

Article

Investigation of Water Hammer Protection in Water Supply Pipeline Systems Using an Intelligent Self-Controlled Surge Tank

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Abstract: A surge tank is a common pressure control device in long pressurized pipelines. The performance is greatly influenced by the location, cross area, and the characteristics of the connector. In order to improve the property of the surge tank, the effect of the connector is numerically analyzed by the method of characteristics (MOC). A hysteretic effect can occur when the discharge capacity is limited. Therefore, the performance of the surge tank can be improved if the discharge capacity of the connector is appropriately controlled according to the different conditions. For the adjustability of the connector's discharge capacity, a kind of intelligent self-controlled surge tank (IST) is proposed. In addition, through simulations and analysis, IST is proved to have advantages in pressure control and applicability compared to normal surge tanks.

Keywords: self-control; surge tank; water hammer; transient flow; numerical simulation

1. Introduction

In long-distance water supply systems, water hammer can be magnified with the length of the pressure pipeline due to the inertia and elasticity. Except for improved operations in long water supply systems [1], devices such as surge tanks [2–4], air chambers, and air valves [5,6] are widely used in some projects to ensure the running security. By breaking the continuity of the pressure conduits, the water-carried energy can be rapidly released by vibrating it up and down in surge tanks [4]. In recent decades, numerical simulation has become the main approach for transient analysis with the development of computer science [7]. Various methods have been proposed and applied to transient simulation, among which the finite difference method (FDM) [8] and finite element method (FEM) [9] are widely used. Especially, the method of characteristics (MOC) is the most popular method, and is widely used to simulate the transient processes in various engineering practices. The MacCormack method is widely used to solve the hyperbolic partial differential equation in computational fluid dynamics as well, especially in free surface flow [10,11]. In fact, it is still difficult to simulate the complex boundary conditions of the devices. Some studies show that many complex devices can be simplified as lump elements, which preserves the physical properties of the original devices [12]. Especially in some simple pipe systems, many boundary conditions can be expressed by some equation system, which accurately represents the physical properties of these complex devices. For regular water hammer simulation, the method is widely used in water pipeline systems. Fang and Chen [13] established a simulation system for a typical hydroelectric power plant with upstream and downstream surge tanks. Through an actual validated case, the simulation system was proved to be accurate and effective. Based on a turbine fuzzy model, Nagode and Skrjanc [14] proposed an internal control model of a power turbine, which turns out to show an improvement compared to previous

methods. Recently, Zhou [15] confirmed a 3D SP-VOF hybrid simulation to be effective by simulating a power-off process in hydropower pumped storage.

In long water supply systems, the surge tank is often used to control transient pressure [16–18]. The location and size of surge tanks can greatly affect the performance of the pressure control. Usually, the closer the surge tanks are placed to the transient generator, such as the valves, pump and turbines, the better the pressure control will be. If the size of the surge tank is insufficient, the transient pressure fluctuation cannot be reduced efficiently. Although a common surge tank is enough to satisfy most applications, there is still much room for improvement. Vereide and Svingen [4] investigated the effects of a surge tank throttling on hydraulic transients in a hydropower plant system. The result shows that the throttling can bring some slight improvement in transient pressure control. Yang and Wang [19] proposed a linear mathematical model of unsteady flow for the tailrace system with an open channel based on the state-space method. They found that the open tailrace channel has a strong influence on the hydraulic transient process by observing the water level fluctuations in tailrace surge tanks. Furthermore, they [20] also investigated the air flow in the ventilation tunnel of a surge tank. Riasi [21] considered the high cost of the surge tank construction, and proposed a surge relief valve to replace an expensive surge tank. Skulovich and Bent [22] optimized the placement and size of a surge tank to improve the transient control by an algorithm method. This method has the computational advantages in solving some specific transient boundaries. They considered a smooth relationship between maximum pressure and tank volume, and proposed that the selection of the protection devices is sensitive to transient event conditions. Zhou [23] proposed an enhanced multi-objective bacterial-foraging chemotaxis gravitational search algorithm, which turned out to be valued in controlling the rise rate of the unit rotational speed and water hammer pressure in a water apply system with two surge tanks at two sides.

However, in some specified project, because of differences in rainfall, reservoir water levels, and artificial operations due to temporal distribution, the optimized design of pressure control devices is not suitable for different operating conditions. In other words, every condition has the different transient processes, and the best parameters of the pressure control devices for one specific case may be not useful, or may even intensify the water hammer, in another operating condition. Thus, it is significant to optimize the flexibility and self-adjustability of the pressure control devices. Meniconi [24] studied and optimized the pressure reducing valves with self-adjustment equipment by experimental analysis.

In order to improve performance of the water hammer protection, a kind of intelligent self-controlled surge tank (IST) is proposed, which can adjust the parameters to be suitable for different conditions. The IST consists of a normal surge tank and an additional self-adjustable flow damper in the connector. The damper is designed to adjust the discharge capacity based on the pressure differences on the two sides of the connector. When the pressure difference is small, the discharge capacity is limited to keep the water volume inside the IST. On the other hand, when the pressure difference becomes large, the damper increases the discharge capacity to fully make use of the IST. The research results show that the IST has advantages in both flexibility and pressure control compared with normal surge tanks.

2. Numerical Model

2.1. Governing Equations

For one-dimensional pressure flow, assuming the heat energy transfer can be ignored, the momentum equation, Equation (1), and the continuity equation, Equation (2), constitutes the governing equations of water hammer [2]:

$$g \frac{\partial h(x, t)}{\partial x} + v(x, t) \frac{\partial v(x, t)}{\partial x} + \frac{\partial v(x, t)}{\partial t} + \tau_w = 0 \quad (1)$$

$$v(x, t) \frac{\partial h(x, t)}{\partial x} + \frac{\partial h(x, t)}{\partial t} - v(x, t) \sin \alpha + \frac{a^2}{g} \frac{\partial v(x, t)}{\partial x} = 0 \quad (2)$$

where h and v denote the water head and velocity, respectively; x and t denote the location and time, respectively; g is the acceleration of gravity; and α denotes the angle between the pipe center line and the horizontal plane. τ_w is the instantaneous wall shear stress. It can be divided into two parts, $\tau_w = \tau_{ws} + \tau_{wu}$. $\tau_{ws} = f \frac{v(x, t)|v(x, t)|}{2D}$ is the quasi-steady component, where f denotes the Darcy friction factor, D denotes the diameter of the pipeline. τ_{wu} represents the unsteady component. To simulate the unsteady component, various numerical methods were proposed. Instantaneous acceleration-based (IAB) models and weighting function-based (WFB) are the two popular models [25]. In this research, the unsteady component is neglected, since the influence of the unsteady friction component on the surge tank is insignificant.

