Research Article

A Water Hammer Protection Method for Mine Drainage System Based on Velocity Adjustment of Hydraulic Control Valve

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Water hammer analysis is a fundamental work of pipeline systems design process for water distribution networks. The main characteristics for mine drainage system are the limited space and high cost of equipment and pipeline changing. In order to solve the protection problem of valve-closing water hammer for mine drainage system, a water hammer protection method for mine drainage system based on velocity adjustment of HCV (Hydraulic Control Valve) is proposed in this paper. The mathematic model of water hammer fluctuations is established based on the characteristic line method. Then, boundary conditions of water hammer controlling for mine drainage system are determined and its simplex model is established. The optimization adjustment strategy is solved from the mathematic model of multistage valve-closing. Taking a mine drainage system as an example, compared results between simulations and experiments show that the proposed method and the optimized valve-closing strategy are effective.

1. Introduction

Mine drainage system is an important part in the safety production of coal mine [1]. Due to the limited space and the high cost of equipment changing, water hammer is a common phenomenon in mine drainage system and its harm is inestimable [2, 3]. The minor injuries of water hammer can cause severe shock or even pipes breaking, and the major injuries can cause equipment damaging, pumping station flooding, or even injuries to underground staff. There are several traditional water hammer protection methods such as installing vacuum valves, exhaust valve, and pressure tank. However, when these water hammer protection methods are used to mine drainage system, the original piping arrangement has to be changed because additional equipment is needed. It is unenforceable to do this in this limited mine space and the cost is too high. In this situation, controlling the time and velocity of valve-closing is an effective means to protect water hammer in mine drainage system. A water hammer is easily to be formed in pipeline if the valve-closing

is fast. On the contrary, the capability of pumps is inefficient if the valve-closing is too slow because pumps in mine drainage system are centrifugal. This inefficient operation has damage for pumps, because power provided by pumps is converted into heat. Therefore, it is important for us to research the critical valve-closing velocity for Hydraulic Control Valve (HCV). Researches of theoretical system and engineering applications for water hammer protection of pipeline fluid delivery areas are increasingly improved [4–6]. But it is still a difficult problem in mine drainage system because of the limited mine space [7, 8].

At present, the theories and methods of water hammer and its protection means become more and more mature. In summary, researches about this problem are mainly in three aspects: hydraulic transient modeling, the calculation, and protection methods of water hammer.

(1) *Hydraulic Transient Modeling*. For the research on hydraulic transient, from the mathematical derivation of the 18th century to the graphical analysis of the mid-20th

century and to the current computer digital simulation, scholars have already made a lot of research results. The major achievements are getting the relationship between multiphase and multicomponent transient flow equations, water hammer equations, and the control equations, such as Joukowsky equation [9]. Based on the transient flow simulation theory, Colombo et al. [10] proposed an aqueducts fault detection technology, Lee et al. [11] proposed the pipe network leak and deterioration over time detection technology by the time domain reflectometry (TDR), Arbon et al. [12] proposed pipeline corrosion and blockage detection technology, Gong et al. [13] proposed a detection technology for pipe friction, wall thickness, velocity, position, and the length of the pipes, and Ferrante et al. [14] presented a leak detection method with coupling wavelet analysis and a Lagrangian model techniques. Meniconi et al. [15] presented a pipe system diagnosis method with the small amplitude sharp pressure waves.

(2) *The Calculation Methods of Hydraulic Transient for Water Hammer.* The calculation methods of hydraulic transient for water hammer include arithmetic method, graphic method, and numerical method.

(i) *Arithmetic Method.* Before the 1930s, the hydraulic transient calculation of water hammer used Allievi equations mostly [16]. Allievi equations can be called Arithmetic method which is used to solve the problems of water hammer that with simple boundary conditions and its workload is very large.

(ii) *Graphic Method.* Graphic method is developed in 1930s to 1960s. Bergeron, Parmakian, and so forth [17] are committed to develop this method. Boundary conditions and the process of water hammer fluctuation are expressed through coordinate graphics of H and V according to this method. Due to the graphics, it is simple and intuitive for the hydraulic transient calculation of water hammer. However, the accuracy is not high because this method is restricted by calculating means and assumptions.

