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Corrosion Study at Elbow Under Different Steam Parameters

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Abstract: In order to study the influence of steam on pipeline corrosion during the transportation of heating pipeline, the three-dimensional elbow model is established by using Fluent numerical simulation method, and the steam condensation is studied from the three aspects of steam flow rate, temperature and pressure change, and the influence on corrosion is further explored through the reaction of condensate droplets and iron ions on the pipe wall. The results show that Steam flow rate, temperature, and pressure on the role of corrosion will be affected by the amount of condensate; pipe wall in the reaction between iron ions and condensate droplets, iron ions into the condensate leads to an increase in the concentration difference between steam and droplets of iron ions, in the role of concentration differences in the condensate ions into the steam, steam entrained with iron ions out of the elbow, resulting in the elbow is corroded. The greater the amount of condensate, the more dissolvable iron ions, the greater the concentration difference between steam and condensate droplets of iron ions, the greater the degree of corrosion on the pipe wall and thus lead to. Through simulation and thesis data collection reference literature data comparison can be seen in the pipe network should control the inflow of steam temperature, pressure control at 200℃ and 0.6 MPa or so, control the control valve opening degree control appropriate, will control the flow rate at 30m / s, when the elbow corrosion of the pipeline minimum.

Key words: steam; Numerical simulation; Elbow; Condensing water quantity; Speed; Temperature: Pressure

1 Introduction

With the vigorous development of centralized heating and cogeneration in cities and towns, steam piping technology has been widely used in China, especially steam overhead piping network has the advantages of high insulation efficiency, significant energy-saving efficiency, high temperature and pressure resistance, good stability, and small footprint. However, the flow of steam in the heating pipeline process due to pressure drop, heat dissipation phase changes, will cause the steam heating pipeline along the way to produce condensate [1-2], high-speed steam mixed with liquid droplets scouring the pipe wall and thus cause scouring corrosion. Scouring corrosion is a phenomenon of metal damage between metal surfaces and fluids due to high-speed relative motion. Compared to scouring wear alone, when there is a certain flow rate of fluid flowing through the pipe, the fluid will not only play a role in mass transfer, but also produce tangential stress on the pipe wall, accelerating chemical corrosion, further accelerating the corrosion rate and leading to thinning of the pipe wall [3]. In the actual production process, in order to change the direction of fluid flow, often use a large number of elbows, elbow section fluid flow rate and pressure will change dramatically, resulting in the probability of corrosion at the elbow is greater than the straight section.

In order to improve the service life of elbows and reduce economic losses, scholars at home and abroad have conducted a lot of research on elbow corrosion, Zhu Juan [4] and others reviewed the status of corrosion research on pipes under fluid scour conditions, different environmental factors and material properties on the impact of the scour corrosion mechanism; Lin Tong [5] and others used ANSYS software to simulate 90° elbow flow accelerated cocorrosion and studied the corrosion behavior and The correlation between corrosion behavior and fluid flow; Shen, Yaxin [6] et al. established a 90° elbow erosion model by Fluent software and analyzed the effect of different inlet flow rates and internal pressure on elbow corrosion; Andrew Sloley [7] et al. studied the extent of scouring corrosion of the pipe wall by steam at different flow rates; Utanohara, Y. [8] used the Fluent numerical simulation method The corrosion effect on the elbow at different temperatures and flow rates was analyzed.

However, in the existing work, the study of elbow corrosion is mainly through microscopy, ultrasound and other methods to measure the depth of corrosion under high temperature, high pressure and high flow rate conditions, and then to determine the effect of some factors on corrosion. But because the corrosion process is slow, the experiment takes too long and some operating conditions have safety risks, so the high temperature, high pressure, high flow rate conditions of steam on the elbow corrosion research is less.

Therefore, this paper uses a combination of VOF (Volume of Fluid) simulation of steam condensation in the pipe and DPM simulation of droplet scouring of the pipe wall to study the corrosion of steam on the pipe under different steam flow rate, temperature and pressure conditions.

