AQUA
Water Infrastructure, Ecosystems and Society



 AQUA — Water Infrastructure, Ecosystems and Society Vol 70 No 8, 1217 doi: 10.2166/aqua.2021.059

# A combined water hammer protective method for optimizing the volume of the air vessel in water supply systems

Jiawen Lyu, Jian Zhang*, Xingtao Wang and Tingyu Xu
Hohai University, Nanjing, China
*Corresponding author. E-mail: jzhang@hhu.edu.cn

JZ, 0000-0001-7557-3602

## ABSTRACT

An air vessel, as an effective and reliable water hammer protective device, is widely used in long-distance water supply systems. However, the volume of the air vessel must be extra-large to guarantee security of the system, especially in a system with a high head and large flow. In this paper, to reduce the volume of the air vessel, a novel protective method combining an air vessel and over pressure relief valve was proposed and verified using a numerical simulation based on a practical project. In addition, the protection performance under the combined protective method was compared with the traditional method. The results show that the combined protective method can significantly reduce the volume of air vessel and exhibit a better protection performance. Furthermore, after analysis and optimization of the rule of opening and closing over the pressure relief valve, the valve should be opened in a short time to produce fast discharge so as to eliminate the large pressure rise rapidly. The duration of opening the over pressure relief valve has little effect on the maximum pressure. The closing time of the over pressure valve should be slow, as much as possible, to avoid producing large pressure wave.

**Key words:** air vessel, over pressure relief valve, water hammer, water supply system

## HIGHLIGHTS

- An optimized protective method by combining air vessel and over pressure relief valve is proposed to reduce the volume of the air vessel.
- The sensitive analysis of operating valve and total cost anaysis are compared, which can make this combined method more effective and reliable.
- The method was verified by comparing with the traditional protective method, and the results can provide a reference for similar situations.

## INTRODUCTION

Most long-distance water supply systems transfer water from low to high elevation via a pump station. When a pump trip accident happens, the high head water supply system will cause large pressure and seriously damage the pipeline. Therefore, many researchers focused on the operation safety of the pump station and the pipeline protection of water hammer (He *et al.* 2017; Hur *et al.* 2017; Bettaieb & Taebura 2020; Salimi *et al.* 2020). Water supply projects are usually protected by various devices such as air vessels, air valves, one-way surge tank, surge chamber, etc. An air vessel is widely used in many water supply projects because of its simple installation and low environmental requirements.

Since the air vessel shows good ability in controlling pressure surge from water hammer accidents, many investigators study the air vessel to eliminate water hammer effectively. The volume of the air vessel is the key parameter for control of water hammer in water supply systems. Wang *et al.* (2013) also indicated that the best installation location of the air vessel is immediately after the pump. To effectively eliminate water hammer, the volume of the air vessel is required to be generally very large in design, which results in high investment cost (Yazdi *et al.* 2019). Therefore, many researchers focus on optimizing the method of sizing a proper shape of air vessel. The initial gas volume, total volume and cross section of the air vessel are the main parameters when sizing an air vessel. Sun *et al.* (2016) proposed the SQP method for an optimal size air vessel in a long-distance water supply pumping system. Considering both the security and cost of the system design, the impulse response method with the GA algorithm is studied to design the surge tank for water supply systems and after optimizing the location and dimensional parameters of the surge tank, the results showed more improvement compared to the other approaches (Kim 2010). The formula for determining the size of the air vessel is implied in the long-distance water supply system (Chen *et al.* 2020). It can be seen that the shape of the air vessel is a very important factor for a protective effect. Moreover, the protective effects between vertical and horizontal air vessels are compared (He *et al.* 2017). Additionally, a spherical air vessel is designed and the water hammer protective performance is analyzed (Shi *et al.* 2019).

As well as optimizing the size of the air vessel, various combined protective methods are studied to improve the effect of water hammer protection and decrease the cost at the same time. The single and combined application of a flywheel, air chamber and in-line check valves are applied and checked for their effectiveness in a protective system. The results showed that single use of those protective devices is found to be insufficient and expensive, whereas the combined protective method of in-line check valves and air chamber can reduce the volume of the chamber and cost of the protective measures remarkably (Vahid *et al.* 2017). In relation to the long-distance water supply pipelines, a combined protection method of air vessel and downstream air valve is proposed to decrease the investment of the air vessel. The two air vessels are installed behind the check valve at the upstream, and at the end of the downstream respectively. (Miao *et al.* 2017). Moreover, the water hammer protective effect of air vessel with a two-way surge tank are compared and analyzed (Balacco & Laucelli 2019). A combination of air chamber and air-inlet valves is studied to optimize transient protection. This combined method obtained the best protective scheme where transient pressures are maintained in a safe standard while minimizing the protection cost (Moghaddas *et al.* 2017). The results of combined protective methods all showed better protective performance and cost-effectiveness.

Furthermore, the location of setting air vessels in long-distance water supply systems is also an aspect to study. The relation between location and pressure amplitude of the air vessel was studied. Based on practical engineering, the only set air vessel in the middle of the pipeline and set air vessels from the middle of the pipeline in series are compared. The results verified that the middle-reach location exhibited better protection performance compared with the traditional location (Wang *et al.* 2019). Based on the analysis of parameters of two surge protective devices, hydropneumatics tank and surge tank, the locations used for installation of protective devices along the pipeline can be optimized. The results show that incorrect designing of the tank and its position showed a marked effect on water hammer behavior of the system (Mubashir *et al.* 2018).

According to all the studies mentioned above, it is indicated that combined device methods are worth investigating to achieve better protective performance in water hammer protection. However, there are still some weak points in combined protective methods. (i) When using a combined devices method to control water hammer, changing the location or parameters of each device influences the location and parameters of other devices. Especially, emergency and improper closure of the valve results in a positive pressure wave upstream and a negative pressure wave downstream of the valve location, which will again negatively affect the protective performance of the complex pipeline system (Pothof & Karney 2011). Therefore, how to make each protective device work in coordination is an important study. (ii) Less researchers consider total cost as the main reason for selecting protective methods. Some research works only discuss the equipment cost but ignore the cost of maintenance, transportation and equipment lifetime.

In this paper, to overcome the weak points mentioned above, an optimized new protective method by combining an air vessel and over pressure relief valve is proposed to achieve better performance in water hammer protection. Based on a practical water supply project, a numerical model was established and the process of hydraulic transient was simulated in a pump trip situation. Moreover, in order to operate all devices properly, and make the over pressure relief valve coordinate with the air vessel effectively, the sensitive analysis of opening and closing law is compared, which can make this combined method more effective and reliable. The cost of this combined protective method is analyzed and compared. The effect of the new combined method was verified by comparison with the simple air vessel protective method, and the results can provide a reference for similar situations in water supply projects.

## COMBINED PROTECTIVE METHOD

### Mathematical model

A numerical model based on the method of characteristics (MOC) is developed and according to one-dimensional transient flow in the pipeline, the momentum and continuity equations are shown in Equations (1) and (2) respectively:

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial H}{\partial x} + f\frac{V|V|}{2D} = 0 \tag{1}$$

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

where $x$ is pipe distance, $t$ is time, $H$ is pressure head, $V$ is longitudinal mean velocity, $g$ is gravitational acceleration, $f$ is friction factor and $a$ is wave speed.