(iii) *Numerical Method.* From 1960s, some numerical methods appeared that can be aided by computers, such as Characteristic (MOC) [18], Wave Characteristic Method (WCM) [19], Implicit Method [20, 21], and Finite Element Method (FEM) [22, 23]. The WCM can solve water hammer problems of complex piping systems and boundary conditions. It is the most common method because of the high accuracy and computing. The Implicit Method divides pipeline into several segments and solves equations of the entire pipeline system simultaneously in each segment. The advantage of Implicit Method can be described in a way that a longer segment is selected and the number of calculations is reduced. However, there is more time needed for calculation in large and complex pipeline network system [24]. FEM with flexibility is used in pipe network system which have complex boundary conditions. However, it has a limitation in solving hydraulic transient problems.

(3) *Water Hammer Protection.* Prevention and controlling means for water hammer are researched with the development of their theory and calculation. Wylie [25–27] has researched several protective devices for water hammer, such as air valves, check valves, pressure tank, and surge tank. Lee [28] and Stephenson [29] discussed the performances of air valves in water hammer protection. However, these researches have not given a quantitative calculation for the problem of water hammer protection.

This paper proposed a water hammer protection method based on velocity adjustment of HCV to deal with the problem of valve-closing water hammer in mine drainage system. The mathematic model of water hammer fluctuations is founded based on MOC according to the hydraulic transient. Then, boundary conditions of water hammer controlling for mine drainage system are determined and the simplex model is established. Finally, the optimization adjustment strategy is solved with simulation and experiment.

The remainder of this paper is organized as follows. Section 2 provides the mathematic model of the propagation and superposition model for water hammer fluctuations. Section 3 provides an optimization method to determine the adjustment strategy for HCV. Section 4 presents a case study. Concluding remarks are offered in the last section of this paper.

2. The Process of Water Hammer Fluctuations

2.1. Mathematic Model

(1) *Foundation Equations.* The momentum equations of transient flow can be expressed as

$$-\frac{1}{g} \frac{\partial V}{\partial t} = \frac{\partial H}{\partial x} + \frac{f}{D} \frac{V^2}{2g} + \frac{\partial}{\partial x} \left(\frac{V^2}{2g} \right), \quad (1)$$

where V is longitudinal mean velocity, H is pressure head, f is friction factor, D is diameter of pipeline, g is gravitational acceleration, x is propagation distance along pipe, and t is time.

The left of the equation represents the time-varying inertia force in a unit volume. In the right, the first item represents the pressure in a unit volume of fluid. The second item is friction loss pressure in a unit length of pipe, and the third item is pressure of transient flow.

The continuity equation is used to describe transient flow and it can be expressed as follows:

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

where a is propagation speed of water hammer wave and θ is the angle between the axis of pipe and the horizontal line.

(2) *The Process of Water Hammer Fluctuations.* Pressures that are caused by friction loss and transient flow velocity are ignored. Furthermore, $V \ll a$ is considered for continuity

equations. Then, the foundation equations can be simplified as

$$\begin{aligned}\frac{\partial H}{\partial x} + \frac{1}{g} \frac{\partial V}{\partial t} &= 0, \\ \frac{\partial H}{\partial t} + \frac{a^2}{g} \frac{\partial V}{\partial x} &= 0.\end{aligned}\quad (3)$$

The second-order partial differential equations about $H(x, t)$ and $V(x, t)$ are obtained through the partial derivative and are taken for variables x and t in (3). Therefore, the momentum equations for water hammer wave in pipeline drainage system are expressed as

$$\begin{aligned}\frac{\partial H^2}{\partial x^2} &= \frac{1}{a^2} \frac{\partial H^2}{\partial t^2}, \\ \frac{\partial V^2}{\partial x^2} &= \frac{1}{a^2} \frac{\partial V^2}{\partial t^2}.\end{aligned}\quad (4)$$

The functions $F(x, t)$ and $f(x, t)$ are introduced along with characteristic lines $dx = \pm dt$. Then, the general solution of (4) can be described as

$$\begin{aligned}H - H_0 &= F\left(t - \frac{x}{a}\right) + f\left(t + \frac{x}{a}\right), \\ V - V_0 &= -\frac{g}{a} \left[F\left(t - \frac{x}{a}\right) - f\left(t + \frac{x}{a}\right) \right],\end{aligned}\quad (5)$$

where H_0 is the initial pressure head, V_0 is the initial flow velocity, and $F(x, t)$ and $f(x, t)$ are direct and reflection fluctuation functions.

