

Water hammer suppression for long distance water supply systems by combining the air vessel and valve

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ABSTRACT

In long distance water supply projects, the air vessel is an effective and reliable protection measure to control water hammer. Although it can effectively eliminate water hammer during the process of hydraulic transient, the volume of the traditional air vessel is large due to the long distance pipeline, resulting in high investment. In this paper, based on the analysis of the transient in long distance water supply pipelines, a protection method, combining the air vessel with the downstream valve, is proposed to reduce the volume of the air vessel, keeping the system pressure within the limit. Furthermore, an innovative arrangement of the air vessel is presented to overcome the risk of the combined protection method. Besides the upstream air vessel, a downstream air vessel is additionally installed to mitigate positive water hammer due to rapid closure of the downstream valve. To verify the effect of the new method, the numerical model was established according to the parameters of a practical water supply project, and hydraulic transient due to pump trip was simulated. Compared with the traditional method, the combined protection method provides effective water hammer protection and greatly reduces the volume of the air vessel.

Key words | air vessel, pump trip, water hammer protection, water supply project

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INTRODUCTION

In long distance water supply projects, the pipeline systems are traditionally protected by mounting surge tanks, air valves, air vessels or other protective devices which keep the pressure in the system from exceeding a specified value after any valve or pump operations (Stephenson 2002; Liu *et al.* 2011; Zhang *et al.* 2011). Among these traditional protective devices, the surge tank is restricted greatly by topography; the poor exhaust performance of air valves leads to high internal pressures; air vessels are more preferable due to their flexibility in topography, good performance in water hammer protection and relatively low investment. Therefore, it is more convenient to use the air vessel as a protective device and its functionality is better (Chaudhry *et al.* 1985; Wang *et al.* 2013).

A scientific and rational size for an air vessel not only provides better protection against water hammer, but also

avoids overlarge volume of the air vessel. Numerous studies on air vessels have been conducted. This research indicates that the initial air volume and installation position of the air vessel had important impacts on water hammer protection (Liang *et al.* 2005; Syed & Wu 2012; Wang *et al.* 2013; Kim *et al.* 2015). Besides, a number of methods to size an air vessel have also been proposed in recent years (Thorley & Lastowiecki 1985; Jung & Karney 2006). Moreover, research on the application of an air vessel combined with other protection methods has also been done, indicating that the combined method can show better protection effect in water hammer protection (Li *et al.* 2013). All the above researchers have made great contributions to the studies and applications of the air vessel.

In this paper, the traditional air vessel protection measure coupled with a proper closure of the downstream

valve is presented to reduce the volume of the air vessel in a water supply system. Besides, in order to avoid over-high pressure due to the closure of the downstream valve, another relatively small air vessel is installed at the downstream end, which can make the new measure more effective and reliable. The numerical model was established according to the parameters of a practical water supply project, and hydraulic transient due to pump trip was simulated. The effect of the new measure was verified by numerical simulation, and the results can provide a reference for similar water supply projects.

COMBINED PROTECTION METHOD

Feasibility and limitation

In a long distance water supply project, as shown in Figure 1, the air vessel is a protection device that is often placed behind the check valve at the upstream end of the pipeline to reflect the water hammer due to pump trip. Usually, the pipeline of the water supply project is long and the water inertia is large. When pump trip happens, the pressure behind the pump will drop quickly, and the water hammer propagates to the pipeline, which may cause pipe break. Therefore, the water in the air vessel will flow into the pipeline to reflect the water hammer, stabilizing the pressure of the system. However, because of the long pipeline and large water inertia, the volume of the air vessel should be large

enough to have sufficient water to flow into the pipeline. Especially in cases where the water level difference between the upstream and downstream reservoirs is small and the pipeline is flat, it will take a long time to stop the flow in the pipe after pump trip, which means the water flows out of the air vessel into the pipe for a long time as well. Therefore, if the pipeline is relatively long, the volume of the air vessel should be accordingly large enough to prevent drainage, which will result in high investment.