2.2. Method of Characteristics

For numerical simulation, the MOC has been widely used to simulate the transient processes. It is also used to simulate the transient processes along the pipeline. Combining Equations (1) and (2) and keeping $dx/dt = \pm a$, the characteristic equation system can be written as follows [2]:

$$\begin{cases} C^+ : h(i, t + \Delta t) = C_P - Bq(i, t + \Delta t) \\ C^- : h(i, t + \Delta t) = C_M + Bq(i, t + \Delta t) \end{cases} \quad (3)$$

in which:

$$C_P = h(i - 1, t) + Bq(i - 1, t) - Rq(i - 1, t)|q(i - 1, t)|$$

$$C_M = h(i + 1, t) - Bq(i + 1, t) + Rq(i + 1, t)|q(i + 1, t)|$$

$B = \frac{a}{gA}$, $R = \frac{f\Delta x}{2gDA^2}$, and $h(i, t + \Delta t)$ denote the water head at section i at time $t + \Delta t$; $q(i, t + \Delta t)$ denotes the discharge at section i at time $t + \Delta t$; $h(i - 1, t)$ denotes the water head at section $i - 1$ at time t ; $q(i - 1, t)$ denotes the discharge at section $i - 1$ at time t ; $h(i + 1, t)$ denotes the water head at section $i + 1$ at time t ; and $q(i + 1, t)$ denotes the discharge at section $i + 1$ at time t . Except all the inner sections at the next time step, which can be determined by adjacent sections, the boundary conditions for different devices need to be solved separately.

2.3. Boundary Conditions

Commonly, if the pipeline is buried shallowly underground, a broad surge pool next to the pump station can ensure the operating security. However, based on the specific water supply pipeline in this research, there is a mountain ridge between the upstream and downstream reservoirs. Considering the limit of particular geological and environmental conditions, the designer planned a 40 km pipeline. Especially, the middle of the pipeline is higher than the two ends, so a surge tank is used to control the hydraulic transient during the pump failure. Figure 1 shows the schematic of the pipeline and surge tank.

In this case, the relevant parameters are listed as: Inner diameter of pipeline: $D = 5.0$ m; wetted perimeter: $X = 15.7$ m; cross area of pipeline: $A = 19.6$ m²; wave velocity in this pressured pipeline: $a = 1048$ m/s; and roughness coefficient: $n = 0.025$.

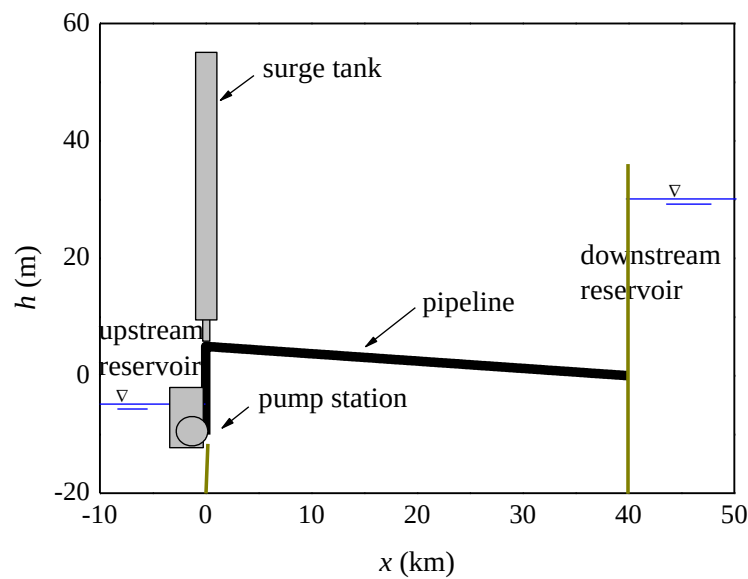


Figure 1. Schematic of the pipeline and surge tank.

Due to the raising pipe behind the pump station, after pump failure a significant negative pressure will occur on the top due to the water hammer event. It may cause pipe and device failure under atmospheric compression. In this case, various boundary conditions need to be solved, including reservoirs, valves, pumps, normal surge tanks, and intelligent self-controlled devices.

2.3.1. Reservoirs

In the water supply project, the water level of the upstream reservoir is -5.0 m, whereas the downstream reservoir water level is 30.0 m. The water level can be considered as a constant during the transient process, since the reservoir is enough large. Then, the boundary condition model of the reservoirs can be established as follows:

$$\begin{cases} \text{upstream reservoir :} & h(0, t + \Delta t) = h_{\text{up}} \\ \text{downstream reservoir :} & h(n, t + \Delta t) = h_{\text{down}} \end{cases} \quad (4)$$

where $h(0, t + \Delta t)$ denotes the water head of the first section at time $t + \Delta t$, which is at the entrance of the pipeline; $h(n, t + \Delta t)$ denotes the water head of the last section at time $t + \Delta t$, which is at the outlet of the pipeline; and h_{up} and h_{down} are the water level of the upstream and downstream reservoirs, respectively. According to Equation (3), the discharge of the boundary nodes of reservoirs can be solved as:

$$\begin{cases} \text{upstream reservoir :} & q(0, t + \Delta t) = [h(0, t + \Delta t) - C_M] / B \\ \text{downstream reservoir :} & q(n, t + \Delta t) = [C_P - h(n, t + \Delta t)] / B \end{cases} \quad (5)$$

where $q(0, t + \Delta t)$ and $q(n, t + \Delta t)$ denote the discharge of the first section and the last section at time $t + \Delta t$.

2.3.2. Valve

To control the inlet flow discharge, a butterfly valve was set up in the water supply pipe. It is located behind the pump station and before the entrance of the main pipeline. Figure 2 shows the relationship of the discharge coefficient and the open ratio of the valve.