2.2. Propagation and Superposition Model of Water Hammer Wave Based on Characteristic Line Method. Pumps and valves are the generating sources of water hammer wave in hydraulic transition process of pipeline fluid delivery system. These two kinds of water hammer wave start at the same time and propagation directions are superimposed. The superposition leads to strengthening of fluctuations for water hammer. In order to control the water hammer pressure effectively, the superposition effects of water hammer wave need to be weakened as much as possible.

The fundamental equations of water hammer can be rewritten as

$$\begin{aligned}L_1 &= g \frac{\partial H}{\partial t} + V \frac{\partial V}{\partial x} + \frac{\partial V}{\partial t} + \frac{fV|V|}{2D} = 0, \\ L_2 &= \frac{\partial H}{\partial t} + V \frac{\partial V}{\partial x} + \frac{a^2}{g} \frac{\partial V}{\partial x} - V \sin \theta = 0.\end{aligned}\quad (6)$$

These equations are combined linearly using an unknown multiplier λ . Let $L = L_1 + \lambda L_2$ be the linear combination. The coefficient λ can be determined by

$$\lambda = \pm \frac{g}{a}. \quad (7)$$

FIGURE 1: Characteristic line grid for water hammer calculation.

In the constraint of characteristic line equation $dx/dt = V \pm a$, (6) converts to ordinary differential equation as follows:

$$\begin{aligned}C^+ &\begin{cases} \frac{dH}{dt} + \frac{a}{g} \frac{dV}{dt} - V \sin \theta + \frac{faV|V|}{2gD} = 0 \\ \frac{dx}{dt} = V + a, \end{cases} \\ C^- &\begin{cases} \frac{dH}{dt} - \frac{a}{g} \frac{dV}{dt} - V \sin \theta - \frac{faV|V|}{2gD} = 0 \\ \frac{dx}{dt} = V - a. \end{cases}\end{aligned}\quad (8)$$

V and $V \sin \theta$ are negligible when $V \ll a$ and the tilt angle of pipeline is less than 25° . The average flow velocity V is replaced by flow Q . The characteristic equations are changed into

$$\begin{aligned}C^+ &\begin{cases} \frac{dH}{dt} + \frac{a}{gA} \frac{dQ}{dt} + \frac{faQ|Q|}{2gDA^2} = 0 \\ \frac{dx}{dt} = +a, \end{cases} \\ C^- &\begin{cases} -\frac{dH}{dt} + \frac{a}{gA} \frac{dQ}{dt} + \frac{faQ|Q|}{2gDA^2} = 0 \\ \frac{dx}{dt} = -a, \end{cases}\end{aligned}\quad (9)$$

where C^+ is the characteristic line of forward wave in x -axis, C^- is the characteristic line of reflected wave in x -axis, and A is cross-sectional area of pipe.

The integral operation and differential conversion are introduced to (9). The discrete characteristic equations of water hammer are obtained as follows. Equation (10) and the characteristic line grid are shown in Figure 1:

$$\begin{aligned}H_P - H_A + \frac{a}{gA} (Q_P - Q_A) + \frac{f\Delta x Q_A |Q_A|}{2gDA^2} &= 0, \\ H_P - H_B + \frac{a}{gA} (Q_P - Q_B) + \frac{f\Delta x Q_B |Q_B|}{2gDA^2} &= 0.\end{aligned}\quad (10)$$

By solving the above equations, transient variables H_P and Q_P in the node i of the pipe over the time Δt are expressed as

$$\begin{aligned} H_P &= \frac{(C_P + C_M)}{2}, \\ Q_P &= \frac{(C_P - H_P)}{B}, \end{aligned} \quad (11)$$

where $B = a/gA$.