These equations can be solved by MOC. In mathematics, MOC is a tool for solving partial differential equations. The method is to transfer a partial differential equation to an ordinary differential equation so that the solution can be achieved from some initial data. Therefore, MOC is widely used for the solution of one-dimensional, hydraulic transient problems (Deng & Jiang 2015).

The hydraulic transient process of the pump trip is the main reason for the change of water hammer pressure. The pump boundary condition is a nonlinear equation group composed of a pump head balance equation and a unit inertia equation, which are completely explained by Wylie & Streeter (1993) and equations of air vessel and combined over pressure relief valve are described below. It is worth noting that the analysis of air vessel model is simulated based on the following assumptions: the air enclosed at the top of the vessel follows the poly tropic relation for perfect gas, then the gas equation of state, flow continuous equation, and volumetric equation can be written as

$$PV^k = C \tag{3}$$

where $P$ is the absolute pressure of gas, PA; $V$ is the volume of gas, $m^3$; $K$ is the poly tropic index of state equation; and $C$ is a constant:

$$Q_1 = Q_3 + Q_2 \tag{4}$$

where $Q_1$ is the pipe flow into the air vessel node, $m^3/s$; $Q_2$ is the pipe flow out of the air vessel node, $m^3/s$; $Q_3$ is the flow into or out of the air vessel, $m^3/s$:

$$V_P = V - \frac{Q_{P3} + Q_3}{2}\,\Delta t \tag{5}$$

where $\Delta t$ is time step; $V$ is the air volume in the vessel at initial time $\Delta t$; $V_P$ is the air volume in the air vessel; $Q_3$ and $Q_{P3}$ are the inflow of the air vessel at the beginning and end of $\Delta t$ respectively.

The over pressure relief valve, as a kind of water hammer protection device, is generally set in the initial section of the outlet pipe behind the pump, because the elevation of this section of the pipeline is low, and the initial internal water pressure is large under conditions of constant flow. When the pump trip accident occurs, the valve behind the pump closes quickly, and the positive pressure wave reflected from the downstream pool produces large water hammer pressure behind the pump, which leads to the maximum positive pressure exceeding the design pressure standard of the pipeline. The function of the over pressure relief valve is that when the water pressure in the pipeline exceeds the set maximum allowable value, the valve will automatically open to discharge water and reduce the positive pressure quickly behind the valve. According to the principle of continuity, it can be concluded that:

$$Q_{P1} - Q_{P2} - Q_{P3} = 0 \tag{6}$$

$$H_{P1} = H_{P2} = H_{P3} = H_P \tag{7}$$

where $Q_{P1}$, $Q_{P2}$ and $Q_{P3}$ are the over pressure relief valve flows of upstream, downstream and before the valve respectively, $m^3/s$. $H_{P1}$, $H_{P2}$ and $H_{P3}$ are the pressure heads of upstream, downstream and before the over pressure relief valve, $m$.

When $H_P$ does not reach the working pressure head $H_{max}$ of the over pressure relief valve, then $Q_{P3} = 0$; when $H_P$ exceeds the working pressure head of the over pressure relief valve $H_{max}$, then the valve is opened for discharge, and the valve flow is:

$$Q_{P3} = C_d A_G \sqrt{2g(H_P - H_O)} \tag{8}$$

where $C_d$ is the flow coefficient; $A_G$ is discharge cross sectional area of the over pressure relief valve after opening, $m^2$; $H_O$ is external pressure head behind over pressure relief valve (general external atmospheric environment), $m$.

In this new combined protective method, it can be seen from Figure 1 that the over pressure relief valve is set in the form of a branch pipe behind the pump. The branch pipe set in the project in this paper is short, and the length is about 1 m, so the function of the branch pipe is not considered in the mathematical model. In the condition of constant flow, the over pressure relief valve is closed, and the flow in the branch pipe is 0, so the pressure in front of the valve is equal to the internal water pressure at the bifurcation point of the main pipe. When the pump trip occurs, the internal water pressure of the high-pressure pipe section behind the pump will increase largely due to water hammer, while the pressure before the over pressure relief valve will increase at the same time. When the positive pressure value is higher than the maximum allowable pressure of the over pressure relief valve, the valve will open. In order to be convenient for daily maintenance and management, the air vessel is usually set behind the pump. The valve diameter and the rule of opening and closing are discussed below based on specific engineering conditions.

## Feasibility analysis

In a long-distance water supply system, when pump trip occurs, the pressure behind the pump drops quickly, and the water hammer propagates to the pipeline, which can damage the pipeline seriously. In a traditional protective method, the air vessel is installed behind the pump station, generally with the compressed air at the top of the air vessel and water at the bottom of the air vessel. When pump trip occurs, the pressure in the pipeline drops rapidly and the water flows out of the air vessel due to the compressed air at the top. When the positive pressure wave reverses, the water flows back into the air vessel to eliminate the large positive pressure in the pipeline. However, due to the water supply system with large flow and large head, the volume of the air vessel is already large enough for sufficient water flowing out to the pipe, which can eliminate the negative pressure, but it still needs to be increased for water flowing back to suppress the positive pressure. Therefore, in this case, the air vessel can not perform a good positive pressure protective effect, unless the volume of the air vessel to be designed is extra large, which results in high investment.

According to the analysis above, if the over large positive pressure caused by reversed flow can be protected by other devices, the volume of the air vessel can be reduced accordingly. Inspired by this, the optimized protective method, combining an air vessel and over pressure relief valve, is proposed. In this method, the volume of the air vessel only needs to meet the

