

Pump-stoppage-induced water hammer in a long-distance pipe: a case from the Yellow River in China

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ABSTRACT

Pump stoppage can instantaneously increase the pressure within a pipeline, which is an extreme condition and poses a severe threat to the safety of long-distance water transmission projects. Reducing positive and negative pressures is essential to reducing this risk, improving operational efficiency, and avoiding system component fatigue. This study investigated the performance of a combination of dimensionless pump parameters and pipeline pressure in providing detailed information for designing protective equipment to mitigate water hammer effects, which are generated by sudden pump stoppage. The conditions of the method of characteristics were satisfied by conducting an overall transient flow analysis to estimate the potential of the increased pressure relevant to all types of operating schemes. Extreme pressure waves, produced by pump failure or rapid valve closure, can be prevented using efficient protective designs. The findings of this study can be instructive to alleviating the potential damage engendered by water hammer.

Key words | air valve, closing valve, long-distance pipeline, pump stoppage, surge tank, water hammer

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INTRODUCTION

Water hammer is a pressure wave occurring when flowing water is suddenly forced to stop within a short time. The pressure generated by unsteady conditions in pipe networks occasionally exceeds the regular working pressure by two times or more (Nikpour *et al.* 2014). Pump tripping induces water hammer, which still poses challenges to large-scale pumping stations with long-distance pipes. In particular, water column separation induces a severe fluid oscillation and structural vibration in pipes. Protective devices should be installed on pipelines to ensure the reliability and properties of hydraulic modules. Regarding pressure management strategies, air valves have the greatest effectiveness in alleviating negative pressures, compared with other types of protective devices against water hammer. Air valves can also sustain a positive pressure in the pipeline during pump stoppage (Bianchi *et al.* 2007). Furthermore, air valves provide a

method for discharging trapped air from pipelines. Specifically, they offer approaches for ameliorating water hammer; for example, transient events can be triggered by rapid valve closure or sudden pump stoppage. Air valves are thus critical for controlled and uncontrolled pipelines in water transmission engineering (Carlos *et al.* 2011). A surge tank is an effective source of potential energy that can be released to minimise pressure. Surge tanks are effective in preventing column separation engendered not only by pump stoppage but also by abnormal valve operation. Moreover, applying valve-closing strategies to overcome pump failure is effective in avoiding water hammer.

This study applied the method of characteristics (MOC), which is commonly used in water hammer calculations, to establish an evaluation model. The study combined boundary conditions to derive a formula for a

basic mathematical model. The discrete vapour cavity model (DVCM) was used to simulate unsteady cavitation flow. Transient flow was considered to be caused by a pump failure for a large-scale, complex water supply system with high head. The results indicated that the probabilistic analysis method could determine the effects of different indeterminate design parameters on system responses under transient conditions and provide detailed information regarding the design stage for water supply engineers and protection equipment.

METHODOLOGY

Pump stoppage can engender water column separation due to negative pressure (Bergant et al. 2010). Vapour pressure is generally -8 m below atmospheric for water at 20°C . The pressure of a vapour cavity in a pipe is assumed to decrease to a certain value, causing discontinuity in the fluid and pressure drop. The DVCM enables shaping of vapour cavities in any computational cross section in the MOC. The pressure can be calculated in a section in which it could become equivalent to, or less than, the vapourisation pressure. The phenomenon of water column separation has been observed through additional laboratory tests. The accuracy of numerical calculation results has been determined to be the same as that of laboratory test results for water column separation occurring in a sloping pipeline due to rapid downstream or upstream valve closure (Bergant & Simpson 1999, 1995; Adamkowski & Lewandowski 2014; Lema et al. 2016).

One-dimensional momentum and continuity equations for transient flow in elastic pipes are given, respectively, as follows (Wylie & Streeter, 1967).

Continuity equation:

$$g \frac{\partial H}{\partial x} + \frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} + \frac{fv|v|}{2D} = 0 \quad (1)$$

Momentum equation:

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

where H , D , and x are piezometric head, the pipe internal diameter, and a space variable, respectively; g , v , and, t are the gravitational constant, velocity (flow divided by cross-sectional area), and a time variable, respectively; and f , a ,

and α are the Darcy–Weisbach friction factor, wave speed, and pipe slope, respectively.