Consider

$$\begin{aligned} C_P &= H_A + BQ_A - \frac{f\Delta x}{2gDA^2} Q_A |Q_A|, \\ C_M &= H_B - BQ_A - \frac{f\Delta x}{2gDA^2} Q_B |Q_B|. \end{aligned} \quad (12)$$

The initial condition of water hammer is that of a steady flow, C_P and C_M in (11) are known, and the parameters on each time step can be solved.

Hydraulic characteristics of HCV can be described through loss coefficient ξ and capacity coefficient C . Consider

$$\begin{aligned} Q_f &= \frac{A}{\sqrt{\xi}} \sqrt{2g\Delta H_f}, \\ Q_f &= C\sqrt{\Delta H_f}, \end{aligned} \quad (13)$$

where A is cross-sectional area of the upstream of HCV and ΔH_f is the pressure difference of HCV in upper and lower.

Let $\tau = (C/C_0)(\tau = \sqrt{\xi_0/\xi})$ be the relative opening displacement of HCV. The dimensionless flow through HCV can be described as

$$q_f = \frac{Q_f}{Q_{f0}} = \tau \sqrt{\Delta h_f}, \quad (14)$$

where Δh_f is pressure difference on HCV. It can be solved as $\Delta H_f/\Delta H_{f0}$. The subscript "0" represents HCV being open completely.

3. Optimization Method for Velocity Adjustment of HCV

3.1. Boundary Conditions. Boundary conditions for pump of outlet are shown in Figure 2. If the inlet loss of pump is ignored, the inlet of pool, pump, and HCV can be combined and dealt with as a boundary of characteristic line in foundational equations of water hammer.

The equilibrium condition for water head is established in this boundary. It can be described as

$$H_f + H - H_l = H_p, \quad (15)$$

where H_f is the depth of pool inlet, H is the work lift of the pump, H_l is the transient resistance loss of HCV, and H_p is the pressure head of HCV outlet.

We take the balance equations of water head which in the characteristic line C^- and inertia equations of pump unit

FIGURE 2: Boundary conditions of pump outlet.

together. And then the boundary conditions can be expressed as follows based on the characteristic lines of pumps:

$$\begin{aligned} x &= \pi + \arctan \frac{q}{\alpha}, \\ WH(x) &= \frac{h}{\alpha^2 + q^2}, \\ WB(x) &= \frac{\beta}{\alpha^2 + q^2}, \end{aligned} \quad (16)$$

where the pump-lift is $h = H/H_R$. The flow of pump is $q = Q/Q_R$. The rotational speed is $\alpha = n/n_R$. The torque is $\beta = T/T_R$. The subscript represents rated working conditions. Then, (16) is generated as follows:

$$\begin{aligned} F_1 &= H_j - C_M - BQ_R q + H_R (\alpha^2 + q^2) WH(x) \\ &\quad - \frac{H_{f0} q |q|}{\tau^2} = 0, \\ F_2 &= (\alpha^2 + q^2) WB(x) + \beta_0 - K_1 (\alpha_0 - \alpha) = 0, \end{aligned} \quad (17)$$

where $K_1 = 2Kn_R/T_R$; $K = \pi GD^2/120g$; and GD^2 is rotational inertia. α_0 and β_0 are rotational speed and torque in the initial state. Then, (17) can be rewritten as follows when variables α and q are introduced:

$$\begin{aligned} F_1 + F_{1q}\Delta q + F_{1\alpha}\Delta\alpha &= 0, \\ F_2 + F_{2q}\Delta q + F_{2\alpha}\Delta\alpha &= 0. \end{aligned} \quad (18)$$

The problem is solved as follows:

$$\begin{aligned} \alpha^{(k+1)} &= \alpha^{(k)} + \Delta\alpha, \\ q^{(k+1)} &= q^{(k)} + \Delta q, \end{aligned} \quad (19)$$

in which $\Delta\alpha$ and Δq are solved through (18).

The iterative errors should meet (19). Consider

$$|\Delta\alpha| + |\Delta q| \leq \varepsilon \quad (\varepsilon = 0.0002). \quad (20)$$

3.2. Optimization Method of HCV Adjustment. The boundary conditions of multistage valve-closing are introduced in the characteristic line calculation of water hammer for which

the best procedure for multistage valve-closing is considered. The displacement of valve-closing at any time can be determined through linear procedure in multistage valve closure.