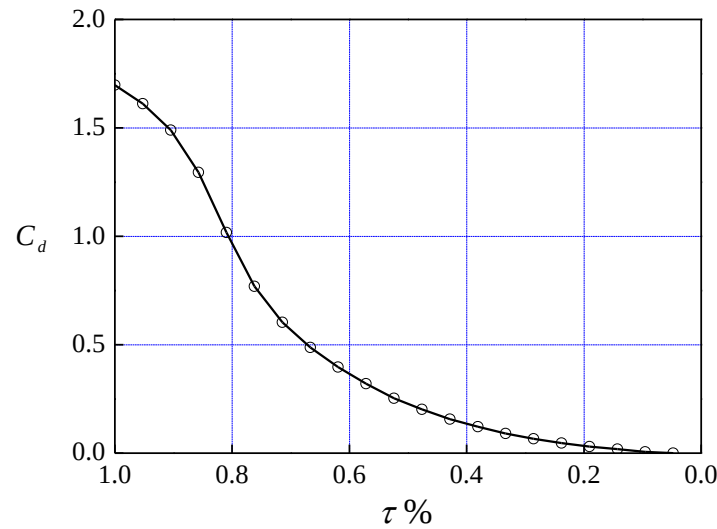


Figure 2. Discharge coefficient and open ratio.

The valve is a flow control device. To prevent the inversion and backflow in the pump system, the valve should be fast closed after pump failure. However, closing valves rapidly will cause water hammer. The boundary equations of the valve can be expressed as follows:

$$q_{\text{valve}} = C_d A \sqrt{2g \Delta h_{\text{valve}}} \quad (6)$$

where C_d is the discharge coefficient of the valve, which depends on the valve performance curve and opening ratio at a special time. Δh_{valve} is the pressure difference of both of its sides.

Thus, according to Equation (3), the water head of the boundary nodes of valves can be solved as:

$$\begin{cases} h_{\text{valve, left}}(t + \Delta t) = C_P - B q_{\text{valve}} \\ h_{\text{valve, right}}(t + \Delta t) = C_M + B q_{\text{valve}} \end{cases} \quad (7)$$

2.3.3. Pumps

A pump station is set next to the upstream reservoir and consists of three pumps to provide adequate energy for the water supply. The complete characteristic curve of the pumps is shown in Figure 3. Where $x_p = \pi + \tan^{-1}(q_p/n_p)$ is the instantaneous position of pump operation, $q_p = Q/Q_R$ is the dimensionless discharge through the pump, $n_p = N/N_R$ is the dimensionless rotated speed. $WH(x_p) = \frac{H/H_R}{(N/N_R)^2 + (Q/Q_R)^2}$, $WB(x_p) = \frac{T/T_R}{(N/N_R)^2 + (Q/Q_R)^2}$. H_R , N_R , Q_R , and T_R are, respectively, the rated head, rated rotate speed, rated discharge, and rated torque.

The characteristic lines of a pump are shown in Figure 4. A working pump provides a water head rise. The water head and discharge on both sides of a pump can be solved using the following set of equations, which combine the complete characteristic curve in Figure 3:

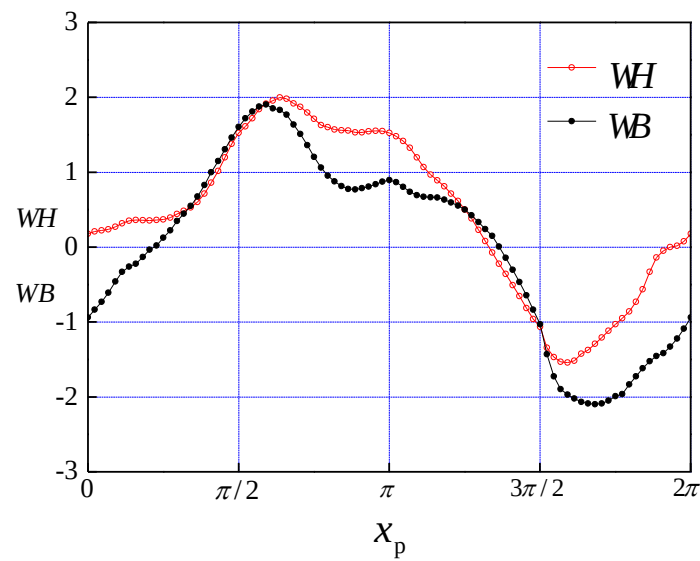


Figure 3. Complete characteristic curve of the pumps.

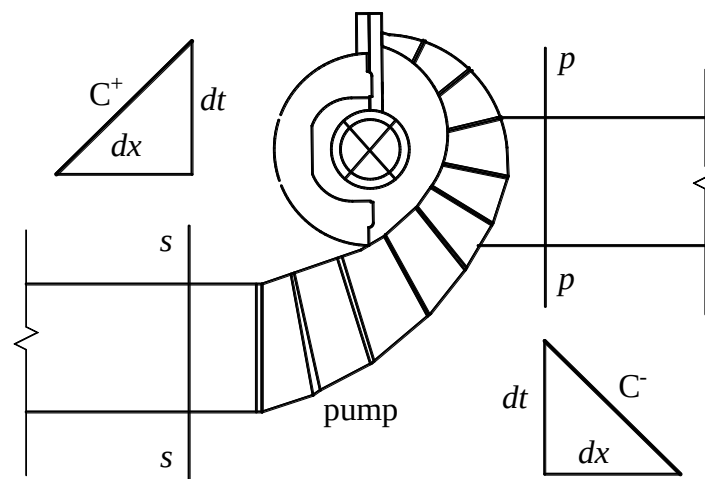


Figure 4. Characteristic lines of a pump.

$$\begin{cases} h(i_{s-s}, t + \Delta t) + \text{tdh} = h(i_{p-p}, t + \Delta t) \\ \text{tdh} = H_R(n_p^2 + q_p^2)WH(x_p) \\ (n_p^2 + q_p^2)WB(x_p) + \frac{T_0}{T_R} - \frac{WR_g^2}{g} \frac{N_R}{T_R} \frac{\pi}{30\Delta t} \frac{N_0 - N}{N_R} = 0 \\ q(i_{s-s}, t + \Delta t) = q(i_{p-p}, t + \Delta t) \\ h(i_{s-s}, t + \Delta t) = C_P - Bq(i_{s-s}, t + \Delta t) \\ h(i_{p-p}, t + \Delta t) = C_M + Bq(i_{p-p}, t + \Delta t) \end{cases} \quad (8)$$

where tdh is the total dynamic head provided by the pump; W is the weight of rotating parts plus entrained liquid; R_g is the gyration radius of the rotating mass.

