Study on Water Hammer Protection of Accumulator for High Pressure Water Descaling System

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Abstract. Use characteristic linear method to establish the general mathematical model of the protection calculation of accumulator from water hammer in high pressure water descaling system pipeline. Through the model, the paper calculated the change of transient water hammer pressure in the main pipe under 3 different conditions: with and without accumulator, different accumulator capacity and different accumulator installing positions. The calculation results show that the pressure fluctuation of the main pipe changes with the descaling procedure; the accumulator provides obvious protective effect on the water hammer of the high pressure water descaling system and the initial volume of the accumulator has an obvious influence on the water pressure changes while the installation positions on the main pipe is with little influence on the protection effect of the accumulator.

1. Introduction
High pressure water descaling system is an important system in hot rolling project which is to transport high pressure water to each descaling point through pipeline, and remove furnace scale iron oxide and rolling process generated iron oxide. Iron oxide on the surface of the rolled piece is stripped and washed away by the impact force of high pressure water on the slab surface. Due to the continuous passage of the slab, the descaling valve has a periodic on and off, therefore, water hammer and pipeline vibration often occur in descaling pipeline, which will cause damage to pipeline and its accessories and threaten the safe operation of high pressure water descaling system in serious situation. So it is necessary to calculate and analyze the water hammer phenomena that may occur in high pressure water descaling system, and put forward reasonable water hammer protection measures in the design, and in-time control the impact of water hammer in the operation process to ensure the stable and safe operation of the descaling system.

The Characteristic Linear Method is a classic method for solving the water hammer problem[1-3]. The combination of the characteristic line method and computer technology greatly promotes the application of this method in water hammer calculation. Domestic experts have made many achievements in the research and successfully solved some water hammer problems in industrial and agricultural field[4-6]. Aiming at the problem of water hammer in high pressure water descaling system, a mathematical model with complex boundary conditions such as accumulator is established, and combines engineering experience to carry out calculations and analyzes the accumulator protection of water hammer the in detail.
2. Characteristic linear method for water hammer calculation

The water hammer change process of high pressure water descaling system with injection valve opening and closing complies with the basic differential equations of unstable flow, and its form is:

Kinematic equation:

$$\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} + g \frac{\partial H}{\partial x} + \frac{V |V|}{2D} = 0$$  \hspace{1cm} (1)

Continuity equation:

$$\frac{\partial H}{\partial t} + V \frac{\partial H}{\partial x} - V \sin \alpha + \frac{a^2 \partial V}{g} = 0$$  \hspace{1cm} (2)

In the equation, \(H\) is the head in the pipeline; \(V\) is the flow velocity in the pipeline; \(f\) is the friction coefficient of the pipeline; \(a\) is the velocity of water hammer wave propagation; \(g\) is the acceleration of gravity; 
\(D\) is the diameter of the pipeline, \(t\) is the time; \(x\) is the distance calculated from the left end of the pipeline; and \(\alpha\) is the angle between the pipeline and the horizontal plane.

Simplify and deduct the kinematic equation and continuity equation into characteristic linear equations to program:

\[ C_+ : \quad H_p = C_p - BQ_p \]  \hspace{1cm} (3)

\[ C_- : \quad H_p = C_M + BQ_p \]  \hspace{1cm} (4)

\[ C_p = H_A + BQ_A - R |Q_A| Q_A \]  \hspace{1cm} (5)

\[ C_M = H_B + BQ_B + R |Q_B| Q_B \]  \hspace{1cm} (6)

In the formula, \(C_+\) and \(C_-\) are characteristic lines; \(B=al/gA\) is the characteristic pipeline constant; and \(R= f \Delta x/2gDA^2\) is the pipeline friction characteristic constant; \(H_p\) and \(Q_p\) respectively represent the head and flow of node \(i\) at time \(t\); \(H_A\) and \(Q_A\) respectively represent the head and flow of node \(i-1\) at time \(t-\Delta t\); \(H_B\) and \(Q_B\) are the head and flow at node \(i+1\) at time \(t+\Delta t\) respectively; the integrated parameters \(C_p\) and \(C_M\) can be calculated first at each calculation period; \(A\) is the pipeline section area; \(a\) is the velocity of water hammer wave. From the equations (3) and (4), the values of \(H_p\) and \(Q_p\) at the nodes in the middle of the descaling water supply pipe can be obtained.