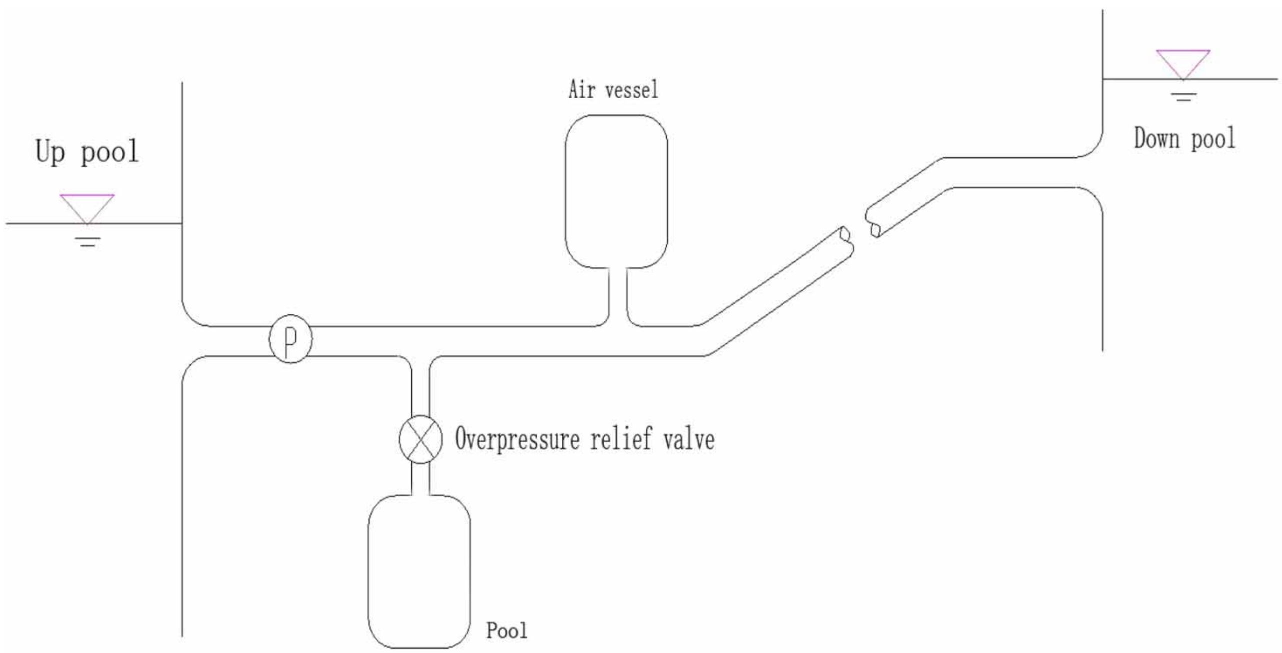


**Figure 1** | Layout of water supply system with AORV combined method.

negative pressure protective requirement, while to the positive pressure protection, the over pressure valve takes a main effect to eliminate the pressure.

## CASE STUDY

The center line, piezometric line and a schematic diagram of the water supply project are shown in Figure 2, and the parameters of the pump station system are listed in Table 1 below.

From the pipe center line in Figure 2, it is clear that the pipeline is flat in the front and steep in the back section. The water level between the up and down pool is large. Based on the method of characteristics, the simulation of transient in the system was established. In this case, when the pump trip happens, it requires that no negative pressure appears in the whole pipeline, and the maximum pressure should not exceed 1.5 times of the internal water pressure under constant flow conditions. In this paper, the pump trip accident is simulated, and various protective methods are optimized based on the practical water supply project conditions, in order to improve the effect of the water hammer protection.

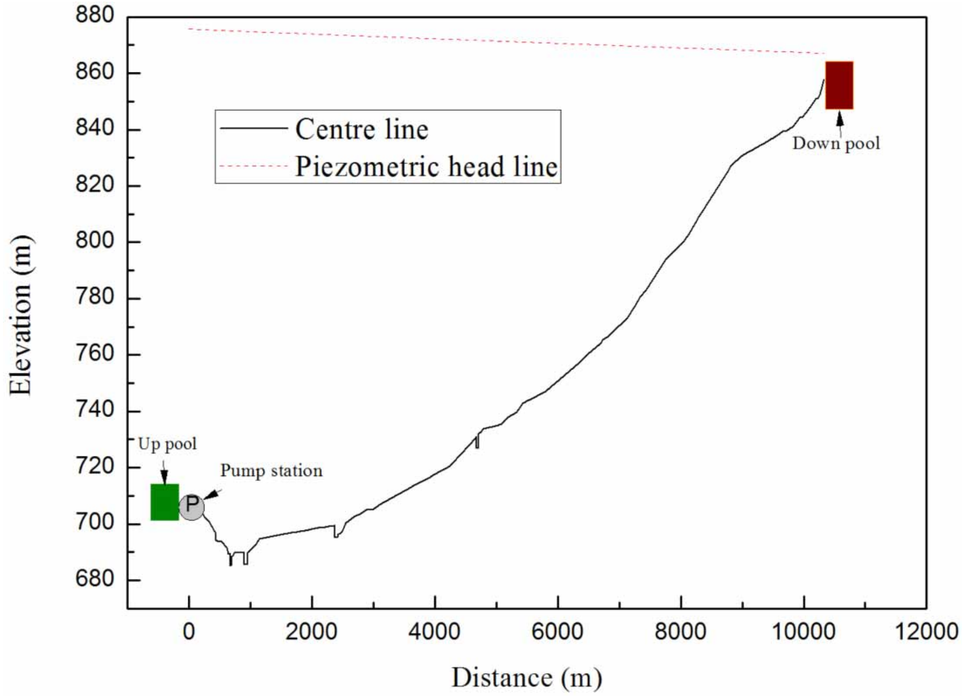


**Figure 2** | Pipe center line, piezometric head line and schematic diagram of the water supply project.

**Table 1** | Parameters of the pipeline system

| | | | |
|---|---|---|---|
| Up pool water level (m) | 711.00 | Roughness coefficient | 0.011 |
| Down pool water level (m) | 867.00 | Quantity of pumps | 3 |
| Pipe diameter (mm) | 1,200 | Rated speed (r/min) | 1,480 |
| Pipe length (km) | 10.40 | Motor power (kW) | 1,250 |
| Flow discharge ($m^3/s$) | 1.30 | Pump head (m) | 165.57 |
| Wave speed (m/s) | 1,000 | Moment of inertia ($kg.m^2$) | 448.18 |

### System without any protective method

From the simulation of a pump trip process, a pressure drop of about 135 m is generated immediately behind the pump, and it is transmitted to the downstream. Both maximum and minimum pressure curves along the pipeline are shown in Figure 3 below.

It can be seen that the middle and lower sections of the pipeline with high elevation generate large negative pressure, and the maximum negative pressure reaches about –67.3 m. The initial water pressure in this section of the pipeline is small and the ability of the downstream pool to reflect the depressurization wave is poor. In Figure 3, most of the minimum pressures are smaller than –10 m (vaporization pressure). It should be noted that the pressure below –10 m is indicated to severity of the pressure drop. The total length of the water pipeline is 10.40 km, and the average wave speed of water hammer is 1,000 m/s. Therefore, after the pump trip happens, the pressure rise wave reflects from the downstream pool to the outlet of the pump in about 21 s (a phase time), which makes the pressure behind the pump begin to increase.

The maximum pressure of the whole pipeline exceeds the positive pressure control standard, and the maximum pressure appears in the inverted siphon section behind the pump, see Figure 3. According to the above analysis, if there is no water hammer protective method, serious negative pressures will appear along the pipeline when the pump trip occurs in the water supply project. Moreover, if the valve behind the pump is closed within a phase time, excessive positive pressure will appear in the low-lying pipe section behind the pump, especially in the pump station with high head. In order to meet the requirements of both positive and negative pressure protection, the water supply system must take water hammer protective measures to ensure the safe operation of this water supply system.

### System with air vessel protective method only

The project simulated in this paper is a long-distance water supply system with high head and large flow. After the pump trip accident happens, the negative pressure in the pipeline is relatively serious. Therefore, the air vessel as a normal protective device is applied to protect water hammer. Based on the analysis of the transient process, two different shapes of air vessel protective methods are designed, which are A and B respectively. The shape parameters of air vessel A and B are shown in Table 2.

After the pump trip happens, based on the method of characteristics, the numerical simulation of the hydraulic transient is established, and the enveloping curves of the maximum and minimum pressure are shown in Figure 4.