2.3.4. Normal Surge Tanks

To reduce the extreme pressure, we set a surge tank at the peak of the pipeline and simulated various water hammer events to study the effects of the connector between the surge tank and pipe on the pressure control. The form and characteristic lines of a surge tank are shown in Figure 5. The boundary condition of a surge tank can be written as follows:

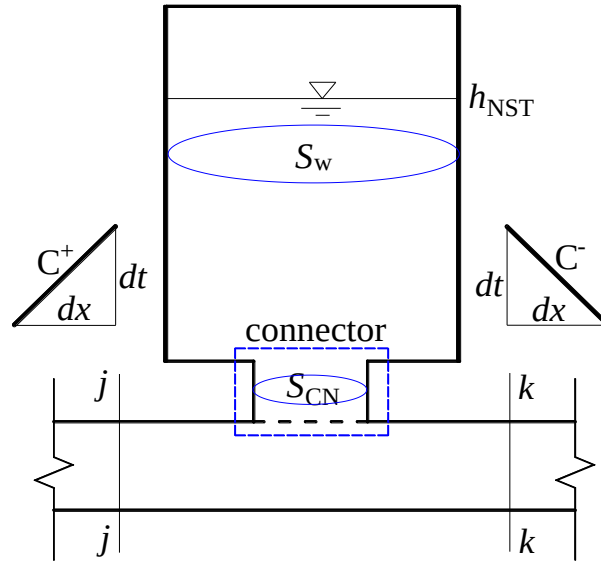


Figure 5. Boundary model of the surge tank.

$$\begin{cases} S_w[h_{NST}(t + \Delta t) - h_{NST}(t)] = \frac{\Delta t}{2} [q(i_{k-k}, t + \Delta t) + q(i_{k-k}, t) - q(i_{j-j}, t + \Delta t) - q(i_{j-j}, t)] \\ \text{ABS}[h_{NST}(t + \Delta t) - h(i_{k-k}, t + \Delta t)] = \xi_{NST} \frac{q_{NST}(t + \Delta t)^2}{2gS_{CN}^2} \\ q_{NST}(t + \Delta t) = q(i_{j-j}, t + \Delta t) - q(i_{k-k}, t + \Delta t) \\ h(i_{k-k}, t + \Delta t) = h(i_{j-j}, t + \Delta t) \\ h(i_{j-j}, t + \Delta t) = C_P - Bq(i_{j-j}, t + \Delta t) \\ h(i_{k-k}, t + \Delta t) = C_M + Bq(i_{k-k}, t + \Delta t) \end{cases} \quad (9)$$

where S_w is the cross area of the surge tank, $h_{NST}(t + \Delta t)$ is the water head at time $t + \Delta t$ in the normal surge tank, and $q_{NST}(t + \Delta t)$ is the discharge at time $t + \Delta t$ through the connector. ξ_{NST} is the local energy loss coefficient of normal surge tank connector, which is valued as 1.0 in this model. S_{CN} is the cross area of the normal surge tank connector.

2.3.5. Intelligent Self-Controlled Surge Tanks

Here, a kind of intelligent self-controlled surge tank (IST) is proposed, which is more flexible and efficient than the normal surge tank. Figure 6 shows an illustration of the intelligent self-controlled surge tank.

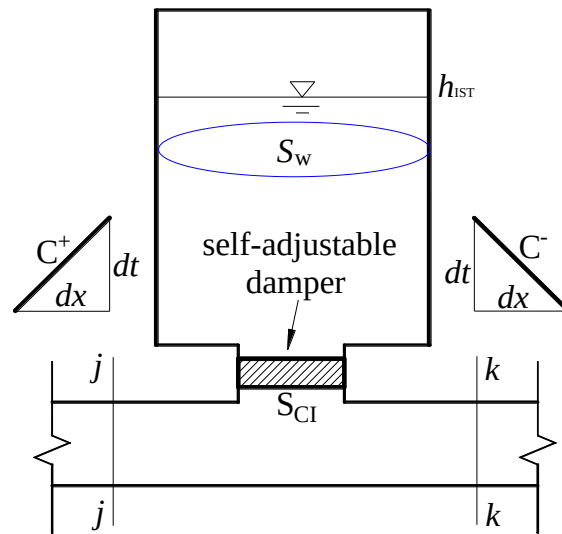


Figure 6. Illustration of an intelligent self-controlled surge tank.

Compared to the normal surge tank, an additional self-adjustable flow damper is equipped at the connector between the IST and the pipeline. It is just like a self-control valve. When the difference of water heads at its two sides is small, it contracts to limit the discharge inlet or outlet. On the other hand, it releases the limitation when the difference increases. In this way, the water in the surge tank will not totally participate in the pipe flow to control water hammer until it is severe. The boundary condition of the IST can be established as:

$$\left\{ \begin{array}{l} S_w[h_{IST}(t + \Delta t) - h_{IST}(t)] = \frac{\Delta t}{2} [q(i_{j-j}, t + \Delta t) + q(i_{j-j}, t) - q(i_{k-k}, t + \Delta t) - q(i_{k-k}, t)] \\ ABS[h_{IST}(t + \Delta t) - h(i_{k-k}, t + \Delta t)] = \zeta_{IST} \frac{q_{IST}(t + \Delta t)^2}{2gS_{CI}^2} \\ h(i_{k-k}, t + \Delta t) = h(i_{j-j}, t + \Delta t) \\ q_{IST}(t + \Delta t) = q(i_{j-j}, t + \Delta t) - q(i_{k-k}, t + \Delta t) \\ h(i_{j-j}, t + \Delta t) = C_P - Bq(i_{j-j}, t + \Delta t) \\ h(i_{k-k}, t + \Delta t) = C_M + Bq(i_{k-k}, t + \Delta t) \end{array} \right. \quad (10)$$

where $h_{IST}(t + \Delta t)$ is the water head at time $t + \Delta t$ in the tank above the damper, and $q_{IST}(t + \Delta t)$ is the discharge at time $t + \Delta t$ through the damper. ζ_{IST} is the local energy loss coefficient, which is valued as 5.0 in this model. S_{CI} is the cross area of the damper, related to $ABS[h(i_{k-k}, t) - h_{IST}(t)]$, which denotes the pressure difference between the two sides of the damper at time t .