It is important to know how to decrease the volume of the air vessel as much as possible and concurrently keep the transient pressure within tolerable limits. According to the above analysis, it can be indicated that the large inertia of the water in the long pipeline causes the large volume of the air vessel. Therefore, if the reduction of the discharge in the pipeline can be accelerated after pump trip, the outflow from the air vessel will be decreased, and the volume of the air vessel can be reduced accordingly. Inspired by this, the artificial pressure difference along the pipeline is introduced by closing the downstream valve after pump trip. With this measure, on one hand, the reduction of the discharge in the pipeline can be accelerated after pump trip and, on the other hand, the pressure drop along the pipeline due to pump trip can be mitigated concurrently by the pressure rise that results from the rapid closure of the downstream valve. Despite the above two advantages of the new method, accurate calculations and reliable closure of the downstream valve are strongly required. Otherwise, adverse effects can be caused, especially in

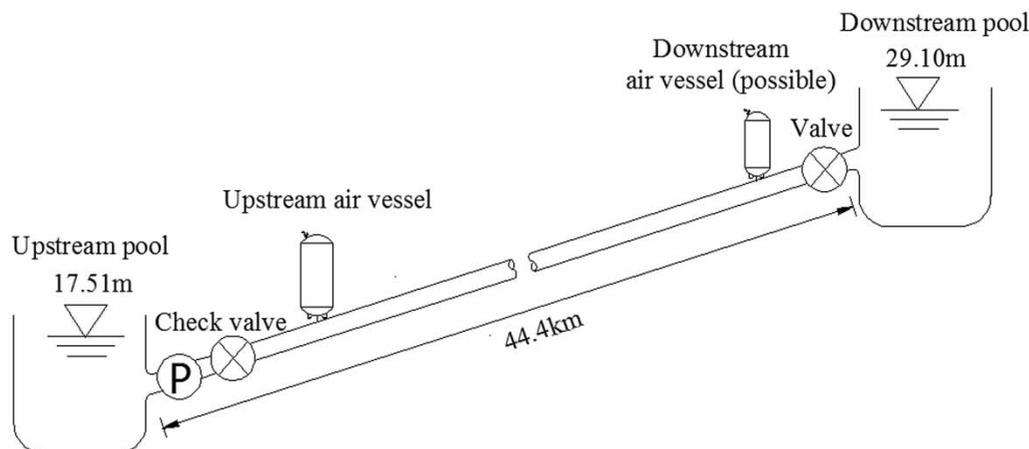


Figure 1 | Layout of the water supply system with air vessel and valve.

relatively long pipelines. If the downstream valve is closed rapidly, huge water hammer is more likely to arise, causing damage to the pipeline system. If it is closed slowly, the pressure difference along the pipe is small and the reduction of the air vessel volume would not be obvious. Therefore, the closure of the downstream valve is a sensitive aspect of the new protection method.

Innovative arrangement of air vessel

Although the combined protection method is theoretically reasonable to reduce the air vessel volume, the prerequisites for the closure of the downstream valve are strictly restricted. In some cases of long pipeline with relatively flat profile, it is rather difficult to select a proper closure rule of the downstream valve. As discussed above, in order to reduce the volume of the air vessel effectively, the downstream valve should be closed quickly to stop the flow in the pipe as quickly as possible. However, it is well known that the downstream valve should be closed slowly to avoid huge water hammer in practice. If this contradiction cannot be resolved, the application of the combined protection method will be greatly restricted. Therefore, it is significant to work out a way to overcome this contradiction for the safe operation of the combined protection method.

Given the above analysis, an innovative arrangement of the air vessel, as shown in Figure 1, is proposed to accommodate the contradiction of the combined protection method. In this innovative arrangement of air vessel, another small air vessel is installed near the downstream valve, which is utilized to reflect the positive water hammer due to the quick closure of the downstream valve. In addition, the added air vessel can keep the downstream pressure at an acceptably high level, accelerating the reduction of the flow in the pipeline when the downstream valve closes.

With this arrangement of the air vessel, a proper closure rule for the downstream valve can be easily obtained, and the contradiction is resolved. Although an additional air vessel is installed in the pipeline system, the total volume of air vessel can be greatly reduced compared with the traditional single air vessel method. The verification of the combined protection method to reduce the air vessel volume is given in the following section, as well as its performance on water hammer protection.