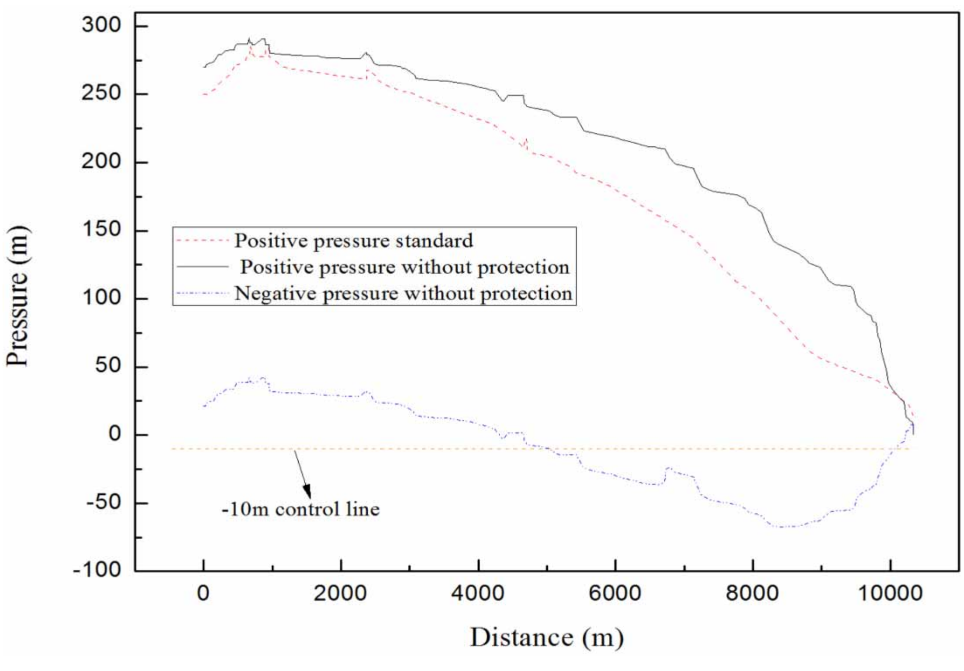


**Figure 3** | Maximum and minimum pressure enveloping curves without any protection.

**Table 2** | Parameters of the air vessel

| Air vessel | Water depth (m) | Air height (m) | Cross-sectional area ($m^2$) | Orifice diameter (m) | Elevation (m) | Volume ($m^3$) |
|---|---|---|---|---|---|---|
| A | 2.5 | 3.0 | 8.04 | 0.8 | 712.50 | 44.22 |
| B | 1.5 | 3.0 | 26.40 | 0.8 | 713.50 | 118.80 |

In method A, the minimum pressure of the pipeline is 2.68 m, which is located at 9,071.52 m. The whole line meets the requirement of negative pressure protection. However, it can be seen from Figure 4 that the maximum pressure of the pipeline in method A exceeds the positive pressure standard of the pipeline. Compared with method A, the minimum pressure increases from 2.68 to 8.97 m in method B. The positive pressure of the pipeline after the pump is also improved, and the maximum pressure decreases from 280.61 to 233.02 m, which is less than the positive pressure standard of the pipeline. Moreover, the volume of air vessel in method B is 74.58 $m^3$ larger than that in method A. Therefore, for the only air vessel protective method, when the negative pressure protective requirement has been achieved, the volume of air vessel still needs to be increased to meet the positive pressure protective requirement. It is concluded that the volume of the air vessel needs to be greatly increased for meeting both negative and positive pressure protective requirements.

### System with combined protective method

In order to effectively protect positive pressure and optimize the volume of the air vessel, the water hammer protective method C is designed, which is combined with the air vessel and over pressure relief valve. The shape parameters of the air vessel are consistent with that in method A. The over pressure relief valve is set in the low-lying pipe section behind the pump where high positive pressure is produced. The purpose of this method is to use the air vessel to reflect the pressure drop wave produced by opening the valve, so as to prevent the high-lying pipe section from generating negative pressure. The setting parameters of over pressure relief valve are shown in Table 3.

Under the protection of method C, the distribution of maximum pressure curve along the pipeline is shown in Figure 5.

It can be seen from Figure 5 that the volume of the air vessel is the same as that in method A. In contrast, the positive pressures are all smaller than the positive pressure standard after installing an over pressure relief valve behind the pump

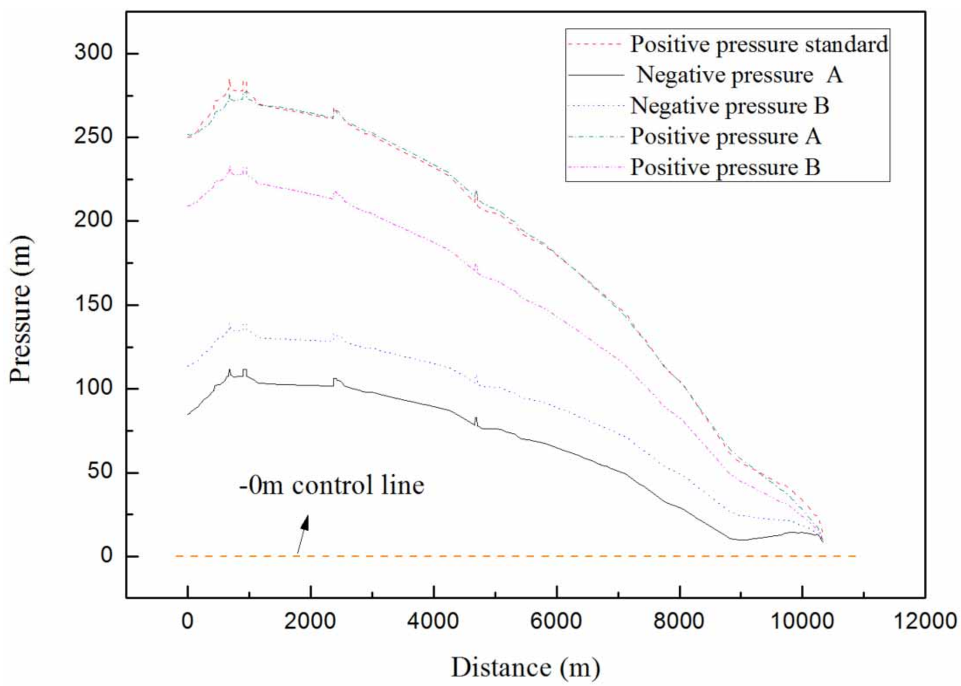


**Figure 4** | Enveloping curves of pressures in methods A and B.

**Table 3** | Parameters of the setting over pressure relief valve

| Location | Diameter (mm) | Starting pressure (m) | Opening law | Duration (s) | Closing law |
|---|---|---|---|---|---|
| 0 + 000 | 100 | 180 | Linear opening in 0.5 s | 60 | Linear closing in 120 s |

