Effects of air vessel on water hammer in high-head pumping station

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Abstract. Effects of air vessel on water hammer process in a pumping station with high-head were analyzed by using the characteristics method. The results show that the air vessel volume is the key parameter that determines the protective effect on water hammer pressure. The maximum pressure in the system declines with increasing air vessel volume. For a fixed volume of air vessel, the shape of air vessel and mounting style, such as horizontal or vertical mounting, have little effect on the water hammer. In order to obtain good protection effects, the position of air vessel should be close to the outlet of the pump. Generally, once the volume of air vessel is guaranteed, the water hammer of a entire pipeline is effectively controlled.

1. Introduction

The abrupt stop of pumps often results in huge pressure change in water diversion projects for a high-head pumping stations. In the worst cases, water column separation may cause a large and instantaneous rise of pressure. The resulting pressure variation threatens the safe operation of pumping stations. Therefore, the water hammer is protected by mounting surge tanks [1-2], air valves [3-4], air vessels or other equipments in actual engineering. For traditional safeguard procedures, there exist some problems that surge tank is restricted by topography and the poor exhaust performance of air valve leads to large pressure. However, as an effective safeguard procedure for water hammer, air vessel is used widely because it has the features of lower investment and easy to maintain.

The total volume, initial air volume and installation position of air vessel have important impacts on water hammer. At present, the widely used methods for determining the total volume of air vessel are graphic method [5], formula method [6] and estimation method [7]. The size of total volume can be determined by trial on the basis of these methods. For the initial air volume of an air vessel, Liu [8] and Liang [9] found that as the initial air volume of air vessel increased, the effect of protecting water hammer was better. Moreover, Syed [10] compared the effects of two different installation positions on water hammer, and pointed out that the water hammer was effectively protected when the position of air vessel was at main line originating just after the parallel line connection; Gao [11] also analysed the effect of position on water hammer, and showed that different positions of air vessel had different effects on water hammer. But the actual installation position was not given.

In this paper, the mathematical model of air vessel is established, and the effects of installation mode and position of air vessel on water hammer process are analyzed by means of characteristics method. The water hammer for a high-head pumping station is protected effectively by designing an air vessel.
2. **Mathematical mode of air vessel**

For a given pipeline equipped with air vessel, when positive surge caused by any transient event is introduced to the system, liquid is discharge from pipe into the vessel to compress the air in the vessel, and when negative surge is introduced to the system, liquid is discharge from vessel to the pipe to avoid the pressure in the pipe down to vaporization pressure. According to the above procedure, the mathematic mode of air vessel is established, as shown in figure 1.

![Mathematical mode of air vessel](image)

**Figure 1.** Mathematical mode of air vessel.

For a single air vessel, the pressure throughout the volume at any instant is assumed to be uniform. The compressibility of the liquid in the vessel is considered to be negligible compared with air compressibility. Inertia and friction could be neglected. The gas is assumed to follow the reversible polytropic relation

\[ PV^{k} = C \]  

where \( P \) is the absolute head equal to the gage plus barometric pressure heads, \( V \) is the gas volume, \( k \) is the polytropic exponent, and \( C \) is a constant. For \( k \), an average value of 1.2 is used in design calculations.

The continuity equation at the junction P can be written

\[ T \dot{Q} = Q + Q_s \]  

where \( T \dot{Q} \) is the discharge into junction P, \( Q \) is the discharge out of junction P, and \( Q_s \) is the discharge through the orifice either in positive or negative direction.

In the air vessel, water and air follow the relation

\[ \frac{dH_s}{dt} = - \frac{dV}{dt} = Q_s \]  

where \( H_s \) is the water level, \( A_s \) is the cross-sectional area of air vessel, and \( t \) is the time.

If the elasticity of water and vessel wall is without consideration, air pressure and water level in the vessel are as follows

\[ H_p = \left( \frac{P}{\gamma} - H \right) + H_s + \sigma \frac{|Q_s| Q_s}{2gA_s^2} \]  

where \( H_p \) is the hydraulic grade at junction P, \( P \) is the air pressure, \( \gamma \) is the gravity, \( H \) is the gage pressure, \( g \) is the gravitational acceleration, \( \sigma \) is the resistance coefficient of orifice, and \( A_s \) is the cross-sectional area of orifice.
3. **Pumping project**

A water diversion project with high-head pumping station is shown in figure 2. The level of intake sump of the pumping station is 1675.6 m, and the level of outlet sump is 1802.0 m. The total length of the DN700 pipeline is 4770 m, and the network discharges a total flow of 0.55 m$^3$/s. Four double-suction centrifugal pumps are installed in which one pump is backup unit. The rated parameters of the pump are shown in table 1. A butterfly valve is mounted at the outlet of pump for one pumping subline. The butterfly valve is set to be in two-period closing mode with fast closing time of 10s and slowly closing time of 30 s in order to prevent runway speed from the abrupt stop of pumps.

![Figure 2. Sketch of pipe system in pumping station.](image)

**Table 1.** Rated parameters of the pump.

| Head (m) | Discharge (m$^3$/s) | Speed (r· min$^{-1}$) | Inertia (kg· m$^2$) | Power (kW) |
|----------|---------------------|-----------------------|---------------------|------------|
| 140      | 0.2194              | 1480                  | 3.74                | 560        |

4. **Water hammer analysis**

4.1. Results without air vessel

![Figure 3. Pressure profile without air vessel.](image)
The calculated results of water hammer without air vessel are shown in figure 3. The results show that the maximum pressure in the pipeline happens at the outlet of pump, and the value is 225.6 m, which exceed 1.5 times of rated pressure of pump outlet (that is bearing pressure); negative pressure which is even to vaporization pressure is emerged in the pipeline. Therefore, it is necessary to take measures to prevent water hammer.

