}{2\hat{\gamma}}(1-\widehat{Z_c}/\widehat{Z_{cd}})e^{-\hat{\gamma}\widehat{L_D}}+\widehat{Z_c}/(\widehat{Z_{cd}}\hat{\gamma}) \tag{23}$$

Pipeline systems having multiple branches with surge tanks

Assuming multiple branched pipelines were connected downstream and the surge tank as shown in Figure 3, the dimensionless hydraulic impedance at upstream of branched element 1 can be expressed as follows,

$$\widehat{Z_{UB1}}=\frac{\widehat{Z_{DJ}}-\widehat{Z_c}\tanh\hat{\gamma}\widehat{L_{D1}}}{1-\widehat{Z_{DJ}}/\widehat{Z_c}\tanh\hat{\gamma}\widehat{L_{D1}}} \tag{24}$$

where $\widehat{L_{D1}}=L_{D1}/L$ and $\widehat{Z_{DJ}}$ can be estimated using Equations (13) or (14) depending on the system.

The dimensionless hydraulic impedance at downstream of branched element 1 can be expressed as follows,

$$\widehat{Z_{DB1}}=\frac{\widehat{Z_{UB1}}}{1+\widehat{Z_{UB1}}/\widehat{Z_{B1}}} \tag{25}$$

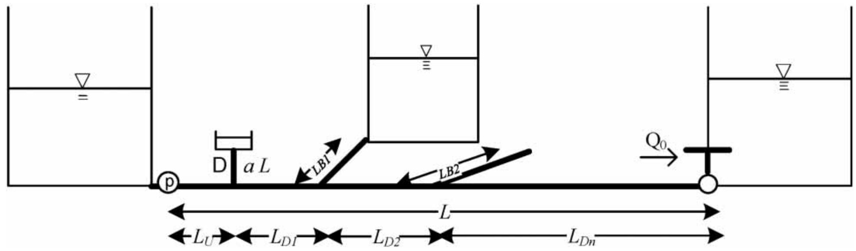

Figure 3 | Schematic of a reservoir pumping station check valve surge tank pipeline valve (R-PS-CV-ST-P-V) system having multiple branches.

where the dimensionless hydraulic impedance at the upstream of 1st branched element can be expressed as

$$\widehat{Z_{B1}} = \widehat{Z_{cB1}} \tanh \widehat{\gamma_{B1}} \widehat{L_{B1}} \tag{26}$$

where $\widehat{L_{B1}} = L_{B1}/L$.

The dimensionless hydraulic impedance at upstream of branched element 2 can be expressed as follows,

$$\widehat{Z_{UB2}} = \frac{\widehat{Z_{DB1}} - \widehat{Z_c} \tanh \hat{\gamma} \widehat{L_{D2}}}{1 - \widehat{Z_{DB1}}/\widehat{Z_c} \tanh \hat{\gamma} \widehat{L_{D2}}} \tag{27}$$

where $\widehat{L_{D2}} = L_{D2}/L$.

The dimensionless hydraulic impedance at downstream of branched element 2 can be expressed as follows,

$$\widehat{Z_{DB2}} = \frac{\widehat{Z_{UB2}}}{1 + \widehat{Z_{UB2}}/\widehat{Z_{B2}}} \tag{28}$$

where the dimensionless hydraulic impedance at upstream of 1st branched element can be expressed as

$$\widehat{Z_{B2}} = \widehat{Z_{cB1}} \coth \widehat{\gamma_{B2}} \widehat{L_{B2}} \tag{29}$$

where $\widehat{L_{B2}} = L_{B2}/L$.

Therefore, the dimensionless hydraulic impedance at the downstream valve can be derived as follows:

$$\widehat{Z_{DV}} = \frac{\widehat{Z_{DB2}} - \widehat{Z_c} \tanh \hat{\gamma} \widehat{L_{Dn}}}{1 - \widehat{Z_{DB2}}/\widehat{Z_c} \tanh \hat{\gamma} \widehat{L_{Dn}}} \tag{30}$$

where $\widehat{L_{Dn}} = L_{Dn}/L$.