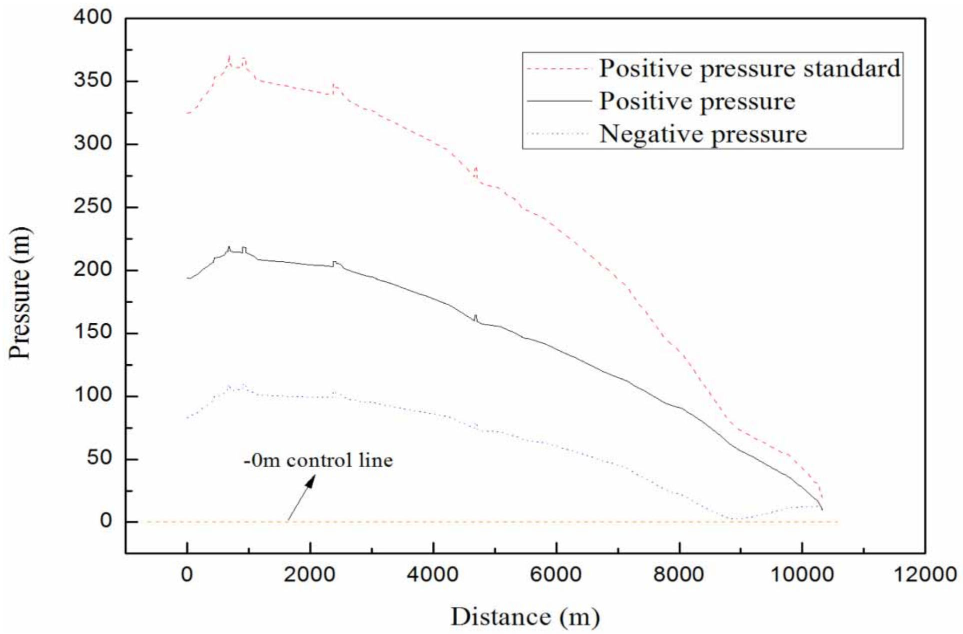


**Figure 5** | The maximum and minimum enveloping curves of the AORV method.

and the negative pressures are similar to those in method A. It is said that installing an over pressure relief valve can effectively protect positive pressure, so as to reduce the volume of the air vessel.

## Sensitive analysis of the opening and closing law of the over pressure relief valve

In order to set the valve diameter and opening and closing law of the over pressure relief valve reasonably, this paper analyzes the sensitivity of the opening time, duration time and closing time of the over pressure relief valve. The proper opening and closing law of the over pressure relief valve can ensure that the depressurization wave generated by opening the valve will not penetrate the air vessel and affect the negative pressure protective effect.

Taking the above water supply system as the research object, under the conditions of certain shape parameters of the air vessel, the influence of opening law, duration time and closing law of the over pressure relief valve on the protection of positive pressure is analyzed respectively. Specific comparison schemes are shown in Table 4.

## The opening law

The opening times of the first three schemes in Table 4 are different, and the shape parameters of the air vessel, duration time and closing laws of the over pressure relief valve are the same.

According to the bottom pressure of the air vessel in Figure 6(a), it can be seen that the faster opening rate of the valve results in the larger discharge. The positive pressure wave reversed back can be relieved quickly due to the fast opening rate of the valve. That is why the fastest opening rate of the valve achieves the most effective positive pressure protection. The maximum pressure enveloping curves of these three schemes are shown in Figure 6(b). The slower opening rate of the over pressure relief valve will result in the worse positive pressure protective effect in the high pressure pipe section after the pump. Therefore, in a practical water supply project, it is generally required that the over pressure relief valve is opened from 0 to full opening in a short time.

**Table 4** | Opening and closing laws of over pressure relief valve in different protective schemes

| Scheme | Dv (mm) | Hv (m) | Opening law (s) | Duration time (s) | Closing law (s) |
|---|---|---|---|---|---|
| 1 | 100 | 180 | 0.5 | 60 | 120 |
| 2 | 100 | 180 | 5 | 60 | 120 |
| 3 | 100 | 180 | 10 | 60 | 120 |
| 4 | 100 | 180 | 0.5 | 60 | 120 |
| 5 | 100 | 180 | 0.5 | 120 | 120 |
| 6 | 100 | 180 | 0.5 | 180 | 120 |
| 7 | 100 | 180 | 0.5 | 60 | 60 |
| 8 | 100 | 180 | 0.5 | 60 | 120 |
| 9 | 100 | 180 | 0.5 | 60 | 180 |

Dv is the diameter of the over pressure relief valve; Hv is the starting pressure head.

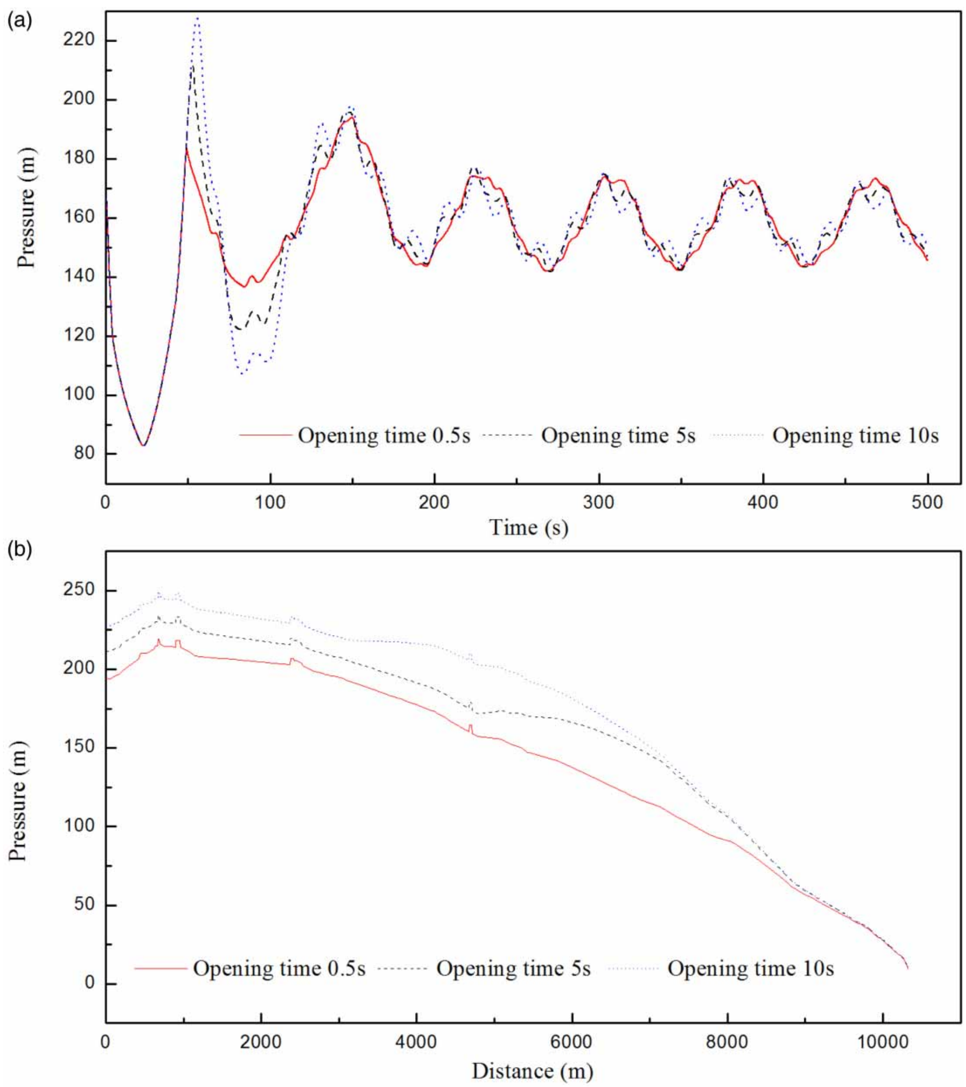


**Figure 6** | (a) Enveloping curves of the maximum pressures along the pipeline in different opening laws; (b) variations of bottom pressure of the air vessel in different opening laws.