3. Boundary Node Equation for Water Hammer Calculation in High Pressure Water Descaling System

3.1 Boundary Node Equation of Descaling Pump

In the high pressure water descaling system, the descaling pump is located in the upstream. Since the billet continuously passes, the descaling pump works without interruption under normal conditions. So the upstream boundary condition is defined by the \(Q-H\) curve of the centrifugal pump. Generally, the performance curve of the pump can be approximated by parabolic formula.

$$H_p = A_0 + A_1 Q_p + A_2 Q_p^2$$  \hspace{1cm} (7)

In the formula, \(H_p\) is the outlet head of descaling pump; \(Q_p\) is the outlet flow of descaling pump; \(A_0, A_1\) and \(A_2\) are parabolic equation coefficients. Combine parabolic equation (7) and the characteristic threaded formula (4) can produce:

$$Q_p = \frac{1}{2A_1} \left[ B - A_1 - \sqrt{(B-A_1)^2 + 4A_2(C_M - A_0)} \right]$$  \hspace{1cm} (8)

3.2 Boundary Node Equation of Injection Valve

In the case of steady flow, the flow through the descaling injection valve is as follows

$$Q_0 = (C_d A_g)_0 \sqrt{2gH_0}$$  \hspace{1cm} (9)

The injection valve is opened and closed according to the rolling sequence, and the flow rate of the injection valve at certain open degree is:
Formulas (9) and (10) are used to relate transient state and initial state flow:

\[ Q_{PNS} = C_d A_g \sqrt{2gH_{PNS}} \]  

(10)

Formulas (9) and (10) are used to relate transient state and initial state flow:

\[ Q_{PNS} = \frac{Q_0}{\sqrt{H_0}} \tau \sqrt{H_{PNS}} \]  

(11)

\[ H_{PNS} = H_N - B(Q_{PNS} - H_N) - R_k Q_N | Q_N | \]  

(12)

\[ Q_{PNS} = -BC_V + \sqrt{(BC_V)^2 + 2C_V C_p} \]  

(13)

\[ H_{PNS} = C_p - BQ_{PNS} \]  

(14)

\[ C_p = H_N + BQ_N - R_k | Q_N | \]  

(15)

\[ C_v = \frac{\tau^2 Q_{A}^2}{2H_0}, \quad \tau = \frac{C_d A_g}{(C_d A_g)_0} \]

In the equation, \( C_v \) is constant, \( \tau \) is dimensionless opening coefficient at the valve. \( Q_{PNS} \) and \( H_{PNS} \) are flow rate and head at the injection valve; \( C_d \) is orifice-metering coefficient of the injection valve; \( A_g \) is the open flow area of the injection valve; \( H_0 \) is the head in front of the injection valve in stable flow. Equations (14) and (15) are used to calculate the head and flow of the injection valve.

3.3 Boundary Node Equation of Accumulator

Normally, the pressure of accumulator varies between the highest and lowest working pressures so the accumulator shut-off valve is usually open and only closed at the lowest pressure. Therefore, the accumulator can be simplified as being always open, and omit the pipe length between accumulator and main pipe. The total volume of accumulator is the sum of water space volume and air space volume in which the volume of water depends on the water supply capacity of the descaling pump while the volume of air is the initial volume of accumulator.