Through a large number of practical tests, the valve closure with a uniform or uniform variable speed is found to have a small influence on the water hammer in the front 2/3 of valve-closing stroke, while there is a large influence on the later 1/3 of valve-closing stroke. Therefore, the valve closure process is divided into multistage. By doing so, the

uniform and uniform variable speeds are both introduced to valve closure process. In the following section we will discuss uniform or uniform variable speed calculation method in valve closure process.

Assuming that the times of valve-closing in multi-stage are $T_1, T_2, \dots, T_i, \dots, T_n$, the corresponding displacements of valve-closing are $s_1, s_2, \dots, s_i, \dots, s_n$. Then, the displacements of valve-closing at any time t are determined as follows:

$$s_i = \begin{cases} \frac{s_1}{T_1} & t \leq T_1, \text{ The 1st stage of valve-closing} \\ s_1 + \frac{s_2}{T_2} (t - T_1) & T_1 \leq t \leq T_1 + T_2, \text{ The 2nd stage of valve-closing} \\ s_1 + s_2 + \dots + s_{i-1} + \frac{s_i}{T_i} (t - T_{i-1}) & T_1 + T_2 + \dots + T_{i-1} \leq t \leq T_1 + T_2 + \dots + T_i, \text{ The } i \text{ stage of valve-closing} \\ s_1 + s_2 + \dots + s_i + \dots + \frac{s_n}{T_n} (t - T_{n-1}) & T_1 + T_2 + \dots + T_i + \dots + T_{n-1} \leq t \leq T_1 + T_2 + \dots + T_i + \dots + T_n, \text{ The } n \text{ stage of valve-closing} \\ s_1 + s_2 + \dots + s_i + s_n = S & t > T_1 + T_2 + \dots + T_i + T_n, \text{ valve-closing is completed,} \end{cases} \quad (21)$$

where s_i is displacement of valve-closing at t and S is the total stroke of valve-closing.

For the valve-closing displacement s_i at any time t , we can calculate the dimensionless opening degree τ using (21) through linear interpolation according to equidistant Δs_i and its input value:

$$\begin{aligned} \tau &= \tau(i) + \frac{u^{(k)}}{2} [\tau(i+1) - k\tau(i)] \tau(i) \\ &\quad + \frac{u^{(k-1)}}{2} [\tau(i+1) - (k-1)\tau(i)] + \dots \\ &\quad + \frac{u^2}{2} [\tau(i+1) - 2\tau(i)] \\ &\quad + \frac{u}{2} [\tau(i+1) - \tau(i)], \end{aligned} \quad (22)$$

$$u = \frac{s_i - s_0}{\Delta s_i} - 1.$$

In the scope of velocity adjustment for HCV, the velocity, displacement, and time of valve-closing have various combinations. This paper adopts a multistage adjustment strategy according to simulation results of water hammer.

The valve closure time for the first stage is equal or close to the time of the flow of pump that is zero. The valve closure time for the following stages is one in four of the previous stage. Consequently, the initial valve closure procedure is determined. Then, search computing is taken to determine the optimization valve closure procedure.

4. Case Study and Experiment

4.1. Working Conditions. The mine with normal water quality was considered. The water normal inflow was $50 \text{ m}^3/\text{h}$ and the maximum inflow was $250 \text{ m}^3/\text{h}$. Water was discharged into

ground by two drain pipes of which the specifications were $D273 \times 12$, respectively (one was used and another was spare). The pipes in this existing and antiquated mine drainage system were seamless steel pipe. The allowed pressure was as lower at 6.4 MPa. The wellhead elevation was 997.991 m and the borehole inclination was 20° . There were three multistage centrifugal pumps and two HCVs were used in Figure 3. And the specification of pumps was MD280-65 $\times$ 6 ($Q = 280 \text{ m}^3/\text{h}$, $H = 390 \text{ m}$). One pump was used and others were maintenance when the mine was with a normal inflow, or two pumps were used and one was spare when the mine was with a maximum inflow.