## Duration time

The duration times of the middle three schemes in Table 4 are different, and the shape parameters of the air vessel, opening and closing laws of the over pressure relief valve are the same.

Due to the same opening and closing time of the valve, the curves of the bottom pressure of the air vessel are similar in Figure 7(a). The positive pressure waves caused by the closing valve are generated differently due to the duration times of 60, 120 and 180 s. It shows that the pressure curves at the bottom of the air vessel are delayed back forward for a responding time. Therefore, on the premise that the closing rate of the over pressure relief valve remains unchanged, extending the duration of opening the over pressure relief valve has little effect on the positive pressure protection. The maximum pressure enveloping curves of these three schemes are shown in Figure 7(b). It is clear that extending the duration of opening the over pressure relief valve has little effect on the positive pressure suppression along the water supply system because the surge in the air vessel tends to be stable after opening the over pressure relief valve for a certain period of time.

## Closing time

The closing laws of the last three schemes in Table 4 are different, and the shape parameters of the air vessel, duration time and opening laws of the over pressure relief valve are the same.

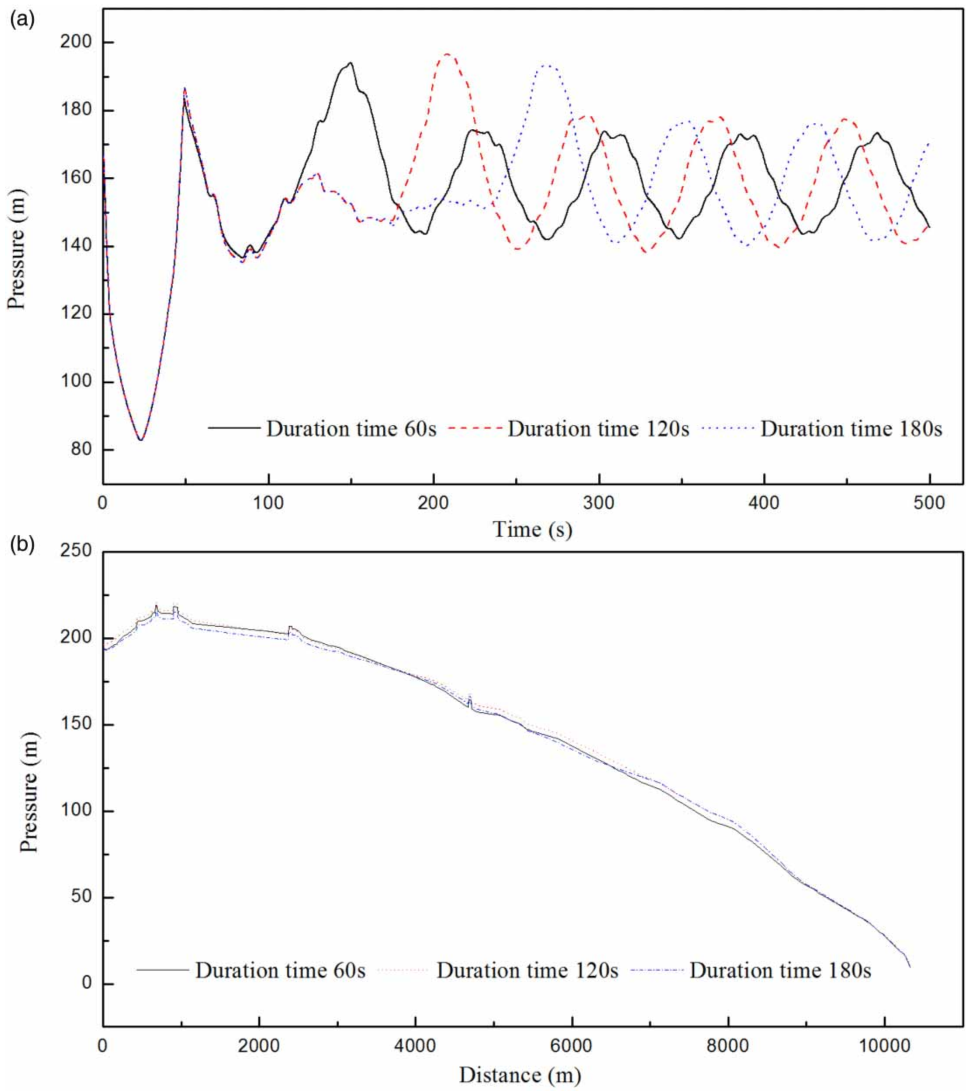


**Figure 7** | (a) Enveloping curves of the maximum pressures along the pipeline under different duration times; (b) variations of bottom pressure of the air vessel under different duration times.

After the first maximum positive pressure wave was eliminated by opening the valve rapidly, the system tends to be stable, see Figure 8(a). The other positive pressure wave will be generated by closing the valve fully and rapidly. That is to say, it is beneficial to reduce the closing rate of the over pressure relief valve properly for water hammer protection. The maximum pressure enveloping curves of these three schemes are shown in Figure 8(b). With the slower rate of closing the over pressure relief valve, the positive pressure along the pipeline of the water supply system decreases more obviously. Because the air vessel used in this project is small, the valve closing rate has a great influence on the maximum pressure of the pipeline.

## DISCUSSION AND ANALYSIS

In this paper, to optimize the volume of the air vessel and improve the water hammer protective effect, the novel AORV combined protective method was proposed. Subsequently, the AORV method was verified using a numerical simulation based on a practical water supply project. Moreover, the results are compared with the traditional simple air vessel protective method. The selection of the water hammer protective method is discussed in this part. The maximum and minimum pressure enveloping curves with simple air vessel method B and combined AORV method C are shown in Figure 9.