The dimensionless pressure head response the downstream of last branched element, $\widehat{Z_{DBn}}$, due to the downstream flow rate can be expressed as

$$\frac{1}{2}(\widehat{Z_{DV}} + \widehat{Z_c})e^{\hat{\gamma}\widehat{L_{Dn}}} + \frac{1}{2}(\widehat{Z_{DV}} - \widehat{Z_c})e^{-\hat{\gamma}\widehat{L_{Dn}}} \tag{31}$$

The dimensionless pressure head response at the upstream of last branched element can be expressed as

$$\widehat{Z_{UBn}} = \frac{\widehat{Z_{DBn}}}{1 - \widehat{Z_{DBn}}/\widehat{Z_{Bn}}} \tag{32}$$

where $\widehat{Z_{Bn}}$ is dimensionless hydraulic impedance upstream of branched element n.

The dimensionless pressure head response at x_n distance upstream from last branched element can be expressed as

$$\frac{1}{2}(\widehat{Z_{UBn}} + \widehat{Z_c})e^{\hat{\gamma}\widehat{x_n}} + \frac{1}{2}(\widehat{Z_{UBn}} - \widehat{Z_c})e^{-\hat{\gamma}\widehat{x_n}} \quad (33)$$

where $\widehat{x_n} = x_n/L$.

Either a point pressure response or line-integrated pressure response can be developed similar to Equations (19)–(23).

Integration with metaheuristic engine

One of the most sensitive variables in surge tank design is the relative surge tank area and the ratio of the surge tank area to the cross-sectional area of the pipeline, not only because of the cost of the hydraulic device but also because of its crucial role in pressure oscillation (Liu *et al.* 2023). Considering the substantial impact of local topographical features such as the elevation distribution along pipeline extension, the potential locations of surge tank installation can be varied between 0.1 and 0.9 in terms of dimensionless distance from upstream to downstream. The developed formulations were used to determine the optimum surge tank area for the available range of dimensionless resistance. To ensure fast computation and optimization, an algorithm was designed considering the iterative evaluation of the dimensionless resistance (Figure 4) and its incorporation into the PSO (Kennedy & Eberhart 1995).

As shown in Figure 3, the dimensionless impedance formulations (Equations (16)–(23)) can be transformed into a time-domain kernel function using a fast Fourier transform algorithm. This time-domain response function can be convoluted with the pressure or flow rate change from a transient driver, such as valve action and pump stoppage. The resulting function is the pressure response at a designated point or the integrated pressure along a section of the pipeline system. The objective function is either the minimization of the point pressure, Equation (34), or the summation of the pressure along a designated section, Equation (35) as follows:

$$\text{OB1} = \text{Minimize} \sum_{i=1}^{n} (\widehat{h_i}^2) \quad (34)$$

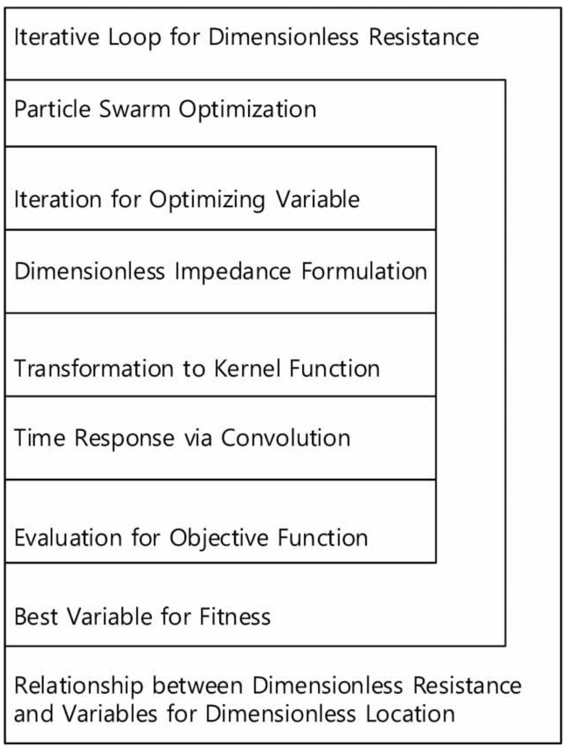

Figure 4 | Integration of PSO and dimensionless solution for pipeline systems.

$$\mathrm{OB2} = \mathrm{Minimize} \sum_{i=1}^{n} \left(\int \widehat{h}_i^{\,2} dx \right) \tag{35}$$

where n is the number of dimensionless time steps and $\widehat{h}_i$ is the dimensionless pressure response.