3. Simulation and Analysis

3.1. Transient Response of Normal Surge Tanks

In this case, the cross area of the surge tank is 100 m^2 , while the cross area of the connector is 10 m^2 . After pump failure, the valve behind the pump station is closed in 50 s to prevent pump reversal. The extreme water head envelope curve is shown in Figure 7.

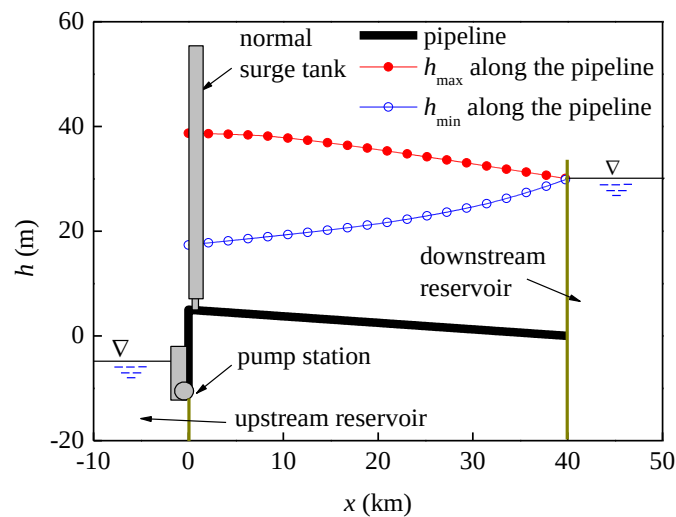


Figure 7. Extreme water head along the pipe after pump failure.

As shown in Figure 7, both the maximum and minimum head occur at the entrance of the pipeline upstream, and converge to the downstream water level along the pipeline. In other words, the hydraulic transient is worst near the surge tank upstream. Changing the cross area of the normal surge tank connector S_{CN} to 8 m^2 , 6 m^2 , 4 m^2 , and 2 m^2 , Figure 8 shows the various transient pressure processes in section $k-k$ and the extreme pressure distribution along the pipe after the pump failure. As shown in Figure 8, the cross area of the connector has a large influence on the performance of the surge tanks.

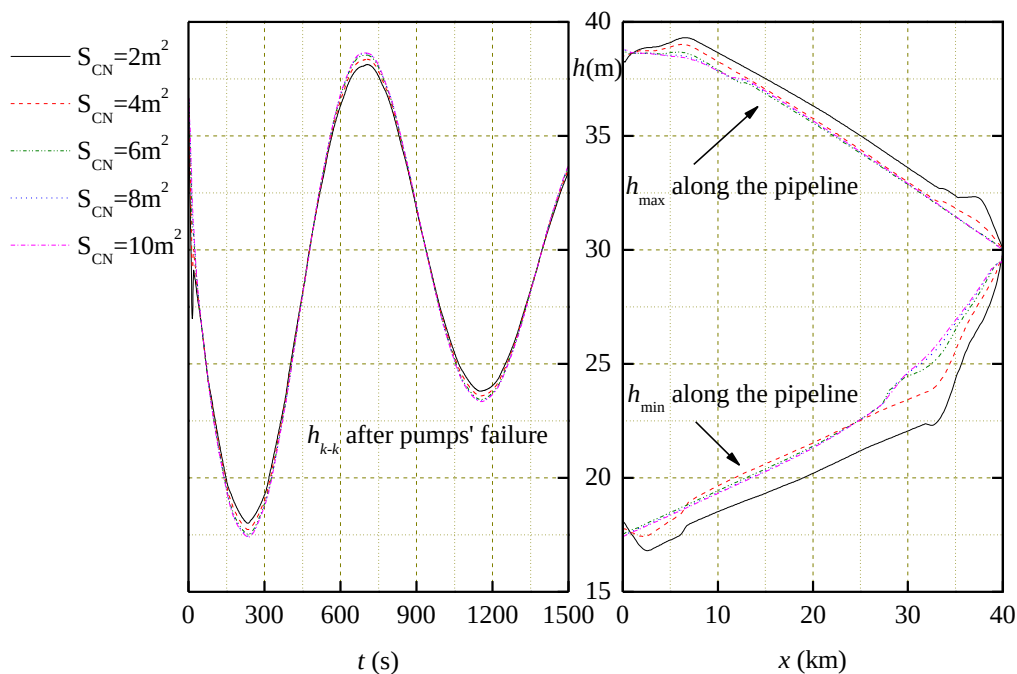


Figure 8. Key transient pressure and the extreme water head along the pipe.

When the cross area of the connector decreases, the fluctuation of h_{k-k} decreases, but the extreme head along the pipeline after the surge tank increases. In other words, adjusting the discharge capacity of the surge tank connector can cause a hysteretic effect, which can reduce the maximum pressure $h_{\max}$ and minimum pressure $h_{\min}$ along the pipe, and enlarge the extreme pressure elsewhere. In this case,

the optimal cross area of the connector should be between 4 and 6 m². However, for a normal surge tank, the discharge capacity of the connector is usually constant. It may not always be the best scale for different operation conditions. Thus, a kind of intelligent self-controlled surge tank is proposed, which can adjust the discharge capacity according to the different operating conditions, maintaining the best hysteretic effect for the pipeline.

3.2. Transient Response of Intelligent Self-Controlled Surge Tanks

The theory of the intelligent self-controlled surge tank is adjusting the discharge capacity of the connector according to the requirement. An adjustable flow damper is set inside the connector. When the pressure difference between the two sides of the connector increases sufficiently, the tank takes charge, releases the damper, and enlarges the discharge capacity. On the other hand, when the pressure difference remains small and transient processes are not severe enough for the IST to work, the damper remains tight and reserves its water for more severe operating conditions. Assume that the function of the flow damper can be expressed as follows:

$$S_{CI} = \begin{cases} 0.7 \text{ ABS}[h(i_{k-k}, t) - h_{IST}(t)] + 3 & , \text{ ABS}[h(i_{k-k}, t) - h_{IST}(t)] \leq 10 \\ 10 & , \text{ ABS}[h(i_{k-k}, t) - h_{IST}(t)] > 10 \end{cases} \quad (11)$$

The mechanism of the damper is designed as shown in Figure 9. When $\text{ABS}[h(i_{k-k}, t) - h_{IST}(t)] = 0$, the cross area keeps as 3 m², which is the minimum condition. As the hydraulic head difference increases, the loads on the clapboards will push them move towards the lower head side. The resistance provided by the resister depends on the pressure difference signs from sensors and the function designed as Equation (11). Thus, the damper cross area expands gradually, and attains a maximum of 10 m² when $\text{ABS}[h(i_{k-k}, t) - h_{IST}(t)] \geq 10$.