Sudden valve closure during operation engenders a considerable pressure surge. Rapid valve closure or opening can generate considerably high and low pressures. Abnormal valve operation can be attributed to employee errors or valve module destruction. A valve is generally installed at the pump outlet to control the pressure surge. The pump water head equation can be written (Chaudhry 2014) as follows:

$$Hp_{i,1} = H_{suc} + Hp - \Delta Hp_v \quad (3)$$

where H_{suc} , Hp , and ΔHp_v are the height of the liquid surface in the suction reservoir above the datum, the pumping head at the end of the time step, and the head loss in the discharge valve for the pump discharge at the end of the time step, respectively. The valve head loss is as follows:

$$\Delta Hp_v = Cv Q_p |Q_{p,i,1}| \quad (4)$$

where Cv and Q_p denote the coefficient of valve head loss and the flow through the pump at the end of the time step, respectively. When $Hp_{i,1}$, ΔHp_v , and $Q_{p,i,1}$ are eliminated, Equation (3) can be written as follows:

$$Q_R v_p = C_n + C_a H_{suc} + C_a H_R h_p - C_a C_v Q_R^2 v_p |v_p| \quad (5)$$

At the beginning of the time step, the variables α , v , h , and β are known. The subscript ‘P’ denotes unknown variables at the end of the time step; that is, α_p , v_p , h_p , and β_p .

$$F_1 = C_a H_R a_1 (\alpha_p^2 + v_p^2) h_p + C_a H_R a_2 (\alpha_p^2 + v_p^2) \tan^{-1} \frac{\alpha_p}{v_p} - C_a C_v Q_R^2 v_p |v_p| - Q_R v_p + C_n + C_a H_{suc} \quad (6)$$

The decelerating torque during power failure is given as follows:

$$T = I \frac{2\pi dN}{60 dt} \quad (7)$$

where I denotes the combined polar moment of inertia of the pump/motor and the entrained liquid and N denotes the rotational speed of the pump. Equation (6) can be written in a finite-difference form by using the rated

parameters N_R and T_R as follows:

$$\frac{\alpha_p - \alpha}{\Delta t} = -I \frac{60T_R \beta + \beta_p}{2\pi I N_R} \quad (8)$$

Equation (8) can be simplified as follows:

$$\alpha_p - C_6 \beta_p = \alpha + C_6 \beta \quad (9)$$

where $C_6 = -15T_R \Delta t / \pi I N_R$.

The rotating mass equation can be written as follows:

$$F_2 = \alpha_p - C_6 a_3 (\alpha_p^2 + v_p^2) + C_6 a_4 (\alpha_p^2 + v_p^2) \tan^{-1} \frac{\alpha_p}{v_p} - \alpha - C_6 \beta \quad (10)$$

These equations can be solved using the Newton-Raphson method.

SYSTEM BACKGROUND

A case study was conducted on water supply system analysis for the Yellow River, located in the northwest of China. Each pumping station consists of a main pipe between two storage tanks. The downstream section of each pump outlet consists of a hydraulic control butterfly valve. To control the transient pressure, installing a one-way surge tank with a total volume of 98.125 m^3 and 13 strategically placed air valves with size combinations is required.

CASE STUDY

The pumping station consists of two units, with each including two double-suction centrifugal pumps. Both units can be considered as individual devices and are supplied by independent suction pipelines from the reservoir. The pipeline elevation range from sea level is 1,154.56–1,236.59 m, whereas the length of the pipe is 5,543.938 m, as shown in Figure 1. The second pumping station consists of two parallel main pipelines with a prestressed concrete cylinder pipe; the pipelines are 2,000 and 1,800 mm in diameter and run from west to east, supplying water to main pipes along their paths. To distinguish the two types of pumps, they were named type A and type B. The flow rates of types A and B are 2.85 and $1.05 \text{ m}^3/\text{s}$, respectively. The rotational speed is 740 r/min. Furthermore, the rated head levels of types A