The automatic drainage system was chosen in this mine. Check valves were installed in pump outlet. There are HCVs in pipeline shown in Figure 3(a) where the stroke was 220 mm with the structure of HCV shown in Figure 4. During normal pump stopping, HCVs were closed first, and then pumps were stopped. The water hammer phenomenon was significant in drains pipeline during this process. Therefore, we should take some measures to prevent the water hammer phenomenon.

4.2. Simulations. An algorithm was developed using commercial simulation software Fluent6.3 based on the water hammer theory described in Section 2. The acceleration, amplitude, pipeline pressure, and valve closure displacement were obtained in the cases of uniform and uniform variable speed through transient simulation for water hammer. The correctness of simulation and the proposed theory were then verified against experimental results. We simulated the valve-closing in single-stage with a constant velocity and in multistage with a variable velocity based on the proposed theory.

(1) *The Simulation of Valve-Closing in Single-Stage with a Constant Velocity.* The velocity $v = 0.01 \text{ m/s}$ of valve-closing in single-stage was determined through repeated simulation.

FIGURE 3: Diagram of drain pipes.

- (1) Hydraulic system
- (2) Explosion-proof motors
- (3) Valve body

FIGURE 4: Structure diagram of HCV.

Then, times of equipment in this situation were obtained using (20) to (21) as shown in Table 1.

The simulation results of valve-closing parameters in single-stage with 0.01 m/s are shown in Figures 5–12.

For Figures 5–12, the static pressure of pipeline was at 3.06 MPa for pump stopping. After the vacuum was completed, the pump was started and HCV was open with a constant velocity. At this moment, pipeline pressure was increased along with the valve-opening displacement of HCV. Then, pressure fluctuations appeared. The valve-opening displacement of HCV was 42.6 mm and the maximum pressure was 3.84 MPa when $t = 12.148$ s. After this moment, the pressure was steady. The valve-opening displacement of HCV was 70.2 mm and the maximum pressure was 3.25 MPa when $t = 15.244$ s. The drainage system pressure reached a steady state along with the increasing of valve-opening displacement. The pressure of pipeline began to drop when $t = 62.436$ s and valve-closing displacement was 53.4 mm. Water hammer phenomenon appeared when $t = 67.211$ s. When $t = 70.6$ s, the maximum boost of water hammer was $\Delta H = 152$ m and the pressure of pipeline at this moment

FIGURE 5: Acceleration in x . FIGURE 6: Amplitude in x .

was 4.77 Mpa. It is 1.47 times the normal discharge pressure (3.25 MPa) and the pressure increased by 50% suddenly. The acceleration and amplitude of pipeline in directions of x , y , and z were changed significantly when water hammer occurred. Maximum acceleration in directions of x , y , and z was 4.83 m/s^2 , 6.46 m/s^2 , and 5.45 m/s^2 and the maximum amplitude was 15.8 mm, 25.8 mm, and 15.3 mm, respectively. Additionally, the total stroke of HCV was assumed to be S . Valve-closing with rapid and constant velocity were taken

TABLE 1: Times of equipment in single-stage valve-closing.

Equipment actions	Pump start	Valve-opening	Full open	Valve-closing	Valve closed	Water hammer finished	Total times
Times t (s)	4.128	7.883	31.590	46.007	67.934	110.500	21.927

FIGURE 7: Acceleration in y . FIGURE 10: Amplitude in z . FIGURE 8: Amplitude in y .

FIGURE 11: Pressure in pipeline.

FIGURE 9: Acceleration in z .

FIGURE 12: Amplitude of HCV.

FIGURE 13: Acceleration in x . FIGURE 14: Amplitude in x .

in the former 2S/3 and a variable velocity was taken in the latter S/3 according to the simulation results of valve-closing water hammer. Due to the velocity of valve-closing that has a large impact on water hammer parameters, it is an effective approach to protect water hammer by choosing a reasonable velocity for valve-closing.

The allowed pressure of pipe is lower and its value was 6.4 MPa. However, the pressure of pipeline reached 4.8 MPa in the case of 22 s valve-closing from the above analysis. This value is near to the allowed pressure of pipe with the pressure being not high, and the water hammer phenomenon was not significant compared with other mine drainage systems. In order to reduce the pressure of pipeline to protection pipeline, it is necessary to develop water hammer protection.