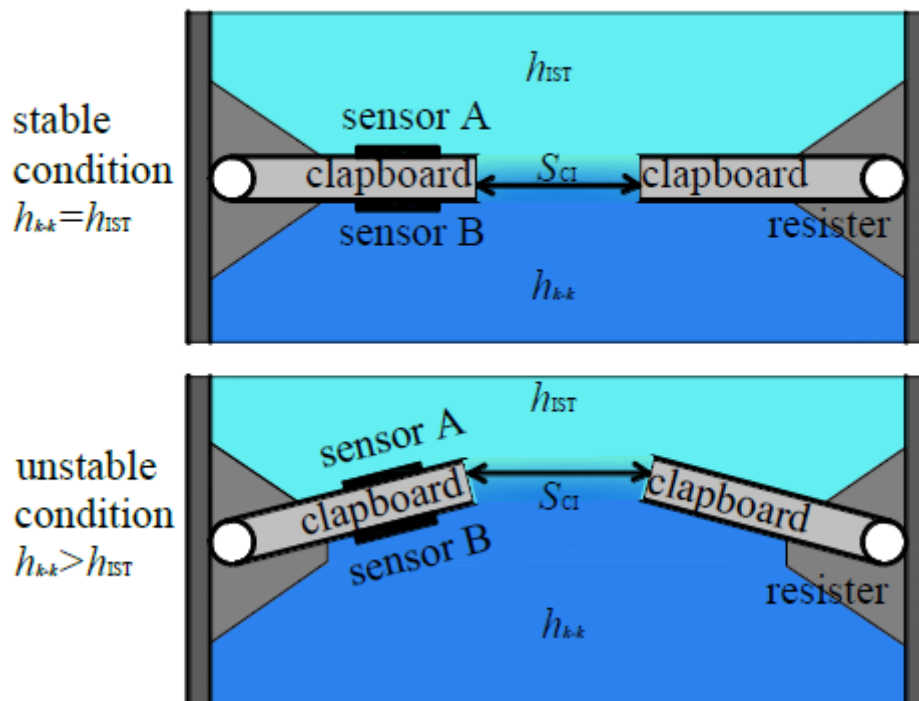


Figure 9. Mechanism of the flow damper in the IST.

Under these conditions, in a transient process, the cross area of the IST connector is adjusted between 3 to 10 m². For a suitable comparison, the cross area of the IST above the connector remains at

100 m², the same as the normal one. The water head process in the IST and at the connector are shown in Figure 10, compared with the water head process using a normal surge tank.

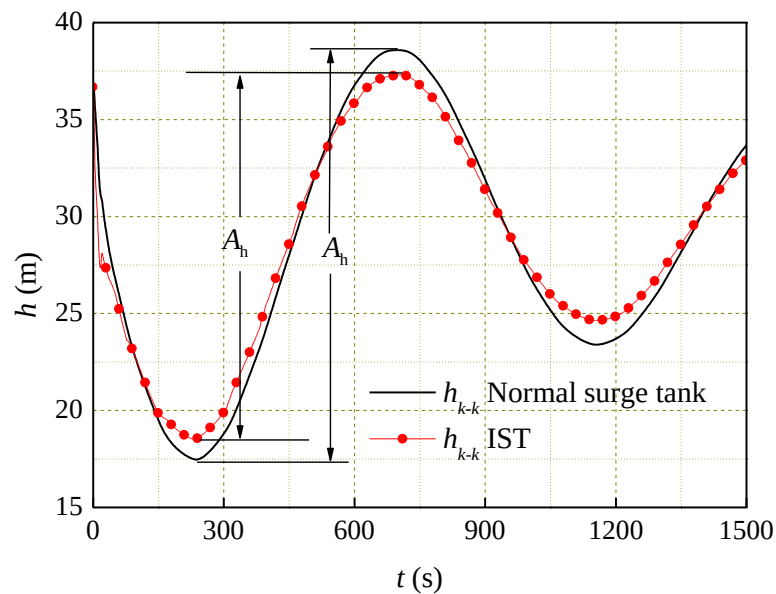


Figure 10. Extreme water head along the pipe after pump failure.

As shown in Figure 10, the extreme water hammer amplitude can be measured by the difference between the first peak and the first trough, $A_h = h_{\max 1st} - h_{\min 1st}$. Obviously, the amplitude of the IST is smaller than that of the normal surge tank. This result shows that the water hammer can be reduced using the IST. In other words, the IST requires less volume or height to provide the same protection as a normal tank. The extreme water head envelope curve using IST is shown in Figure 11.

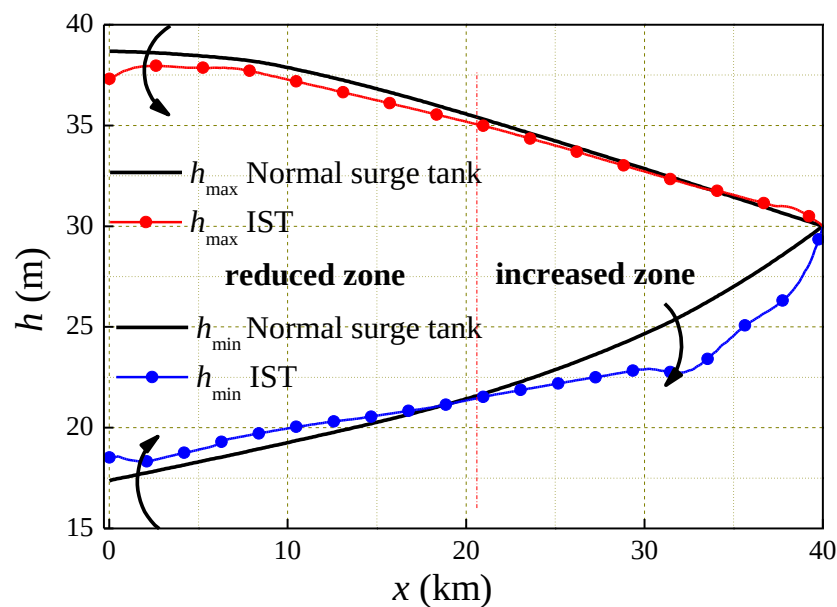


Figure 11. Extreme water head along the pipe after pump failure using the IST.