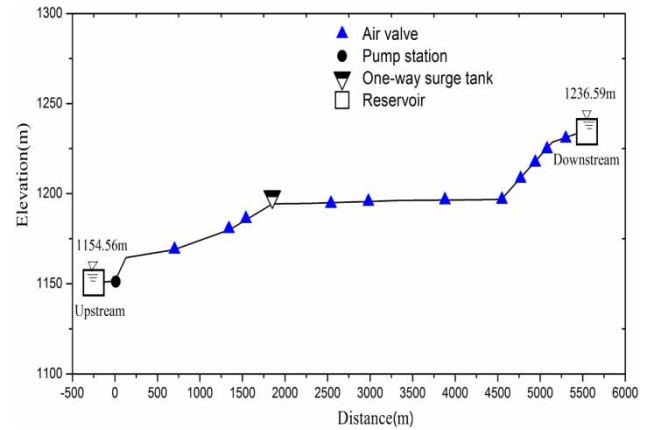


Figure 1 | Sketch of pipeline system.

and B are 90 and 88.7 m, respectively. The moment of inertia of types A and B are 3,162.9 and $794.12 \text{ kg}\cdot\text{m}^2$, respectively. Dimensionless parameters referring to the point of rated conditions are used as a reference and defined by the following variables, where the subscript R denotes rated conditions:

$$v = \frac{Q}{Q_R}, h = \frac{H}{H_R}, \alpha = \frac{N}{N_R}, \beta = \frac{T}{T_R} \quad (11)$$

α , h , v , and β denote the relative angular velocity, relative head, relative flow moment, and relative hydraulic moment of the pump, respectively.

In water supply systems, the same pump types are generally used in a parallel pump unit; combining two types is rare. Therefore, a system involving combined pumps was used in this study as the research object.

RESULTS AND DISCUSSION

The water hammer occurring during an unexpected pump stoppage in the water supply system was calculated through programming code. The pump was considered to have stopped immediately. The calculation time for the transient analysis was set to 500 s. In the simulation process, the first step was executed without considering protective measures, and the second step was executed by considering the use of air valves and butterfly valves. Multiple combinations of protective devices were achieved by combining the butterfly and air valves, by using a one-way surge tank and applying it to the system. The final objectives were achieved with minimised construction and maintenance costs for the safety of

the water delivery system. When the two pumps stopped, the valves were closed in two stages. The protection schemes and the main calculation results are presented in Table 1.

As shown in Table 1, when the two pumps were stopped without closing the valves, the positive pressure in the pipeline was greater than the load capacity of the pipe by 209.31 m, whereas the negative pressure was less than the local atmospheric pressure by 8 m, which could cause cavitation in the pipeline. The results were obtained from numerical calculations performed by not considering air valves and by considering 13 air valves. When hammer protection devices were not considered and the valves were closed in two stages, pump stoppage engendered an extremely high pressure wave in the pipeline. Without the air valves, the pipeline had a negative pressure and the pump outlet had a relatively high positive pressure. The 13 air valves were considered to be installed at strategic points or at high positions. Extensive column separation was still observed, and the subsequent pressure was even higher than the pressure observed when valves were not closed. The liquid column separation result indicates that the air valves were ineffective. Therefore, a one-way surge tank with a volume of 98.125 m³ was installed to replace one of the air valves for controlling the pressure surges. The diameter and height of the one-way surge tank were measured to be 5 m, with the tank having two water supply pipes with an inner diameter of 600 mm. The optimal closure law was determined by conducting a series of trial-and-error valve-closing operations. Accordingly, for an emergency shutdown, the minimum pressure was stipulated to be -8 m, and the reverse flow speed ratio was stipulated to be less than 1.2 times the rated speed ratio. For the final solution, the valve-closing time was determined as follows: The valve must be closed from a completely open angle to 15° in 5 s and then from 15° to fully closed in 60 s. Table 1 indicates that minimum and maximum pressures under emergency shutdown were -4.34 m and 120.51 m, respectively. The results are acceptable under these conditions. Although the results are unsatisfactory under regular working conditions, they can be relatively reasonable in extremely infrequent situations.