2 Theoretical calculation model

2.1 VOF model

Water is introduced as a variable in the calculation unit, and water is set as the main phase and steam as the second phase.The equation of VOF [9] can be expressed as:

$$\frac{\partial F_1}{\partial t}+\nabla.(F_1V)=-\frac{\dot{m}_c}{\rho_1}$$

where m_c is the mass source term from condensation; F is the volume fraction of each phase，and in each calculation cel $F_l+F_v=1$， the subscripts and refer l and v the liquid and gas phases。

The sum of the momentum equations for the gas-liquid phases is expressed as:

$$\frac{\partial}{\partial t}\left(\rho_m\overrightarrow{\upsilon_m}\right)+\nabla\left(\rho_m\overrightarrow{\upsilon_m}\right)=-\nabla p+\left[\mu_m\left(\nabla\overrightarrow{\upsilon_m}+\nabla\overrightarrow{\upsilon_m^T}\right)\right]+\rho_m\vec{g}+\vec{F}+\nabla\left(\sum_{\kappa=1}^{2}\rho_b\vec{\upsilon}_{dr.b}^{2}\right)$$

where，F→ is the volumetric force，N;

μ_m is the mixed kinetic viscosity of gas-liquid phase，Pa.s;

ρ_b is the gas density，kg/m^3;

is the drift velocity of the gas phase with respect to the fluid phase，$\vec{v}_{dr.b}=\vec{v}_d-\vec{v}_1$，m/s

2.2 DPM model

DPM [10-11]The discrete phase model, consisting of vapor and droplets in a dispersive multiphase flow [12-15] system, treats the vapor as a continuous medium and the droplets as a discrete medium.

$$\frac{\partial}{\partial t}(Pk)+\frac{\partial}{\partial x_j}\left(Pv_jk\right)=\frac{\partial}{\partial x_j}\left(\frac{\mu_e}{\sigma_k}\frac{\partial_k}{\partial_{x_j}}\right)+G_k+G_s+P\varepsilon$$

$$\frac{\partial}{\partial t}(P\varepsilon)+\frac{\partial}{\partial x_j}\left(Pv_j\varepsilon\right)=\frac{\partial}{\partial x_j}\left(\frac{\mu_e}{\sigma_E}\frac{\partial k}{\partial x_j}\right)+\frac{\varepsilon}{k}\left(C_{\varepsilon1}G_k+C_{\varepsilon2}P\varepsilon+C_{\varepsilon3}PG_s\right)$$

$$G_k=\mu T\left(\frac{\partial\upsilon_i}{\partial x_j}+\frac{\partial\upsilon_j}{\partial x_i}\right)+\frac{\partial\upsilon_i}{\partial x_j}$$

$$G_s = -\sum k \sum i \frac{P_s}{\tau_{rs}} \left[2\left(k - C_k \sqrt{kk_s}\right) + v_i \frac{v_s}{\sigma_s n_s} \frac{\partial n_s}{\partial x_i} \right]$$

where: p—pressure, Unit Pa;

k—turbulent kinetic energy;

k_s—turbulent kinetic energy of the particle phase;

ε—turbulent dissipation rate;

t_{rs}—response time of particle dynamics;