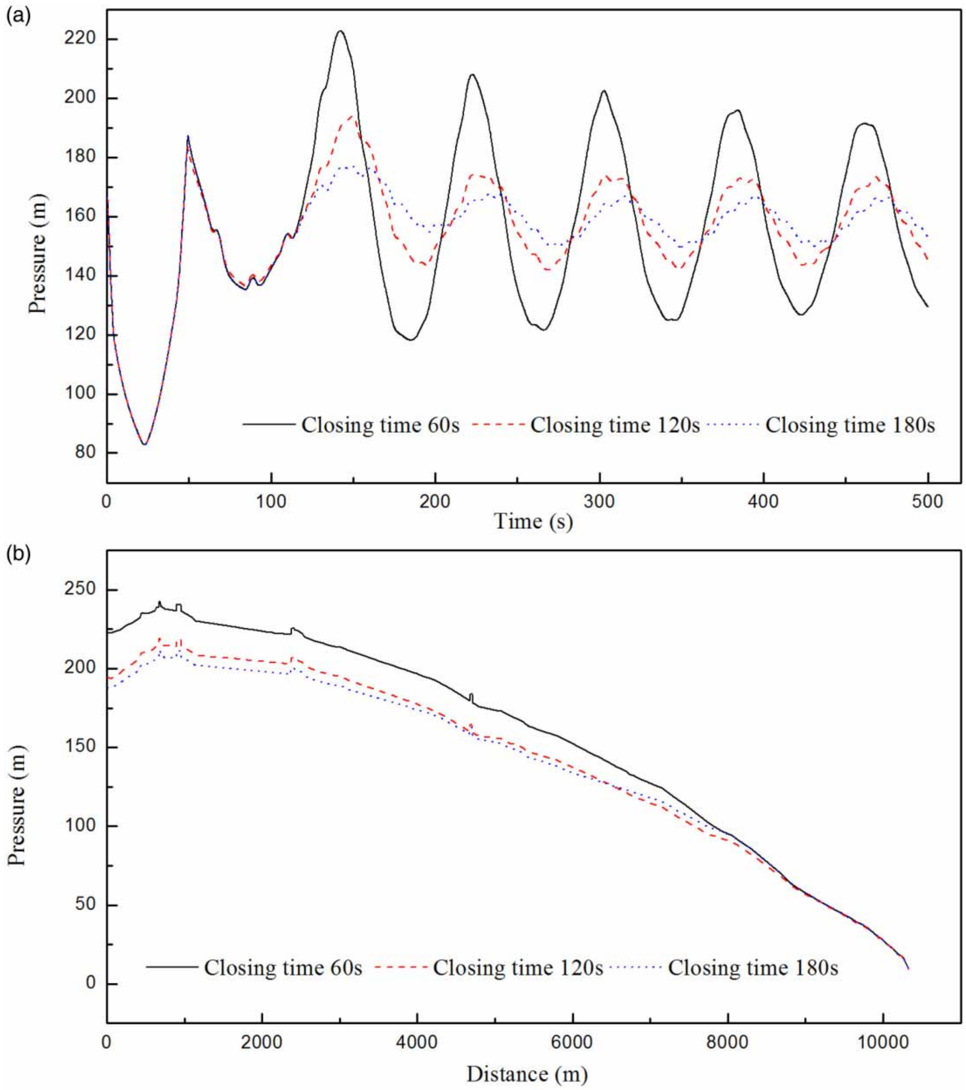


**Figure 8** | (a) Enveloping curves of the maximum pressures along the pipeline in different closing laws; (b) variations of bottom pressure of the air vessel in different closing laws.

First, from Figure 9, the AORV combined protective method C has a better positive pressure protective effect than that in simple air vessel protective method B in front of the 7,344.52 m location, and worse positive pressure protective effect at the location from 7,344.52 to 10,400 m. However, the positive pressure protective effect of method C in the high-pressure pipe section behind the pump is obviously much better, and the safety margin is large. The maximum water pressure of the whole pipeline is 219.24 m. Compared with method B with simple air vessel protection, the safety margin is increased by 6.28%.

Second, under the same protective requirements, the total air vessel volume between the traditional simple air vessel and AORV combined methods are compared. The parameters of the air vessel are shown in Table 1. The volume of the air vessel in the traditional method should be 118.80 $m^3$ large to meet both negative and positive pressures protective requirements. However, in the AORV combined method, the volume of the air vessel only needs to be 44.22 $m^3$. The results indicate that the volume of the air vessel in the AORV combined method can be reduced by 62.78%. According to the water supply system discussed in this paper, the reason for the difference in air vessel volume is that the over pressure relief valve takes main device to suppress the positive pressure, so that the volume of the air vessel only needs to be large for eliminating negative pressure. Therefore, under the same protective requirements, it can be considered that the AORV combined method can effectively reduce the volume of the air vessel compared to the traditional simple air vessel protective method.

Third, total costs include the equipment costs, all construction and civil works and maintenance costs. According to the unit prices calculated from a local company, the details of the cost analyses are presented in Table 5. As mentioned above, using an air vessel alone in large scale water supply systems required larger volume with more costs. In other combined methods, although the cost of air vessel is reduced, other devices incur more costs on maintenance. For instance, in some combined protective methods with a one-way tower, air-inlet valve and air vessel the regular maintenance will cost

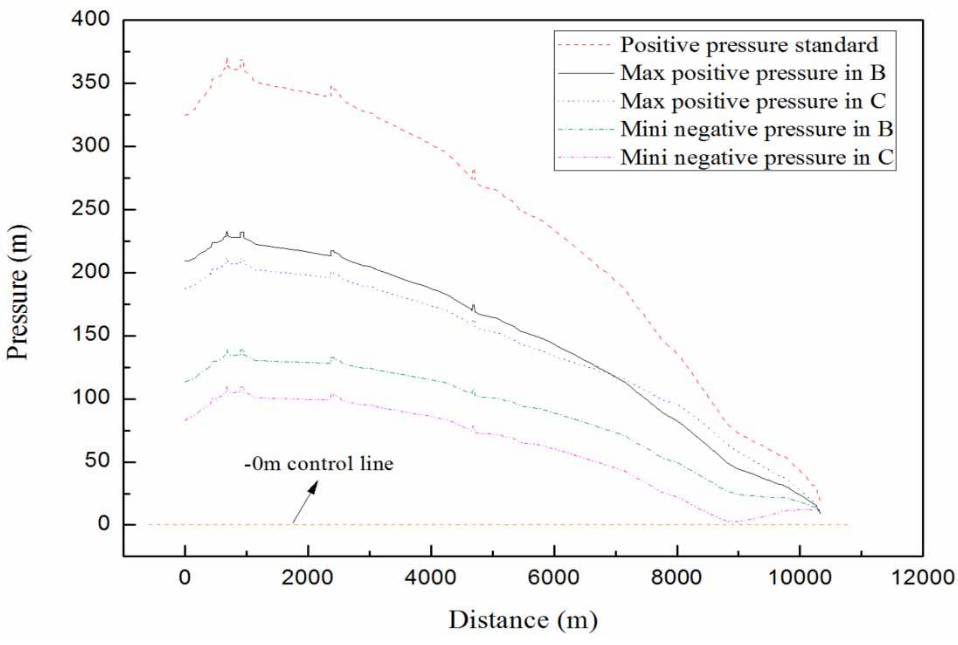


**Figure 9** | The maximum and minimum pressure enveloping curves in different protective methods.

**Table 5** | Cost analysis of the protective methods

| Scheme | Main devices | Equipment cost (×$10^3$ ¥) | Description | Total cost (×$10^3$ ¥) |
|---|---|---|---|---|
| Single device | Air vessel | 238 | Installation, maintenance, transportation | 328 |
| AORV combined device | Air vessel<br>Over pressure relief valve | 95 | Installation, maintenance, transportation | 165 |

more since these protective devices are installed in different locations. However, in the AORV combined method, properly setting the location and parameters of over pressure relief valve with relatively low cost can reduce the volume of the air vessel and protective costs. More importantly, the over pressure valve and air vessel are both installed after the pump as it is convenient to maintain and manage. In order to ensure the valve can be closed and opened accurately after pump trip happens, it needs to be checked regularly. Regular maintenance of the system can extend the service life of the equipment. Above all, considering the total cost of the protective system, the AORV combined devices method is more economical.