CASE STUDY

The schematic diagram of a long distance water supply project in China is shown in Figure 2, and the parameters of the system are listed in Table 1. The pipeline is long and relatively flat with a few high points marked from A to D in the diagram. The water level difference between upstream and downstream is small. A butterfly valve is installed at the upstream end, and a needle valve is installed at the downstream end. Based on the method of characteristics, the numerical model of hydraulic transient in the pipeline system was established, which has been verified in many studies (e.g. Streeter & Wylie 1967; Wylie et al. 1993; Chaudhry 2014). In this case, it is required that no negative pressure should appear along the pipeline and that the maximum pressure along the pipeline should be below 60 m. In order to meet the requirement of water hammer protection, different protection measures were applied to the real project, and the pump trip condition was simulated.

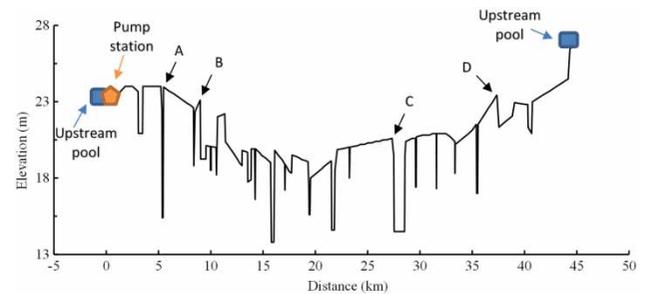


Figure 2 | Schematic diagram of the water supply project.

Table 1 | Parameters of the pipeline system

Upstream water level (m)	17.51	Roughness coefficient	0.012
Downstream water level (m)	29.10	Quantity of pumps	2
Pipe diameter (m)	1.2	Rated speed (r/min)	990
Pipe length (km)	44	Motor power (kW)	800
Flow discharge (m^3/s)	1.32	Pump head (m)	68
Wave speed (m/s)	1,000	Moment of inertia ($\text{kg}\cdot\text{m}^2$)	4,200

System without protection

Assume that there are no protection methods in this case. The discharge and pressure behind the pump begin to decrease after power failure, resulting in negative pressure behind the pump. The maximum and minimum pressure curves along the pipeline are shown in Figure 8. Most of the minimum pressures along the pipeline are below vaporization pressure (-10 m) after power failure. Therefore, it is necessary to take protection measures to achieve the safe operation of the water supply system. Additionally, it should be noted that vaporization of water was neglected in the numerical simulation and that the pressures below -10 m are meant to indicate the severity of the pressure drop.

System with upstream air vessel method

As shown in Figure 1, an air vessel is installed close to the outlet of the pump station at $K0 + 281$ to relieve the negative water hammer due to pump trip. When the pump trip occurs, the upstream check valve is closed in 10 s, whereas the downstream valve does not take any action. The parameters of the air vessel were optimized by trials, and they are shown in Table 2.

The variations of the water depth in the air vessel and variations of the pipe centerline pressure of the air vessel are shown in Figure 3. When the pump fails, the pressure behind the pump begins to reduce, and the water hammer waves propagate through the pipeline. As a result, the water in the air vessel began to flow into the pipeline to mitigate the pressure drop. Then, both the water depth in the vessel and the bottom pressure of the vessel begin to decrease after power failure. Since the pipeline is long and flat, the momentum of the subsequent reverse flow is relatively low. Consequently, the corresponding positive water hammer due to the reverse flow is not severe, which makes the water depth in the air vessel and the positive pressures along the pipeline far below the tolerable maximum values

during the hydraulic transients. Therefore, it can be indicated that the most economical volume of the air vessel is mainly determined by the minimum water level in the air vessel as well as the minimum pressures along the pipeline, which means that a higher minimum water level in the vessel and higher minimum pressures along the pipeline will lead to a smaller volume of air vessel. Inspired by this, the artificial pressure difference along the pipeline can be introduced by closing the downstream valve after pump trip. In this way, the water depth in the vessel and the pressures along the pipeline can be increased to some extent so that the volume of air vessel can be reduced accordingly.

System with combined protection measure

In this combined protection method, the upstream check valve is closed in 10 s after pump trip while the downstream valve is also closed at the same time. In this case, it is rather difficult to find a proper closure rule of the downstream valve that can achieve both the downstream water hammer protection and the upstream vessel volume reduction concurrently. Therefore, the innovative air vessel arrangement is applied in this case.