2.3Ion motion model

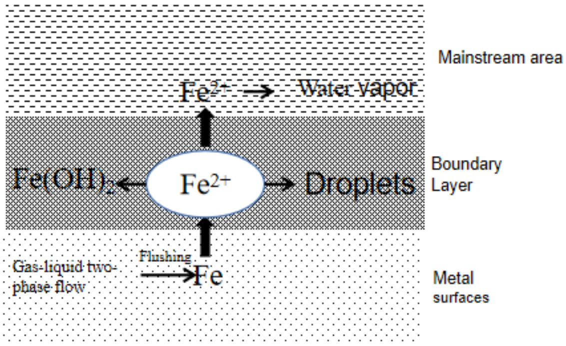


Fig1 Ion motion diagram

As can be seen from Figure 1, the first process is in static equilibrium when the fluid is stationary, and when the steam starts to flow, the steam entrains the droplets and forms a gas-liquid two-phase flow that continuously scours the pipe wall, leading to the dissolution of the metal matrix; the second process is the reaction between the iron ions and the droplets on the metal surface to form an oxide film. The inner layer of the oxide film structure is dense, the outer layer of the structure is loose, the metal matrix generated by the soluble iron-containing components through the pores of the oxide film diffusion to the boundary layer; the third process of iron ions into the droplets, compared with the condensing droplets in the mainstream of the low content of iron ions, in the concentration difference caused by the migration of iron-containing components from the metal matrix to the mainstream area, and the mainstream area of high-speed fluid will continue to carry away the iron-containing components, resulting in the elbow inside Continuous corrosion of the surface of the elbow.

3 Model construction and meshing

3.1 Model Construction

Tab. 1 Basic parameters of the pipeline model

Parameters	Numerical value
Pipe outside diameter/mm	200
Pipe thickness/mm	6.00
Design pressure/MPa	0.5
Poisson's ratio	0.25

The closer the geometric structure is established, the higher the accuracy of the simulation, but it is also often accompanied by an increase in the difficulty of modeling and calculation, and the establishment of an accurate and effective geometric model is the preliminary basis for the research work of computational fluid dynamics. Therefore, this paper adopts a three-dimensional modeling method. In this study, the elbow in the overhead steam pipe network is selected, and its structure is shown in Figure 2.A steam overhead pipe network with a pipe length of 6m was established, with a pipe size of 200mm, a pipe wall thickness of 6mm, and an insulation layer thickness of 40mm.The pipe material is 20#, and the insulation material is glass wool.

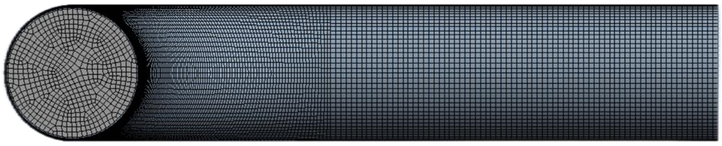


Fig2 Overhead pipe model

3.2 Meshing

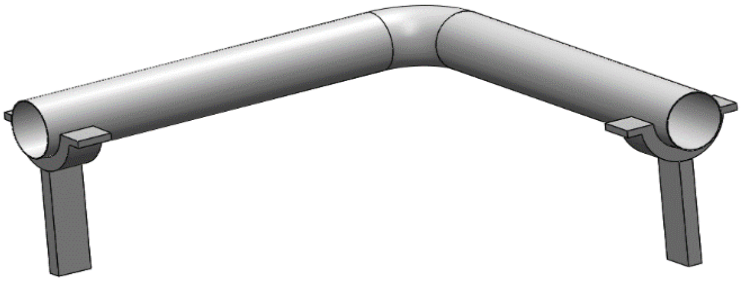


Fig3 Model meshing

The three-dimensional hexahedral mesh in Fluent software is used to divide the model. The model uses a 90° elbow with a pipe diameter of 200 mm and an elbow radius of curvature of 400 mm, whose geometric model is shown in Figure 3, and the pipe material is carbon steel. The number of nodes divided in this model is 709280, the number of grid cells is 689997, and the grid size of the elbow section is 1 mm. the inlet boundary condition is defined as the flow inlet, and the outlet boundary is defined as the initial pressure outlet with a pressure of 0. The standard k-ε model and standard wall function were chosen for the model, and the PISO method was used. the VOF model simulated the steam condensation process, and the DPM simulated the liquid droplet scouring wall process. The simulation is performed under the condition that the Reynolds number of steam flow in the pipe is greater than 2500.