(2) *The Simulation of Valve-Closing in Multistage with a Variable Velocity.* The optimization strategy of valve-closing adjustment for HCV is generated using boundary conditions according to optimization method of valve-closing adjustment that is proposed in this paper. It is a multistage valve-closing with a variable velocity. In the front 2/3 of valve-closing stroke, the velocity is constant and its value is 0.01 m/s. In the later 1/3 of valve-closing stroke, the velocity is a variable (the deceleration is constant) and the initial value is 0.01 m/s. The total time of valve-closing is 43.823 s. Times of equipment in multistage valve-closing are shown in Table 2.

The simulation results of valve-closing parameters in multistage are shown in Figures 13–20.

The pipeline pressuring, acceleration, and amplitude in the directions of x , y , and z are significantly reduced in multistage valve-closing with a variable velocity. Valve-closing with a constant velocity is started at 46.007 s, and valve-closing with a variable velocity is started at 60.6 s. The HCVs are closed and pumps are stopped at 89.83 s. In this process, the maximum pressure of water hammer is 3.49 MPa. No effect of water hammer occurred under this situation.

4.3. Experiments. The experimental devices include multifunction data acquisition instrument, vibration sensor, pressure sensors, and cable displacement encoder. Multifunction

FIGURE 15: Acceleration in y .

data acquisition instrument has 16 channels and its acquisition frequency is 102.4 kHz. Data of acceleration, amplitude, flow, pressure, and displacement of valve-closing were acquired by this multifunction data acquisition instrument. Vibration sensor was used to measure piping vibration under the influence of water hammer. It was disposed along with the x , y , and z direction of the pipe. Pressure sensors were used to measure pipeline pressure. Its measurement accuracy and range are 0–10 MPa and ± 0.5 FS. Cable displacement encoder was used to posit the displacement of valve-closing. The arrangement diagram of sensors and flow chart of pumps are shown in Figures 21 and 22.

HCVs control system was designed in this experiment which is shown in Figure 23. Sensors were used to collect signals of pressure and acceleration in pipeline. PLC unit was used to analyze pipeline pressure and vibration for water hammer on the basis of pressure and acceleration signals. An expected running speed was given to HCVs. And then, voltage, current, power, and fault protection information of pumps, pressure, flow, temperature, vacuum, and HCVs status information were monitored at real time. These multi-parameter data were integrated using of fuzzy control theory with calculus and control strategy. The HCVs control system

TABLE 2: Times of equipment in multistage valve-closing.

Equipment actions	Pump start	Valve-opening	Full open	Valve-closing	Valve closed	Water hammer finished	Total times
Times t (s)	4.128	8.5	39.504	46.007	89.830	128.816	43.823

FIGURE 16: Amplitude in y .

FIGURE 19: Pressure in pipeline.

FIGURE 17: Acceleration in z .

FIGURE 20: Displacement of HCV.

FIGURE 18: Amplitude in z .

can control starting and stopping of pumps automatically and can monitor the signals in system running process timely.

For the total stroke of valve S , the experimental conditions are as follows. In the front $2/3$ of the stroke, the velocity was constant and its value was 0.01 m/s. In the later $1/3$, the velocity is variable (the deceleration is constant) and the initial value was 0.01 m/s. The full valve-closing times were 44 s. Measured values of water hammer parameters in multistage are shown in Table 3.

FIGURE 21: Arrangement diagram of sensors.

FIGURE 22: The flow chart of test for pumps.

FIGURE 23: Composition of HCVs control system.

TABLE 3: Measured values of water hammer parameters.