The related parameters of the air vessels in the innovative arrangement are shown in Table 3. According to the innovative air vessel arrangement, a downstream air vessel is additionally installed at $K44 + 175$ near the downstream valve as shown in Figure 1. Due to space limitations, the optimization process is not presented here. With this arrangement, the closure time of the downstream valve can be shortened to 50 s.

As shown in Figure 4, when pump trip happens, the pressure behind the pump drops quickly and the water flows out of the upstream vessel into the pipeline. Meanwhile, the downstream valve is closed in 50 s. When the positive pressure wave caused by the rapid closure of the downstream valve reaches the upstream end at about

Table 2 | Parameters of the air vessel

Water depth (m)	Air height (m)	Vessel height (m)	Cross-sectional area (m ²)	Orifice diameter (m)	Installation elevation (m)	Initial absolute pressure (m)	Total volume (m ³)
5.5	2.0	7.5	75	0.6	23.5	58.0	525

The orifice discharge coefficient (inflow/outflow) is 0.6 in the numerical calculations.

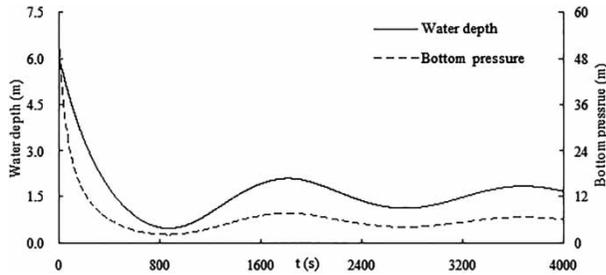


Figure 3 | Variations of the water depth and bottom pressure of the air vessel.

$t = 44$ s, the upstream pressure drop begins to be mitigated along with the water level drop in the upstream vessel.

The downstream valve is closed 50 s after the pump trip happens. As shown in Figure 5, the downstream air vessel relieves the positive pressure due to the valve closure, keeping the maximum pressure below 60 m. Furthermore, it makes the downstream pressure remain at an acceptably high level, accelerating the reduction of the flow in the pipe after the pump trip, greatly reducing the amount of feed-water from the upstream vessel.

Comparison of results

In Figure 6 and Table 4, A and B stand for the traditional upstream air vessel protection method and the combined protection method respectively; C stands for no protection method. According to the numerical results, with both A and B no negative pressures occur along the pipeline and the maximum pressure along the pipeline is below 60 m. In addition, the minimum pressure along the pipeline obtained with A is lower than that obtained with B, indicating that B performed better in negative water hammer protection than A. Moreover, compared with A, the total volume of air vessel obtained with B is reduced by 55.3%, from 525 m³ down to 234.5 m³ (150 m³ of the upstream air vessel plus 84.5 m³ of the downstream air vessel), and the volume of the upstream air vessel is reduced

by 71.4%, from 525 m³ down to 150 m³. Accordingly, the required investment can be greatly reduced.

DISCUSSION AND ANALYSIS

In this section, the selection of the upstream air vessel volume is discussed, and the selection of the downstream valve closure rule is also studied.

In Table 5, three upstream air vessels with different volumes are listed, and their protection performances were calculated respectively. In the calculations, the downstream air vessel is the same as that mentioned previously, and the downstream valve is closed 50 s after pump trip. The numerical results are shown in Figures 7 and 8. Figure 7 indicates that, when a pump trip occurs, a larger volume of air vessel can relieve the pressure drop behind the pump better. As a result, the pressure drop due to pump trip propagating to the pipeline will not be relatively serious in Scheme c. Figure 8 also shows that, as the volume of the upstream vessel increases, the minimum pressures along the pipeline grow accordingly. That is because a larger air vessel does better in negative water hammer protection. However, the upstream air vessel cannot be overlarge without limitations. First, an overlarge volume of air vessel is not helpful to reduce costs, and second, the maximum pressures along the pipeline are the superposition of the negative pressure wave due to pump trip and the positive pressure wave due to downstream valve closure. If the upstream air vessel is overlarge, the pressure drop due to pump trip will not be low enough to relieve the positive pressure due to downstream valve closure, causing high positive pressures that will exceed the pressure limit along the pipeline. Then, it is clear that the volume of the upstream air vessel can be neither too large nor too small when the downstream air vessel and valve closure rule have been properly selected. If it is too large, the maximum pressure along the pipeline