3.3 Mesh irrelevance test

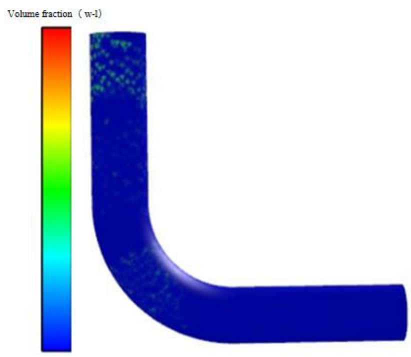
Considering the capacity of the computer, in order to effectively improve the accuracy of the grid calculation and thus the operation in Fluent, the hexahedral grid is used, the boundary layer grid is refined, and the pipe wall segment is set as the main simulated flow field [16]。The grid division schematic is shown in Figure 3. In order to ensure both the accuracy of the calculation and to complete it in the least amount of time, the maximum corrosion depth caused by the steam flow rate in the pipe is chosen as the basis for determining whether the grid is accurate when the grid irrelevance test is performed. The number of grids selected for 307091, 6899997, 8899997, 1286705 simulations, respectively. By comparing the last three groups of data found that the last two groups of corrosion depth data relative to the second group of data relative deviation of only 0.01%, indicating that the model meets the grid-independent verification, even if the number of grid changes again on the calculation results will have a smaller impact, therefore, the number of grids selected for the case of 689997 for subsequent numerical simulations.

Tab. 2 Grid independence test

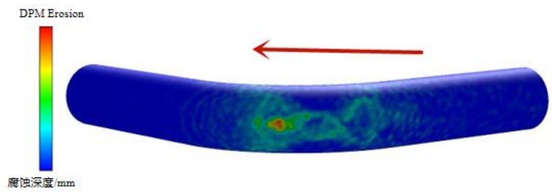
Number of grids/Unit	Corrosion depth/mm
307091	0.079
689997	0.083
889997	0.082
1286705	0.083

Calculation results and analysis

The steam condensation process is relatively rapid, and this paper simulates the condensate volume of the steam condensation process per unit time [17-18]. Due to the small amount of condensate, the impact of corrosion at the elbow of the pipe is small, so through the time conversion of a year of corrosion depth to calculate the simulation is more informative. From Figure 4 can be seen in different steam flow rate, temperature, pressure conditions elbow condensation, corrosion location is basically the same. Steam at the entrance and the pipe wall for full heat transfer and then condensed into droplets distributed on the wall, as the steam flow through the elbow, the steam because of the change in flow direction and cold wall contact and then condensed into droplets; steam flow through the elbow because of the change in flow direction, droplets a large number of wash wall [19], and then cause corrosion at the elbow.



(**a**)Condensation



(**b**)Corrosion

Fig.4 Steam pipe elbow condensation, corrosion cloud

4.1. Effect of steam flow rate on corrosion

Table 3 gives the condensation amount of steam flowing through the elbow at a steam temperature of 150℃ and a pressure of 0.5Mpa at flow rates of 20m/s, 25m/s, 30m/s, 35m/s, and 40m/s. As the flow rate increases, at 25m/s the steam and the wall heat exchange is the most adequate, and the amount of condensate reaches the maximum; when the flow rate is greater than 25m/s the steam and the wall heat exchange time is less, and the amount of condensate gradually decreases; as the flow rate increases to 35m/s, the pressure drop increases, and as the pressure decreases the steam condenses more easily, and the amount of condensate increases compared to that at 30m/s; when the flow rate increases to When the flow rate increases to 40m/s, the pressure drop increases, but the heat exchange time between the steam and the tube wall decreases, which leads to a trend of decreasing condensate volume.

Tab. 3 The amount of condensed water at different speeds

Speed m/s	Thermal conductivity	Kinetic viscosity	Volume fraction of water	Condensate volume kg/s
20	2.96%	399.73	1.99×10^{-2}	21.87
25	2.88%	485.92	2.57×10^{-2}	49.31
30	2.81%	569.96	5.98×10^{-3}	13.25
35	2.76%	652.26	6.99×10^{-3}	18.07
40	2.71%	733.11	4.48×10^{-3}	13.24

From Figure 5 can be seen with the flow rate increases, the degree of corrosion first increases and then decreases, and shows an undulating change in 25m/s to reach the maximum, 30m/s minimum; flow rate of 3m/s and 40m/s condensation water close, but the degree of corrosion, the same, indicating that the flow rate can increase the degree of corrosion; flow rate of 30m/s and other flow rate parameters compared to the condensation water has a significant gap, the degree of corrosion is also very different. Therefore, the degree of corrosion and condensation is proportional to the amount of condensate, the greater the amount of condensate, the more dissolved iron ions, the greater the concentration difference between steam and oxide, which in turn leads to the greater the degree of corrosion.