RESULTS AND DISCUSSION

Results

The dimensionless approach provides an identical solution for different flows, frictions, and lengths and diameters of the pipeline, as long as the dimensionless parameters between the two different systems are identical. As presented in Equations (3) and (4), a dimensionless parameter, dimensionless resistance, can holistically characterize system behavior. This implies that we can effectively explore the general response features of the system behavior by changing the dimensionless resistance. Considering that the location of the surge tank is frequently determined by field conditions, such as feasibility and elevation distribution, the size of the surge tank is the most important parameter for the design of surge tank protection from hydraulic transients.

Figure 5 presents the optimization results of the surge tank area for the R-P-ST-P-V system shown in Figure 1 for minimization of the one-point pressure. Instant valve closure in the downstream valve introduces a water hammer event. The objective function for Figure 5 is given by Equation (24) at a point adjacent to the downstream valve. Depending on the potential dimensionless location of the surge tank, between 0.1 and 0.9, the optimum dimensionless surge tank varies between 5 and 40. However, such variations in the optimum dimensionless surge tank appear to be less significant if the dimensionless resistance is less than 0.0001. The variation in the optimum dimensionless surge tank area showed a decreasing trend for a dimensionless resistance between 0.02 and 0.1. However, increasing trends in the dimensionless surge tank area were observed for a dimensionless resistance between 0.2 and 1. This means that dimensionless resistance can be an effective criterion for understanding the behavior of a system in the context of surge tank area design.

The optimization of the dimensionless surge tank area using OB2 in Equation (25) for identical conditions of transient generation, flow, and pipeline systems is shown in Figure 6: The line-integrated pressure is expressed by Equation (20), which is the sum of the pressures in the surge tank connecting the point to the downstream valve. As presented in Figure 6. The dimensionless surge tank areas tend to decrease in dimensionless resistance between 0.01 and 0.2 and increase from 0.2 except for one dimensionless location in 0.8. The impact of the dimensionless resistance on the dimensionless surge tank area is less meaningful if the dimensionless resistance is less than 0.0001, as shown in Figure 5.

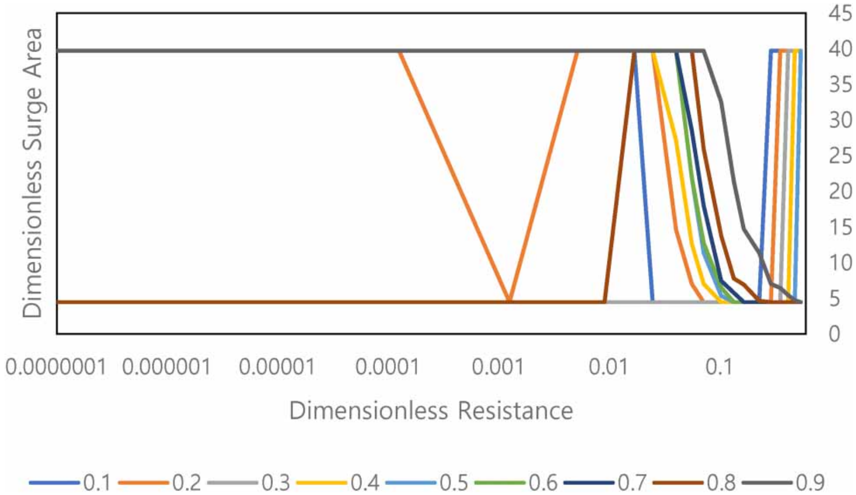

Figure 5 | Optimized dimensionless surge tank area about dimensionless resistance for dimensionless locations (0.1 and 0.9) of surge tank using a point pressure at valve (OB1) for R-P-ST-PV (system in Figure 1).