As shown in Figure 11, the water hammer intensity is better controlled by the IST in the upstream zone. On the other hand, the water hammer intensity is slightly severe by the IST in the downstream

zone, where the water hammer is commonly smaller than the upstream. Generally, the IST can improve the water hammer protection, since the transient pressure fluctuation is reduced in the worst location.

As shown in Figure 12, h_{IST} represents the pressure at the side in the tank, while h_{k-k} represents the pressure at the side in the pipe, $t = -1500$ s represents the time the pump starts, and $t = 0$ s represents the time of pump failure. On the whole, compared with h_{IST} , h_{k-k} changes in advance. As seen in Figure 12, S_{CI} only increased twice, once at the time the pump started and the other at the time of pump failure, ranging from 3 to 7 m^2 in this case. In addition, the mapping relationship between the discharge capacity and head difference plays an important role in the damper's efficiency. To establish the best mapping form, three kinds of functions are simulated numerically, and expressed as Equation (12).

$$\begin{aligned}
 F1 : S_{CI} &= \begin{cases} 0.07 \text{ABS}[h(i_{k-k}, t) - h_{IST}(t)]^2 + 3 & , \text{ABS}[h(i_{k-k}, t) - h_{IST}(t)] \leq 10 \\ 10 & , \text{ABS}[h(i_{k-k}, t) - h_{IST}(t)] > 10 \end{cases} \\
 F2 : S_{CI} &= \begin{cases} 0.7 \text{ABS}[h(i_{k-k}, t) - h_{IST}(t)] + 3 & , \text{ABS}[h(i_{k-k}, t) - h_{IST}(t)] \leq 10 \\ 10 & , \text{ABS}[h(i_{k-k}, t) - h_{IST}(t)] > 10 \end{cases} \\
 F3 : S_{CI} &= \begin{cases} \frac{7}{\sqrt{10}} \text{ABS}[h(i_{k-k}, t) - h_{IST}(t)]^{0.5} + 3 & , \text{ABS}[h(i_{k-k}, t) - h_{IST}(t)] \leq 10 \\ 10 & , \text{ABS}[h(i_{k-k}, t) - h_{IST}(t)] > 10 \end{cases}
 \end{aligned} \quad (12)$$

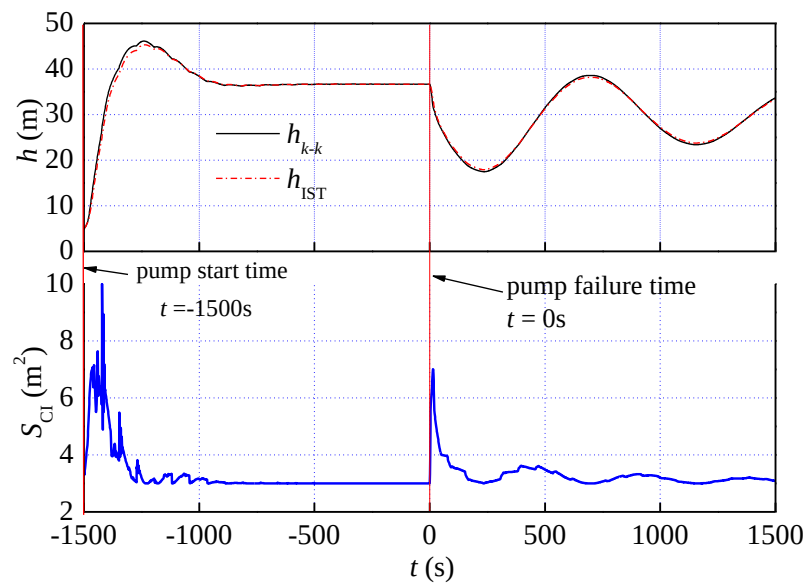


Figure 12. The transient process in the IST.

Figure 13 shows the comparisons on the transient processes using these three different functions. These functions can be realized by electrically controlling the mapping relationship between the resistor and sensors signals, shown as Figure 9. Function 1 is the convex function form, function 2 is the linear function form, and function 3 is the concave function form. Concerning h_{k-k} , using the convex function form seems to be the best choice for reducing the water hammer intensity. However, taking into consideration the extreme head along the pipeline, the downstream extreme head may be more severe, whereas the linear form shows an advantage in stability. On the other side, the concave function form is the most conservative choice, but with the least improvement in pressure control compared to a normal surge tank.