Table 3 | Parameters of the air vessels

Installation location (m)	Water depth (m)	Air height	Vessel height (m)	Cross-sectional area (m ²)	Orifice diameter (m)	Installation elevation (m)	Initial absolute pressure (m)	Total volume (m ³)
Upstream end (K0 + 281)	5.5	2.0	7.5	20.0	0.6	23.5	58.0	150
Downstream end (K44 + 175)	1.0	5.5	6.5	13.0	0.3	24.5	12.4	84.5

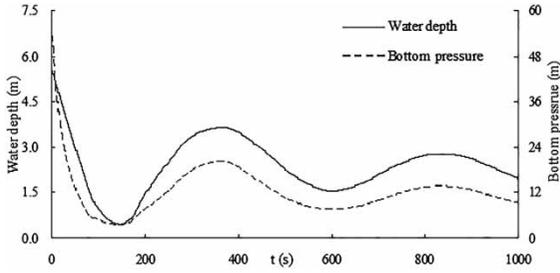


Figure 4 | Variations of the water depth and bottom pressure of the upstream air vessel.

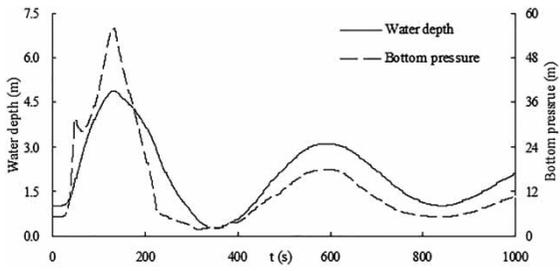


Figure 5 | Variations of the water depth and bottom pressure of the downstream air vessel.

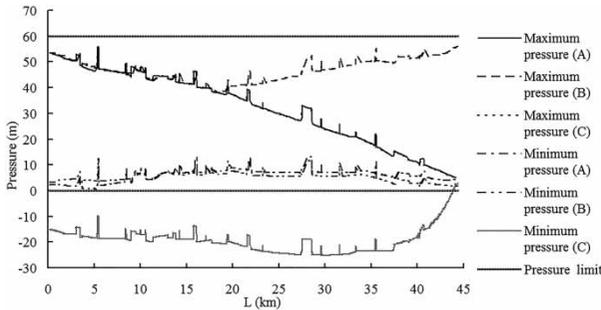


Figure 6 | Enveloping curves of pressures along the pipeline with different protection methods.

Table 4 | Statistics of two protective strategies

Protection method	Air vessel volume (m ³)	Maximum Pressure (m)	Minimum pressure (m)
A	525	56.0	0.6
B	150 + 84.5	56.0	1.7
C	\	56.0	-25.0

will exceed the limit. If it is too small, the minimum pressure will also go below the limit. Therefore, in this case, Scheme b is the most appropriate for the water supply project.

As shown in Figure 9, in order to explain the selection of a proper closure rule of the downstream valve, the calculation results of three closure rules are given: 40 s, 50 s and 60 s. In the calculations, the upstream and downstream air vessels are from Scheme b. Figure 9 shows that, with the increase of the valve closure time, the maximum and minimum pressures along the pipeline both decrease. That is because a longer closure time will lead to a lower positive water hammer pressure at the downstream valve. Accordingly, the pressures along the pipeline will reduce. However, if the closure time is too long or too short, either the minimum pressure or the maximum pressure along the pipeline will be beyond acceptable limits. In this case, 50 s is suitable as the closure time of the downstream valve, and there is some safety margin for the operation of the valve with this closure time.

The above results and analysis indicate that, as long as the downstream air vessel is properly selected, an appropriate upstream air vessel and a proper closure rule of the downstream valve can be obtained accordingly. Although the rule of selecting the downstream air vessel is not given in this paper, a reliable downstream air vessel can still be obtained by trial calculations.