For the accumulator, assume the gas in accumulator as ideal gas and comply with ideal gas state equation. Compared with the compressibility of gas, the elasticity of liquid and solid container walls can be neglected and gas compressibility in the accumulator is subject to a variable process:

\[ H_A V^n = C \]  

(16)

\[ H_A = H_p - kQ_{P3} - Z + H_b \]  

(17)

\[ \frac{dZ}{dt} = \frac{1}{A_c} Q_{P3} \]  

(18)

\[ Q_{P3} = Q_{P1,NS} - Q_{P2,1} \]  

(19)

\[ H_p = H_{P1,NS} = H_{P2,1} \]  

(20)

\[ H_{P1,NS} = C_p - B_1 Q_{P1,NS} \]  

(21)

\[ H_{P2,1} = C_{M2} + B_2 Q_{P2,1} \]  

(22)

In the formula. \( H_A \) is the gas pressure in the accumulator; \( V \) is the volume of gas in the accumulator; \( n \) is \( 1.2 \), which is the variable index of the gas state equation; \( C \) is the constant related to the initial state of gas in the accumulator; \( H_P \) is the pressure at the pipeline node; \( Q_{P3} \) is the flow into the accumulator; \( k \) is the local loss coefficient of local resistance; \( Z \) is the water level in the accumulator; \( H_b \) is atmospheric pressure; \( A_c \) is the accumulator cross-section area; \( Q_{P1,NS} \) is the upstream node flow of the accumulator; \( Q_{P2,1} \) is the downstream node flow of the accumulator.
The flow rate and head of accumulator can be calculated by the united formula (16) ~ (22), and the changes of gas volume, pressure and water level in accumulator can also be calculated.

3.4 Boundary Node Equation of Complex Pipeline in High Pressure Water Descaling System

In the actual high pressure water descaling system, the pipelines are usually with different pipe diameters, wall thicknesses and different materials connected through different pipe fittings. Each pipe is regarded as a basic calculation unit, and the calculation of water hammer at the internal and boundary nodes of pipelines is relatively independent. In order to solve the water hammer calculation of pipelines with different properties, besides the characteristic linear equation, the head at the boundary node of the pipeline should be approximated as equal, and the corresponding boundary condition equation should be established in conjunction with the continuity equation.

3.4.1 Boundary Node Equation of Tee Pipe Fittings. Regarded as the joints of branch pipelines, the local resistance at tee joints of pipelines is usually omitted. The corresponding boundary condition equations are established by combining the continuity equation as follows:

\[ H_p = H_{P1,NS} = H_{P2,1} = H_{P3,1} \] (23)

\[ Q_p = Q_{P2,1} + Q_{P3,1} \] (24)

The characteristic linear equations of boundary nodes along C+ and C- are established for each pipeline respectively:

\[ Q_{P1,NS} = \frac{1}{B_1} \left( C_{P1} - H_{P1,NS} \right) \] (25)

\[ Q_{P2,1} = \frac{1}{B_2} \left( H_{P2,1} - C_{m2} \right) \] (26)

\[ Q_{P3,1} = \frac{1}{B_3} \left( H_{P3,1} - C_{m3} \right) \] (27)

By combining the above 5 equations, we can get:

\[ H_p = \frac{C_{P1} + C_{m2} + C_{m3}}{B_1 + B_2 + B_3} \] (28)

After \( H_p \) is solved, the flow rate of the pipe at the connection point is calculated according to the formulas (25), (26) and (27).

3.4.2 Boundary Node Equation for Elbow and Reducer. In the system, there are branch pipes with different diameters in series. Omit the local resistance loss of the joint at the pipeline connection, so the joint head at the pipeline connection is equal, and the elbow is calculated according to the same diameter in series. From the continuity equation and water head condition, it can be obtained that:

\[ Q_{P1,NS} = Q_{P2,1} \] (29)

\[ H_{P1,NS} = H_{P2,1} \] (30)