## CONCLUSIONS

In this paper the new optimized protective method, which combined an air vessel and over pressure relief valve, is proposed to reduce the volume of the air vessel. The opening and closing law of over pressure relief valve is analyzed based on the practical water supply project. The main conclusions are discussed below.

According to the pipeline, which is flat in the front and steep at the back, the simple air vessel protective method needs to increase the volume of air vessel to achieve both positive and negative pressure protective requirements. In this case, the new optimized combined protective method, AORV, is proposed to reduce the volume of the air vessel. After the volume of the air vessel is large enough to satisfy with the negative pressure protective standard, the over pressure relief valve installed behind the pump can take main device to reduce the overlarge positive pressure effectively.

The opening and closing laws of the over pressure relief valve have influence on the air vessel protective effect. Proper setting of the valve can ensure that the depressurization wave will not penetrate the air vessel so as to impact the negative pressure protective effect. To achieve reasonable operation of the over pressure relief valve, the sensitive analysis of opening and closing law is studied. The results show that the valve should be opened in a short time to produce a fast discharge in order to eliminate the large pressure rise as soon as possible. Additionally, the duration of opening the over pressure relief valve has little effect on the maximum pressure along the water supply system, since the surge in the air vessel tends to be stable after opening of the over pressure relief valve for a certain period of time. However, the duration time after opening should not be too short, in order to fully relieve the pressure rise caused by water hammer. As for the closing time, it is beneficial to slow the closing rate of the over pressure relief valve properly for water hammer protection. If the valve closes too fast, the positive pressure wave will generate largely to effect the bottom pressure of the air vessel. Therefore, the closing time of the valve should be slow.

Compared with the simple air vessel protective method, the combined AORV method has a more obvious effect on positive pressure water hammer protection, which improves the safety margin of the pressure, optimizes the shape of the air vessel, and greatly reduces the investment cost. By analyzing different opening and closing laws of the over pressure relief valve, it is clear that the efficiency of water hammer protection can be obviously improved by proper opening and closing law of the valve based on sensitive analysis. In this optimized AORV combined method, the total cost is minimized by nearly 49% and system pressures are controlled within defined standards. The results of this optimized method are thought to provide guidance for designing and operating water supply engineering. The experimental verification of the protective performance with the AORV combined method could be a future research objective.

## ACKNOWLEDGEMENTS

This study was supported by the National Natural Science Foundation of China (Grant No. 51879087), the National Key R&D Program of China (Grant No. 2016YFC0401810), and the Culturing Funds for the fifth '333 Project' of Jiangsu Province (Grant No. BRA2018061).

## DATA AVAILABILITY STATEMENT

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

## REFERENCES

Balacco, G. & Laucelli, D. 2019 Improved air valve design using evolutionary polynomial regression. *Water Supply* **19** (7), 2036–2043.

Bettaieb, N. & Taebura, E. H. 2020 Assessment of failure modes caused by water hammer and investigation of convenient control measures. *Journal of Pipeline Systems Engineering and Practice* **11** (2), 1–9.

Chen, X. Y., Zhang, J., Li, N., Yu, X. D., Chen, S. & Shi, L. 2020 Formula for determining the size of the air tank in the long-distance water supply system. *AQUA-Water Infrastructure Ecosystems and Society* **70** (1), 30–40.

Deng, L. A. & Jiang, J. 2015 Research on protective properties of air vessel for pump-stopping water hammer protection of long distance pipelines. *Engineering Journal of Wuhan University* **48** (3), 402–406.

He, C., Zhang, J., Zheng, Y., Wang, Y. K. & He, D. Y. 2017 Protective properties of horizontal air vessel for water hammer. *Journal of Drainage and Irrigation Machinery Engineering* **35** (2), 138–143.

Hur, J. S., Kim, S. H. & Kim, H. J. 2017 Water hammer analysis that uses the impulse response method for a reservoir-pump pipeline system. *Journal of Mechanical Science and Technology* **31** (10), 4833–4840.

Kim, S. H. 2010 Design of surge tank for water supply systems using the impulse response method with the GA algorithm. *Journal of Mechanical Science and Technology* **24** (2), 629–636.

Moghaddas, S. J. M., Hossein, M. V. S. & Ali, H. 2017 Transient protection optimization of pipelines using air-chamber and air-inlet valves. *Journal of Civil Engineering* **21** (5), 1991–1997.

Miao, D., Zhang, J., Chen, S. & Yu, X. D. 2017 Water hammer suppression for long distance water supply systems by combining the air vessel and valve. *Journal of Water Supply: Research and Technology* **66** (5), 319–326.

Mubashir, A. S., Hassan, A., Muhammad, B. J. & Umair, S. 2018 Numerical analysis and parametric optimization of surge protection devices in a long up-pumping water pipeline. *Journal of Mechanical and Technology* **33** (1), 367–376.

Pothof, I. W. M. & Karney, B. W. 2011 Guidelines for transient analysis in water transmission and distribution systems. *Water Loss Conference*. doi:10.5772/53944.

Salimi, A., Karami, H. & Farzin, S. 2020 Design of water supply system from rivers using artificial intelligence to model water hammer. *ISH Journal of Hydraulic Engineering* **26** (2), 153–162.

Shi, L., Zhang, J., Yu, X. D. & Chen, S. 2019 Water hammer protective performance of a spherical air vessel caused by a pump trip. *Water Science and Technology: Water Supply* **19** (6), 1862–1869.

Sun, Q., Yue, B. W., Xu, Y. & Jang, T. U. 2016 Optimal sizing of an air vessel in a long-distance water supply pumping system using the SQP method. *Journal of Pipeline Systems Engineering and Practice* **7** (3), 1–6.

Vahid, R., Melinda, C. & Zefer, B. 2017 Performance of pumped discharge line with combined application of protection devices against water hammer. *Journal of Civil Engineering* **21** (4), 1493–1500.

Wang, L., Wang, F. J., Zou, Z. C., Li, X. N. & Zhang, J. C. 2013 Effects of air vessel on water hammer in high-head pumping station. In: *6th Int. Conference on Pumps and Fans with Compressors and Wind Turbines IOP*. Vol. 52, Issue 7, pp. 7–13.

Wang, X. T., Zhang, J., Yu, X., Shi, L., Zhao, W. & Xu, H. 2019 Formula for selecting optimal location of air vessel in long-distance pumping systems. *International Journal of Pressure Vessels and Piping* **172**, 127–133.

Wylie, E. B. & Streeter, V. L. 1993 *Fluid Transients in Systems*. Prentice Hall, New Jersey, USA.

Yazdi, J., Hokmabadi, A. & Jalili Ghazizadeh, M. R. 2019 Optimal size and placement of water hammer protective devices in water conveyance pipelines. *Water Resources Management* **33**, 569–590.

First received 8 May 2021; accepted in revised form 3 September 2021. Available online 22 October 2021