CONCLUSIONS

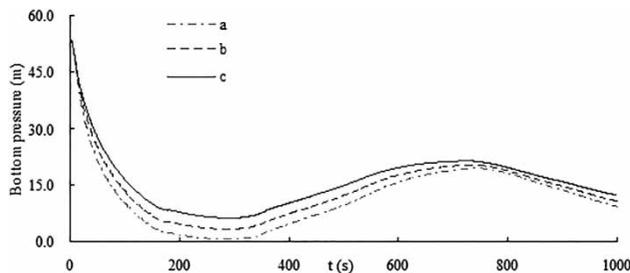
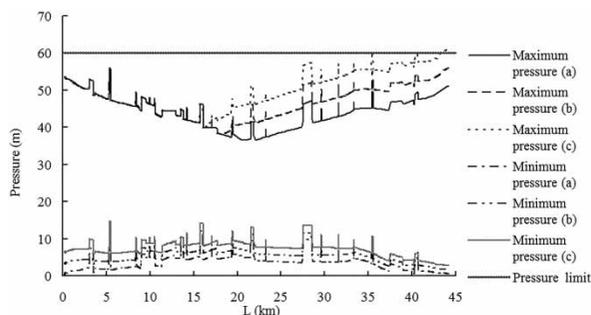
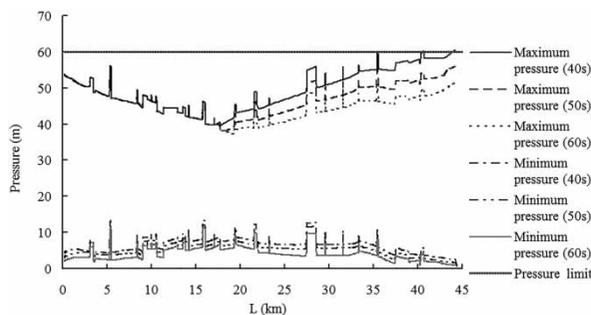
In this paper, the new protection measure, which combines the air vessel protection measure with the downstream valve closure, is presented to reduce the volume of the air vessel in long distance water supply projects. The main conclusions are drawn below:

1. The combination of the air vessel and downstream valve is proposed here to optimize the volume of the air vessel. However, it is also found that, if the difference between the upstream and downstream water level is small and the pipeline is relatively flat, it is rather difficult to obtain a proper closure rule of the downstream valve to achieve both the downstream water hammer protection and the reduction of upstream air vessel volume concurrently.
2. To accommodate the contradiction between the downstream water hammer protection and the reduction of the upstream air vessel volume in this combined

Table 5 | Schemes of the upstream air vessel

Scheme	Cross-sectional area (m ²)	Water depth (m)	Air height (m)	Vessel height (m)	Initial absolute pressure (m)	Total volume (m ³)
a	15	7	2	9	56.5	135
b	20	5.5	2	7.5	58.0	150
c	25	5.5	2	7.5	58.0	187.5

For Scheme a, in order to avoid air leakage, the water depth differs from those of the other two schemes.

**Figure 7** | Variations of bottom pressures of different upstream air vessels.**Figure 8** | Enveloping curves of pressures along the pipeline with different upstream air vessels.**Figure 9** | Enveloping curves of pressures along the pipeline with different closure rules.

method, an innovative air vessel arrangement is proposed and studied, which can make the combined method widely applicable and effective.

- The numerical model was established according to the parameters of a practical water supply project, and hydraulic transient due to pump trip was simulated. The results showed that the proposed combined method could provide effective water hammer protection, reducing the volume of air vessel concurrently.
- The rules for selecting the size of the upstream air vessel and the closure time of the downstream valve were given in this paper. Additionally, it can be implied that, if the water level difference is relatively large and the pipeline is relatively steep in a water supply project, the reduction of the air vessel volume is not obvious by this method.
- Despite the advantages of the combined method, there are also some drawbacks in its application. In this combined method, the downstream pipe has to be thickened to some extent to bear the relatively high pressure due to the downstream valve closure, which is not economical in practice. Therefore, it is important and necessary to find the trade-off point between reducing the volume of air vessel and thickening the downstream pipe. Besides, since another air vessel and a valve are additionally installed in the combined method, careful and regular maintenance is required to ensure that the downstream valve can be closed accurately after pump trip, and the regular maintenance of the system becomes more complicated and expensive.

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