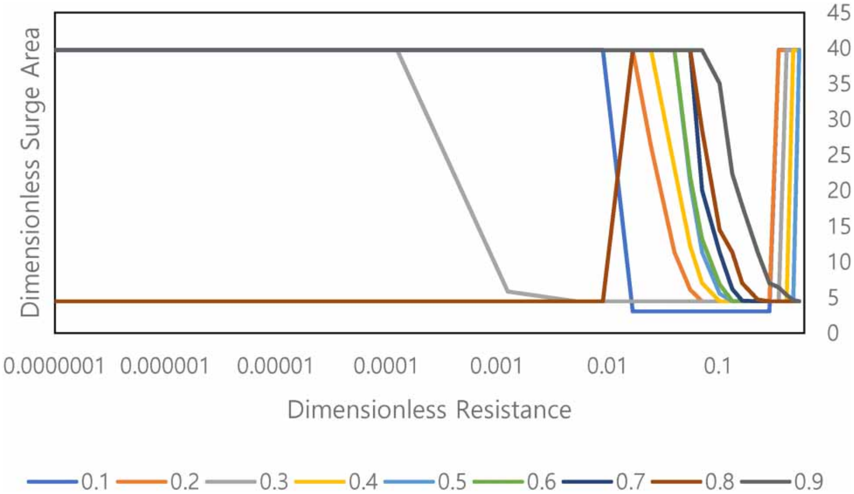

Figure 6 | Optimized dimensionless surge tank area about dimensionless resistance for dimensionless locations (0.1 and 0.9) of surge tank using line-integrated pressure (OB2) for R-P-ST-P-V (system in Figure 1).

Figure 7 presents the optimization results of the surge tank area for the R-PS-CV-P-ST-P-V system shown in Figure 2 using the objective function of OB1. An instant valve closure in the downstream valve identical to that in Figure 5 introduces the water hammer event, transient generation from the downstream valve propagates upstream, and the check valve is closed with the stoppage of the pumping station. The optimized dimensionless surge tank area varied substantially for dimensionless resistances between 0.00001 and 0.5.

These complex optimization results may be associated with hydraulic structures that are more complicated than those shown in Figure 1. Both the downstream and upstream pumping stations with check valves can be potential exciters of system response, and the optimum surge tank area can be affected by the interaction between multiple surge generation devices and pipeline features in terms of dimensionless resistance.

Figure 8 shows the optimization of the dimensionless surge tank area using the line-integrated pressure between the surge tank connecting point and downstream valve, Equation (23) for instant valve closure and subsequent pump stoppage. Unlike many previous results, the variation in the dimensionless surge tank area appeared to be limited to a dimensionless resistance between 0.01 and 0.1. Complicated resonance from multiple hydraulic structures can be compensated for by integrating the

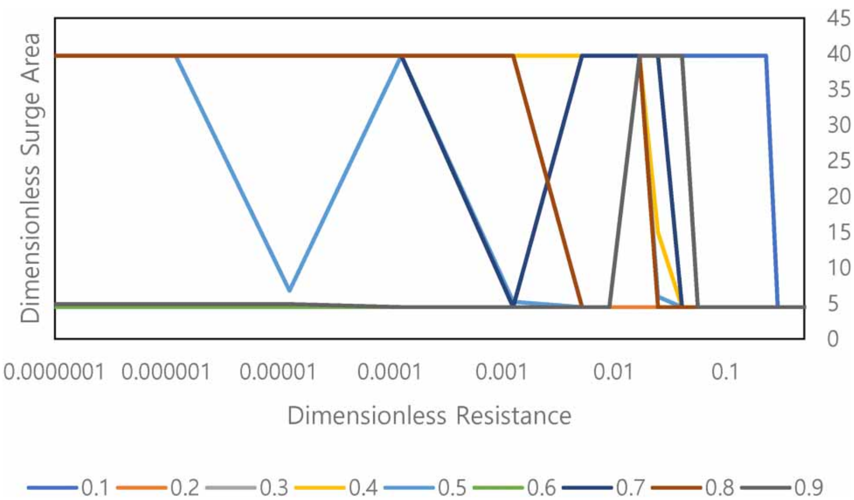

Figure 7 | Optimized dimensionless surge tank area about dimensionless resistance for dimensionless locations (0.1 and 0.9) of surge tank using a point pressure at valve (OB1) for R-PS-CV-P-ST-P-V (system in Figure 2).