The effects of the protection equipment are presented in Figure 2, as calculated for a condition involving simultaneous pump stoppage, where α is the relative angular velocity, h is the relative head, v is the relative flow

Table 1 | Protection schemes

Protection schemes	No measures of protection		Close valve rule		Thirteen air valves		Combination of thirteen air valves and one-way surge tank	
	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B
Close valve rule	Do not close	Do not close	Two stages: 5 s/ 75°, 60 s/15°	Two stages: 5 s/ 75°, 60 s/15°	Two stages: 5 s/ 75°, 60 s/15°	Two stages: 5 s/ 75°, 60 s/15°	Two stages: 5 s/ 75°, 60 s/15°	Two stages: 5 s/ 75°, 60 s/15°
Reverse flow time(s)	6.96	5.82	6.99	5.96	6.99	5.96	6.21	5.60
Reverse rotation speed ratio	-1.69	-1.51	-1.42	-1.51	-1.42	-1.51	-1.16	-0.88
The pressure in the pipeline	Max pressure (m) 209.31	Min pressure (m) -8	Max pressure (m) 224.96	Min pressure (m) -8	Max pressure (m) 224.96	Min pressure (m) -8	Max pressure (m) 120.51	Min pressure (m) -4.34

moment, and β is the pump's relative hydraulic moment. At the initial stage of pump stoppage, the discharge, head, and rotational speeds of pumps A and B suddenly decreased. As indicated in Figure 2(a), the reverse discharge of pump A during emergency valve closure was approximately $-1.81 \text{ m}^3/\text{s}$, and the reverse discharge of pump B increased up to approximately $-0.76 \text{ m}^3/\text{s}$; moreover, the backflow induced a change in the rotational speed from $+740 \text{ r/min}$ (normal rotation) to -473.6 r/min (reserved rotation) within 35.46 s . The maximum and minimum pressure distributions of the water distribution system with water hammer protection are presented in Figure 2(c). Under the pump stoppage condition, the negative pressure was appropriately controlled by connecting the air valves to the one-way surge tank, because the butterfly valve was gradually closed within the first $4,500 \text{ m}$. The minimum hydraulic grade line (HGL) was noted to be lower than pipe elevation, which generated negative pressures in the final $1,000 \text{ m}$ of the pipeline. The

negative pressure was calculated to be less than the vapour pressure, particularly in the final $1,000 \text{ m}$, which may lead to column separation and cavitation phenomena in these sections. Moreover, the calculated maximum pressure for the pipeline was 120.51 m , which is approximately 0.36 times less than the theoretically calculated value (337.68 m). The maximum allowable pressure of 135 m in the pipeline was not exceeded, and the calculated minimum pressure was not lower than the vapour pressure. However, to ensure secure and reliable operation, protection equipment should still be installed to ease pressure variations for emergency valve shutdown after pump stoppage. The water level of the one-way surge tank continued to decrease up to 2.75 m ; hence, the one-way surge tank had a significant effect on the pressure regulation of the pipeline. Because air valves have a risk of failure, installing a one-way surge tank can ensure the effectiveness of the water hammer protection. Therefore, engineers are