The above two equations combined with the characteristic linear equation can obtain the following equation:

\[ Q_p = \frac{C_{P1} - C_{M2}}{B_1 + B_2} \] (31)
4. Case Analysis

4.1 Case Basic Information

A simplified model of high pressure water descaling finish rolling system in a steel plant is shown in Figure 1, which consists of descaling pumps, accumulator and injection valve group. Two descaling pumps operate in parallel with the rated flow rate Q of 420 m$^3$/h and the rated outlet pressure H of 15.5 MPa. The parabolic equation of the descaling pump $Q-H$ curve is

$$H_p = \frac{B_2 C_{pl} + B_1 C_{M2}}{B_1 + B_2}, \quad (32)$$

The accumulator has an initial volume of 7 m$^3$ and is located downstream the main pipe at position B. The 4 injection valves have the same time order in one descaling cycle. As shown in Table 1, the flow rate of the injection valves are 259.2 m$^3$/h, 259.2 m$^3$/h, 164.4 m$^3$/h and 96.6 m$^3$/h respectively, and the on opening and closing is 2 s. The wave speed of the main pipe and the pump branch pipe is 1307 m/s, and 1339 m/s for the valve branch pipe. Specific data are shown in Table 2. A mathematical model is established by using the characteristic linear equation and boundary conditions to calculate and analyze the transient pressure change of pipeline caused by the opening and closing of injection valve in high pressure water descaling system.

| Injection valve | Open time /s | Close time /s | Open time /s | Close time /s | Open time /s | Close time /s |
|----------------|--------------|---------------|--------------|---------------|--------------|---------------|
| 0              | 77           | 87            | 164          | 174           | 251          |

| pipe length /m | pipe diameter /mm | The number of pipes | resistance coefficient |
|----------------|-------------------|---------------------|-----------------------|
| Main pipe      | 200               | 200                 | 1                     | 0.02                   |
| pump branch pipe | 50              | 200                 | 2                     | 0.02                   |
| valve branch pipe | 20            | 150                 | 4                     | 0.02                   |

4.2 Calculation Results and Analysis

When the accumulator cut-off valve is closed (Fig. 2), with the switch of descaling valve, pipeline pressure fluctuates violently in the form of "square wave". The pressure fluctuation range is large and the period is short, and serious water hammer will occur in the first few seconds of valve closure. Under
the same working conditions, but with the accumulator into normal operation, the pipeline pressure fluctuates in the form of “serration”, and the pressure changes slowly, which will not produce high water hammer pressure. The accumulator has a significant protective effect on water hammer.

The influence of the initial volume of accumulator on the pressure change of main pipe is shown in Figure 3. When the parameters of high pressure water descaling system are fixed and the accumulator installation position is the same, the accumulator with larger initial volume can more effectively control the water hammer. While the initial volume is small, the fluctuation of main pipe pressure grows larger with steep peak and gentle trough. The head difference between the two peaks is up to 160m. It indicates that increasing accumulator volume in high pressure water descaling system can effectively reduce water hammer pressure and improve the protection performance of the whole system. But in the actual system, the volume of accumulator is affected by economic and spatial factors.

The protective effect of accumulator installed at different position of A and B is shown in Fig. 4. The protective effect of accumulator installed at B is slightly better than A, but there is no significant difference in eliminating the effect of water hammer. Because the pipeline system of high pressure water descaling system is short and the installation position of accumulator on main pipe is limited, the effect of different installation position of accumulator on eliminating water hammer is not obvious.

Fig. 2 The main pipe pressure variation without/ with accumulator

Fig. 3 Variation of main pipe for accumulator in different initial air volume
5. Conclusion
In the high pressure water descaling pipeline system, the water hammer problem in the periodic operation of descaling rhythm is caused by the frequent switch of the injection valve. Aiming at the problem of water hammer in high pressure water descaling pipeline system, a complex model for calculating water hammer in high pressure water descaling pipeline and a general mathematical model for accumulator boundary conditions are established, and the characteristics of accumulator protection against water hammer are simulated and analyzed by taking practical engineering experience as an example. This paper draws the following conclusions:

1) In high pressure water descaling system, accumulator can effectively protect pipeline from water hammer damage caused by frequent opening and closing of descaling injection valve.
2) The larger the initial volume of accumulator, the more effective it will be to prevent water hammer.
3) In the high pressure water descaling system with short pipeline and high pressure, the influence of accumulator installation position on eliminating water hammer pressure fluctuation is not obvious.

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