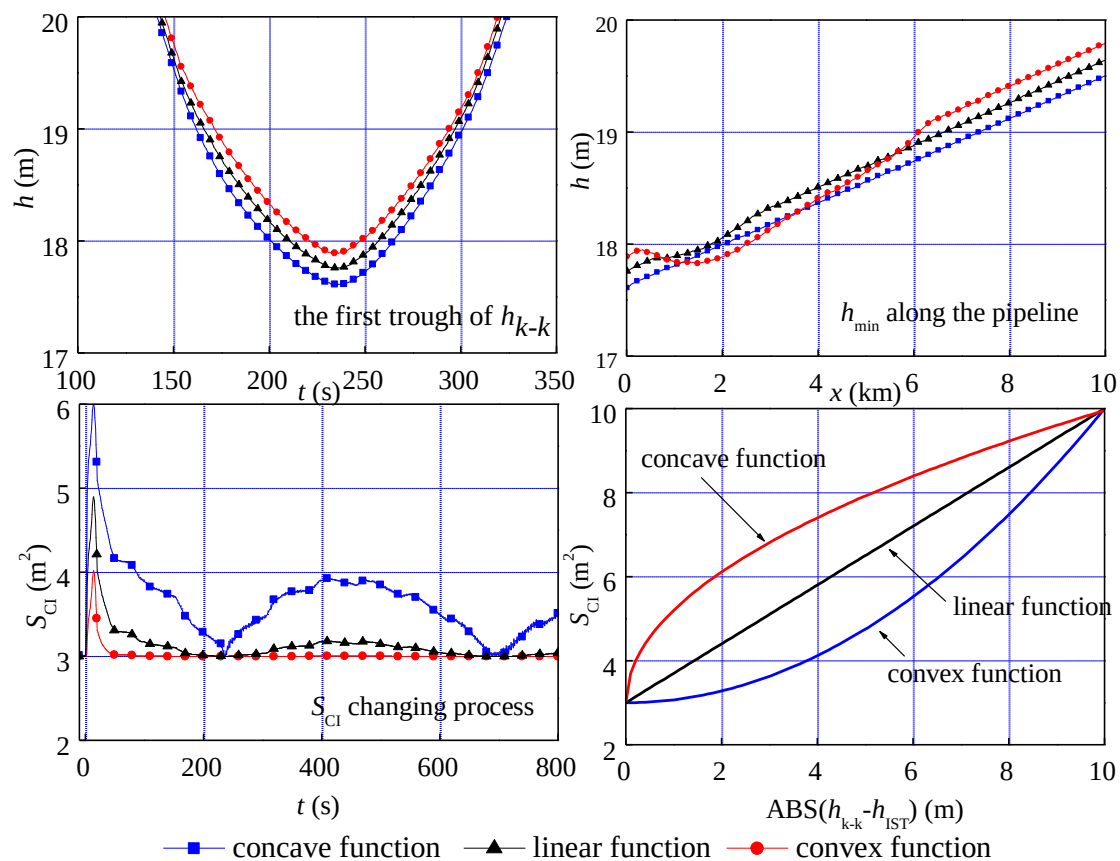


Figure 13. Comparison of the three functions of the IST.

4. Discussion

A surge tank is a common pressure control device in water supply systems. Since it is limited by the diameter of the pipeline, the cross area of the connector between the surge tank and the pipeline is always much smaller than the cross area above it. This research demonstrates the influence of the connector's parameters on the performance of the surge tank to control water hammer. Although not as significant as the location and cross area of surge tanks, insufficient connector discharge capacity may intensify water hammer elsewhere in the pipeline. For instance, in the case analyzed, the pressure wave will obviously intensify when the cross area of the connector is small, while a large connector may reduce the water hammer intensity. However, the cross area is a constant for a normal surge tank, which means it cannot fit different operating conditions that may occur in the water supply pipelines. Apparently, a constant connector cannot always work at the best condition. This is in good agreement with Vereide et al.'s [4] previous work, in which the effect of the throttling shows a similar law.

In this research, the intelligent self-controlled surge tank is proposed to improve the performance of the surge tank. It is actually a normal surge tank with an additional self-controlled discharge damper at the connector to the main pipe. The feature of the IST is that the discharge capacity has a positive relationship with the pressure difference between the two sides of the connector. Therefore, the IST can maintain a suitable discharge capacity due to the transient pressure condition in the system. Obviously, the mapping relationship between the pressure difference and the discharge capacity of the adjustable flow damper in the IST greatly affects the ability of water hammer control in the pipe system. In this study, three different function forms are used and analyzed. Simulations and comparisons show that the convex function form is the most efficient in water hammer control, whereas the concave function form is the most conservative. Thus, the mapping function and size limits may be different for various project scales.

5. Conclusions

In a water supply pipe system with surge tanks, a hysteretic water hammer effect will occur when the cross area of the connector is too small. It can significantly reduce the pressure amplitude at the worst location where the surge tanks are connected. For a specific operating condition, there is always a best connector design to keep the hysteretic effect positive for water hammer control. With a self-adjustable flow damper inside, the proposed IST can adjust the discharge capacity of the connector according to various operating conditions. Compared to normal surge tanks, the IST is more flexible, and can better control the water hammer intensity in the worst zone. Moreover, a suitable mapping relationship between the discharge capacity and the head difference can improve the efficiency of the IST.

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Nomenclature

g	Acceleration of gravity (m/s^2)
h	Pressure head (m)
x	Distance along pipe from inlet (m)
t	Time, as subscript to denote time (s)
v	Flow velocity (m/s)
τ_w	Instantaneous wall shear stress
τ_{ws}	The quasi-steady component
τ_{wu}	The unsteady component
α	The angle between pipe and the horizontal plane.
a	Speed of pressure wave (m/s)
f	Darcy friction factor
D	Main pipe diameter (m)
i	Serial number of nodes (s)
Δt	Time step (s)
q	Discharge (m^3/s)
Δx	Length of segment (m)
h_{up}	Head of upstream reservoir (m)
n	Number of sections
h_{down}	Head of downstream reservoir (m)
q_{valve}	Discharge through the valve (m^3/s)
C_d	Discharge coefficient
τ	Valve opening ratio
A	Cross area (m^2)
Δh_{valve}	Head difference of valve's two sides (m)
x_p	Instantaneous position of pump operation
π	Constant
q_p	Dimensionless discharge of the pump
n_p	Dimensionless rotated speed of the pump
H	Head of the pump (m)
H_R	Rated head of the pump (m)

N	Rotate speed of the pump
N_R	Rated speed of the pump
Q	Discharge through the pump (m^3/s)
Q_R	Rated discharge of the pump (m^3/s)
T	Torque of the pump (Nm)
T_R	Rated torque of the pump (Nm)
tdh	Head difference of pump's two sides (m)
W	The weight of rotating parts plus entrained liquid (kg)
R_g	The radius of gyration of the rotating mass (m)
S_w	Cross area of normal surge tank (m^2)
h_{NST}	Head in normal surge tank (m)
ζ_{NST}	The local energy loss coefficient of normal surge tank connector
q_{NST}	The discharge through the normal surge tank connector (m^3/s)
S_{CN}	Cross area of the normal surge tank connector (m^2)
h_{k-k}	Head at the connector in pipe (m)
h_{IST}	Head in IST (m)
ζ_{IST}	The local energy loss coefficient of IST connector
q_{IST}	The discharge through the IST connector (m^3/s)
S_{CI}	Cross area of the IST damper (m^2)
h_{max}	Maximum head along pipeline (m)
h_{min}	Minimum head along pipeline (m)
A_h	The extreme water hammer amplitude (m)

Acronyms

MOC	Method of Characteristics
IST	Intelligent Self-controlled Surge Tank

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