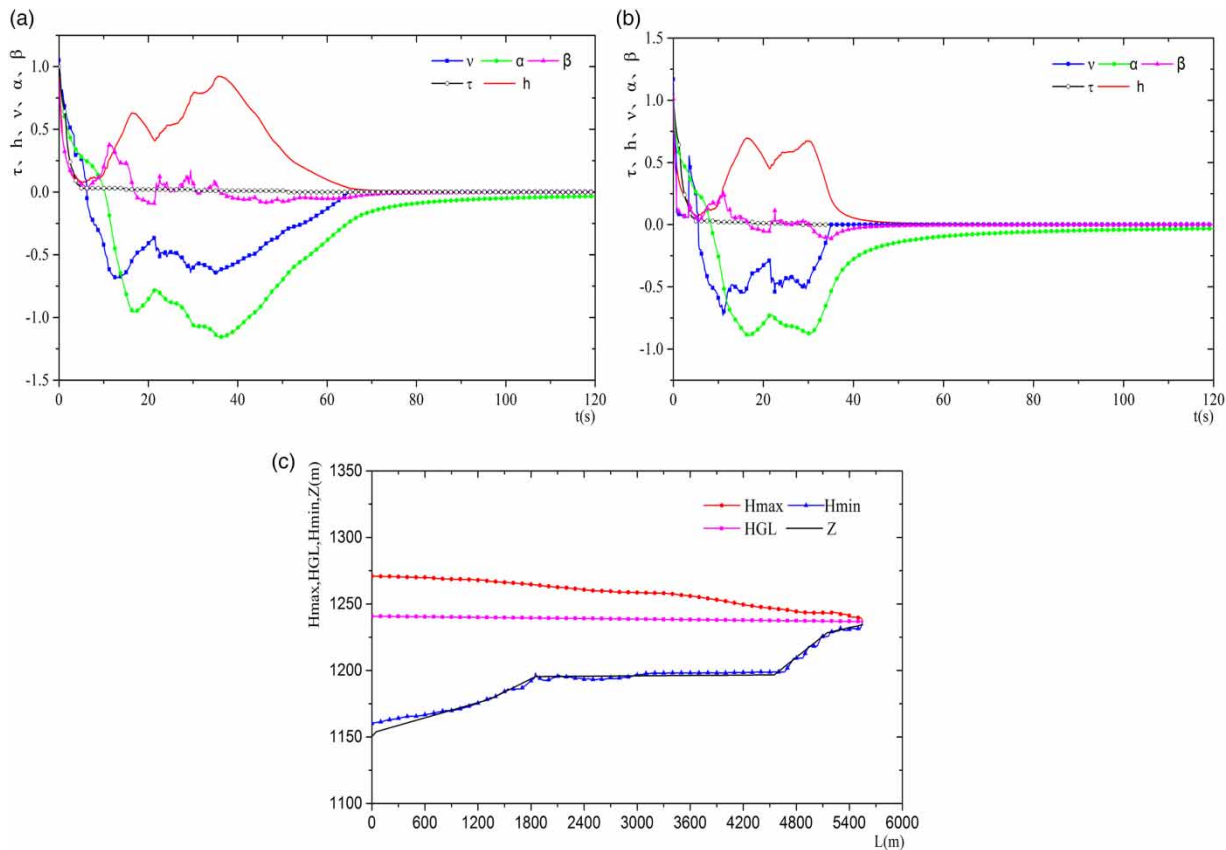


Figure 2 | Transient results of second pump station. (a) Dimensionless parameters of a pump (Type A); (b) dimensionless parameters of a pump (Type B); (c) pipeline profile and curve of pressure.

recommended to combine a one-way surge tank and air valves for the pipelines at each pump station as the final protection system.

CONCLUSIONS

This paper presents a comprehensive evaluation of abnormal pressures associated with water hammer and presents appropriate tools for controlling this phenomenon. Simulation results indicate how to protect water distribution systems and reduce the influence of pressure waves, and the results also provide a valuable reference for protecting large-scale, long-distance water supply systems with high head against pump stoppage. The conclusions derived from this study are summarised as follows:

- (1) In the long-distance and high-head water supply system, because pump stoppage induced changes in the state of water in the pipelines, emergency valve shutdown engendered a sudden change in pressure in the pipelines. The water supply system should be protected against water hammer. Installing air valves at strategic points or at high positions of the pipelines could reduce the pressure in the piping system by more than two times. The influence of liquid column separation due to separate cavities engendered by water hammer in the pipelines was not obvious after the air valves were installed, and gas could not be discharged out of the pipeline. Therefore, to increasing protective effects, valves must be combined with a surge tank. Installing a surge tank ensures the elimination of spike pressure and cavitation.
- (2) Cavitation problems easily occurred in the water supply system; this can be attributed to steady-state pressure, which was lower than the pipeline elevation in portions of the long horizontal main pipe. Selecting an appropriate location for protective equipment can prevent extreme pressures. Moreover, installing protective equipment can reduce hazard levels.
- (3) The same or different valve-closing laws could be applied to different pump combinations. The valve-closing time must be less than the pump start to backflow; otherwise, the impeller would begin to rotate in the reverse direction.

These protective measures were observed to be satisfactorily effective.

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