Measured parameters	Acceleration (m/s ²)			Displacement (mm)			Pressure <i>P</i> (Mpa)
	<i>a</i> (<i>x</i>)	<i>a</i> (<i>y</i>)	<i>a</i> (<i>z</i>)	<i>S</i> (<i>x</i>)	<i>S</i> (<i>y</i>)	<i>S</i> (<i>z</i>)	
Valve-closing times (s)							
22	4.8308	6.4582	5.4457	15.7662	28.5192	15.3051	4.5865
25	4.8207	6.4581	5.4453	15.7515	28.5139	15.3012	4.5564
28	4.7986	6.3215	5.4394	15.7495	28.4632	15.2036	4.4952
31	4.5689	6.1265	5.2563	13.6938	26.8576	13.0369	4.4678
33	4.5389	6.1063	5.1935	13.5963	24.6985	12.6325	4.4612
36	4.3236	5.9638	5.0632	12.6985	23.8965	11.7652	4.2675
39	1.7231	1.1023	1.6352	9.2514	6.3656	11.3251	3.5615
42	1.7016	1.0363	1.5426	9.0356	6.1563	10.9968	3.5423
44	1.6987	0.8692	1.4112	8.9482	5.9354	10.6432	3.5006
48	1.6886	0.8629	1.4003	8.9235	5.9139	10.6365	3.5006

5. Results and Discussion

The reliability and effectiveness are illustrated through the comparison between the results of simulation and experiment.

(1) *Results of Valve-Closing in Single-Stage with a Constant Velocity and in Multistage with a Variable Velocity Are Compared.* Pipeline pressures and displacements of valve-opening under these two conditions are shown in Figures 24 and 25, respectively. The red curves represent the variations in single-stage with a constant velocity while the black curves represent the variations for multistage with a variable velocity.

Figures 24 and 25 show a significant water hammer effect in single-stage valve-closing with a constant velocity, and the valve-closing time is shorter (22 s). On the other hand, water hammer phenomenon was found to be considerably improved for multistage valve-closing condition with a variable velocity and the valve-closing time was extended (44 s). It shows that valve-closing in multistage with a variable velocity can control the water hammer phenomenon effective in mine drainage system.

(2) *Results of the Simulation and Experiment Are Also Compared.* Results for valve-closing with a variable velocity are shown in Table 4.

FIGURE 24: Pressure in pipeline.

It can be seen from Table 4 that the simulation for valve-closing with a variable velocity shows good agreement with the experiment. The errors between simulation and experiment are less than 5%. Therefore, the valve-closing in

TABLE 4: Results comparison of simulation and experiment.

Parameters	Max acceleration (m/s^2)			Max displacement (mm)			Max pressure
	$a(x)$	$a(y)$	$a(z)$	$S(x)$	$S(y)$	$S(z)$	P (Mpa)
Simulation	4.5830	6.2672	5.2341	16.5122	27.3335	14.8726	4.5798
Experiment	4.8308	6.4582	5.4457	15.7660	28.5192	15.3051	4.5867
Errors	4.6%	2.9%	3.9%	4.7%	4.2%	2.8%	0.2%
Simulation	1.6876	0.8446	1.3651	8.6395	5.6689	10.4653	3.4901
Experiment	1.6987	0.8692	1.4112	8.9482	5.9354	10.6432	3.5006
Errors	0.7%	2.8%	3.3%	3.4%	4.4%	1.7%	0.3%

FIGURE 25: Displacement of HCV.

multistage with a variable velocity can reduce the impact from water hammer in mine drainage system.

6. Conclusions and Future Work

Limited space and high cost of equipment changing are the main characteristics for mine drainage system. For the problem of valve-closing water hammer protection in mine drainage system, this paper proposed a protection method based on velocity adjustment of HCVs. The mathematic model of valve-closing water hammer is established based on fundamental equations. The strategy of valve-closing in multistage with a variable velocity is obtained by velocity adjustment strategy of HCVs, and it is effective in protecting the valve-closing water hammer without change piping arrangement or addition equipment. The results of simulations and experiments in different adjustment velocity are compared. We obtained that the water hammer phenomenon is not obvious with valve-closing velocity in the front 2/3 of its stroke, and it is very seriously within the later 1/3. Therefore, we take a two-stage valve-closing strategy. In the first stage, the velocity is constant and its value is 0.01 m/s. In the second stage, the velocity is variable (the deceleration is constant) and the initial value is 0.01 m/s.

Extending errors in the theoretical wave speed have an important influence on prediction of the closure rate

before a water hammer occurs in the actual pipeline. A very challenging mathematical task is variable. This is beyond the scope of this paper and may be considered as a future work.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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