4.2. Results with air vessel
In order to avoid maximum and minimum pressure, an air vessel is installed on main line originating just after the parallel line connection. After several trial calculations, three volume sizes of 40m$^3$, 45m$^3$ and 50m$^3$ are selected by using methods for determining the total volume of air vessel. And the initial air volume fraction to total volume is set as 60% in this study. The effects of installation mode and position of air vessel on water hammer are as follows.

4.2.1. Effect of installation mode on water hammer.

**Table 2. Schemes of air vessel shape and calculation results.**

| Scheme | Total height (m) | Cross-sectional diameter (m) | Total volume (m$^3$) | Ratio | Maximum pressure (m) | Minimum pressure (m) | Bearing pressure (m) |
|--------|-----------------|-----------------------------|---------------------|-------|----------------------|----------------------|----------------------|
| (1)    | 5.7             | 3.0                         | 40                  | 0.5   | 197.29               | 0.33                 | 210                   |
| (2)    | 4.4             | 3.4                         | 40                  | 0.8   | 197.29               | 0.33                 | 210                   |
| (3)    | 3.5             | 3.8                         | 40                  | 1.1   | 197.29               | 0.33                 | 210                   |
| (4)    | 2.9             | 4.2                         | 40                  | 1.5   | 197.29               | 0.33                 | 210                   |
| (5)    | 6.4             | 3.0                         | 45                  | 0.5   | 189.94               | 0.32                 | 210                   |
| (6)    | 5.0             | 3.4                         | 45                  | 0.7   | 189.94               | 0.32                 | 210                   |
| (7)    | 4.0             | 3.8                         | 45                  | 1.0   | 189.94               | 0.32                 | 210                   |
| (8)    | 3.2             | 4.2                         | 45                  | 1.3   | 189.94               | 0.32                 | 210                   |
| (9)    | 7.1             | 3.0                         | 50                  | 0.4   | 184.82               | 0.31                 | 210                   |
| (10)   | 5.5             | 3.4                         | 50                  | 0.6   | 184.82               | 0.31                 | 210                   |
| (11)   | 4.4             | 3.8                         | 50                  | 0.9   | 184.82               | 0.31                 | 210                   |
| (12)   | 3.6             | 4.2                         | 50                  | 1.2   | 184.82               | 0.31                 | 210                   |

As shown in table 2, twelve schemes of air vessel shape are selected. Meanwhile, the ratio of cross-sectional diameter to total height represents the installation mode. That is to say, the ratio is less than 1 for vertical installation and greater than 1 for horizontal installation.

The results in table 2 show that the maximum pressures are within the bearing pressure and the minimum pressures are protected above atmospheric pressure for three selected volume sizes; the maximum pressures in the system decline with increasing volumes of air vessel, and the smaller volume vessel is priority to choose with considering maintenance cost. Compared schemes (1), (2), (3) with (4), or schemes (5), (6), (7) with (8), or schemes (9), (10), (11) with (12), the results show that changing the total height and cross-sectional diameter has no effect on pressure for a fixed vessel volume. So there is little significant effect on water hammer for horizontal or vertical mounting.

4.2.2. Effect of installation position on water hammer. Air vessel is usually installed at the outlet of pump, hindering pressure drop by feed-water and absorbing pressure rise by compressing air in the vessel. But in the water diversion project with rugged topography, water column separation occurs easily at local high point of pipeline, which causes a large and instantaneous rise in pressure. Therefore, three installation positions are selected in this paper, as shown in figure 2. And point A is at
the outlet of pump, point B is at the local high point of one-third pipeline, and point C is at the local high point of two-third pipeline.

Table 3. Calculation results of pressure for three installation positions.

| Installation position | Total volume (m³) | Maximum pressure (m) | Minimum pressure (m) | Bearing pressure (m) |
|-----------------------|------------------|----------------------|----------------------|----------------------|
| A                     | 40               | 197.29               | 0.33                 | 210                  |
| B                     | 40               | 184.40               | 0.49                 | 210                  |
| C                     | 40               | 171.42               | -7.23                | 210                  |

Figure 4. Pressure profile for three installation positions.

Taking the total volume of 40 m³ as an example, the calculation results for three installation positions are shown in table 3 and figure 4. The results show that the water hammer can be effectively protected when the positions are selected at point A and point B; the pressure in the pipeline from pump outlet to installation position is not prevented from water hammer when the position is at point C. Therefore, air vessel plays a protective role to pipeline that located after its installation position. So it is suggested that vessel position is close to the outlet of pump. If the volume of air vessel is exactly determined, the water hammer is effectively protected for the entire pipeline.

5. Conclusions

The water hammer caused by the abrupt stop of pumps could be protected effectively by an air vessel. The volume size, installation mode and installation position have important influences on water hammer protection. With increasing of volume of air vessel, the maximum pressure decreases. Once the total volume is fixed, changing vessel shape has little effect on water hammer. Namely, there is not significant effect on water hammer for horizontal or vertical mounting. Because air vessel plays protective role to pipeline only located after the installation position, it should be installed close to the outlet of the pumping station.

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