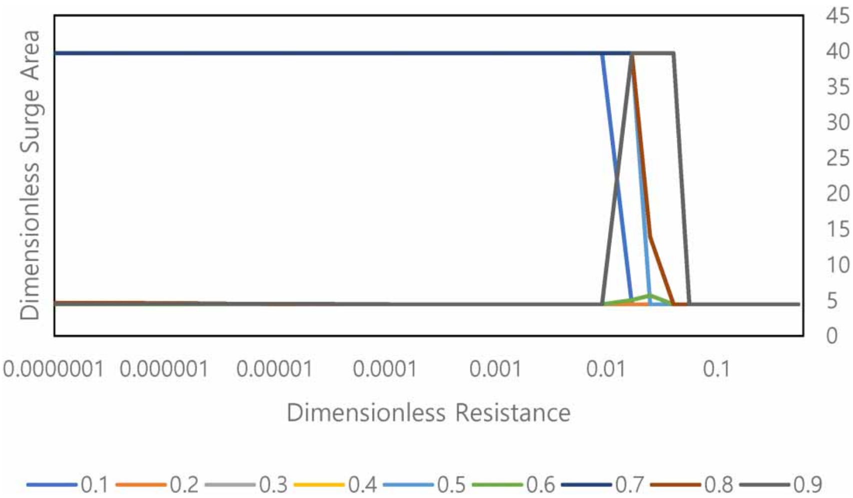

Figure 8 | Optimized dimensionless surge tank area about dimensionless resistance for dimensionless locations (0.1 and 0.9) of surge tank using line-integrated pressure (OB2) for R-PS-CV-P-ST-P-V (system in Figure 2).

pressure along the pipeline. Figure 8 indicates that the optimum design of the surge tank area is less meaningful if the dimensionless resistance is less than 0.008 or greater than 0.1 regardless of the dimensionless surge tank.

DISCUSSION

Kim (2023) validated the dimensionless approach by comparing the existing method with a developed scheme in the time-domain response. This study explored the optimization of the surge tank design using a dimensionless formulation. The optimization results shown in Figures 5–8 are based on the pressure response minimization in the time-domain. A surge event through instant velocity changes and abrupt pressure variations is a widely used transient event for the safe design of surge tanks. However, the field conditions may be more flexible than the hypothetical consideration of water hammer events. Modulated valve maneuvers can be used in many pipeline systems, even though sudden pump stoppage due to power failure can generate a shape surge event. Therefore, an alternative approach can be considered for the optimization of pipeline systems in the context of a wider scope of unsteady events. The kernel function for the convolution of the time-domain response can be obtained through an inverse fast Fourier transformation of the response functions, and its amplitude of kernel function depends on the frequency response functions (for example, Equations (16)–(23)). In other words, the optimization of the surge tank may not necessarily be limited to the time-domain response. The developed frequency response functions can be used to optimize pipeline systems. Depending on the system characteristics in terms of frequency response, a designated frequency range can be used for the objective function. This implies that the system can be designed based on the response feature of dimensionless response in the frequency domain. Further exploration of system optimization in the frequency domain has not yet been attempted, but the potential of frequency domain optimization may provide a wider comprehensive solution for all possible frequency ranges of the impulse input. Considering the substantial factors, assumptions, and uncertainties in the frequency domain model, further developments in modeling should be made for the optimum design of the system using an enhanced frequency objective function. Therefore, the optimal design of pipeline systems with a dimensionless frequency response is a topic for future research.

In this study, the parameters of the system were optimized based on the assumption that the water hammer was generated by an instantaneous valve closure. The optimization should be extended if the transient introduced is different from the transient caused by abrupt flow rate changes. Friction is another factor to consider. A steady friction model can provide satisfactory results when the water hammer is caused by an instant change of boundary condition, as the surge wave is mainly caused by the initial pressure wave. The attenuation of subsequent pressure waves can be important if the transient introduction is slow. Further development incorporating an unsteady friction model can be a future research topic, especially for transients caused by a slow valve action.

Experimental validation of dimensionless transient models for pipeline systems with surge tanks is both critical and challenging. There are numerous real-life systems that can exist for a dimensionless solution designed for a specific dimensionless system, which is an important underlying assumption for dimensionless approaches. Real systems with different physical dimensions and properties will need to be tested under identical dimensionless time scales, which will be different time scales between the various systems. Therefore, systematic studies of dimensionless transient models can be important research topics for the future.

CONCLUSIONS

In this study, a dimensionless solution for a transient event was used for the optimum design of pipeline systems with surge tanks. The developed dimensionless equations indicate that a one dimensionless parameter, dimensionless resistance, can holistically address the effects of friction, diameter, length, wave speed, and mean flow rate. The PSO scheme was incorporated into the time-domain response of the pressure from the developed dimensionless expressions. Both point- and line-integrated pressures can be used for the objective function to minimize the pressure response. Considering the importance of the surge tank area in the design, the distribution of the optimum dimensionless surge tank area can be obtained for the possible dimensionless locations of the surge tank and the dimensionless resistance. Depending on the system features and objective function, the optimum dimensionless surge tank area exhibited distinct responses for the dimensionless resistance range. The optimization results provide a general solution for the surge tank area if the dimensionless resistance and location are identical to those of multiple real-life systems. The further development of a dimensionless model for a more general design of the system response could be a future research topic for various transient impulses in the frequency domain.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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