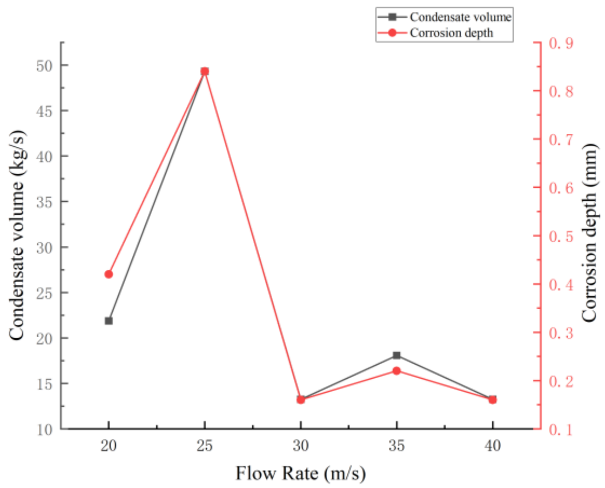


Fig.5 Relationship between steam flow rate and corrosion depth, condensation water

When high-speed steam just entered the straight section, steam and cold pipe wall heat transfer and condensation into droplets, steam entrained droplets [20] scouring the wall; steam flow through the elbow because of changes in the direction of flow, droplets in large numbers scouring the wall, so that the inner surface of the steam pipeline is difficult to form an effective protective film (steam scouring the wall of iron ions and hydroxide in water react to form a layer of oxide film), with the increase in time and flow rate , the concentration of iron ions in the steam in the mainstream area is very low compared with the concentration of iron ions at the interface of the oxide film solution, under the effect of the concentration difference, the iron ions at the oxide solution diffuse to the mainstream area, the steam takes away the iron ions in the mainstream area, the diffusion process continues, corrosion intensifies, resulting in continued thinning of the wall thickness.

4.2. Effect of steam temperature on corrosion

Table 4 gives when the steam flow rate of 30m / s, pressure 0.5mpa, steam temperature of 150℃, 160 ℃, 170℃, 180℃, 190℃, 200℃ when the steam flow through the elbow of the condensation amount, it can be seen that 170℃ at the maximum amount of condensation, 200℃ at the minimum amount of condensation.

Tab. 4 Condensation water at different wall temperatures

Temperature/℃	Thermal conductivity	Kinetic viscosity	Volume fraction of water	Condensate volume kg/s
150	3.16%	1.40×10-5	1.99×10-2	31.78
160	3.23%	1.44×10-5	3.30×10-2	54.02
170	3.29%	1.48×10-5	4.29×10-2	68.33
180	3.35%	1.52×10-5	4.06×10-2	63.01
190	3.42%	1.56×10-5	2.48×10-2	37.54
200	3.49%	1.60×10-5	1.68×10-2	24.82

As can be seen from Figure 6, at a certain flow rate and pressure, as the steam temperature [21] increases, the temperature difference between the steam and the pipe wall increases, resulting in a rising trend in the amount of condensate; When the steam temperature reaches 180°C, the curvature thermal resistance of the free surface of the droplet decreases, and the free surface area of the droplet increases to a certain extent which leads to the condensing droplet starting to absorb heat and turn into steam, and the condensation volume decreases, which is less obvious at this time; As the steam temperature gradually increases, the tendency of the droplets to absorb heat and turn into steam increases, which in turn leads to a gradual decrease in the amount of condensation. The higher the temperature of the steam, the more heat is absorbed by the droplets, which in turn leads to more droplets turning into steam and less condensation.

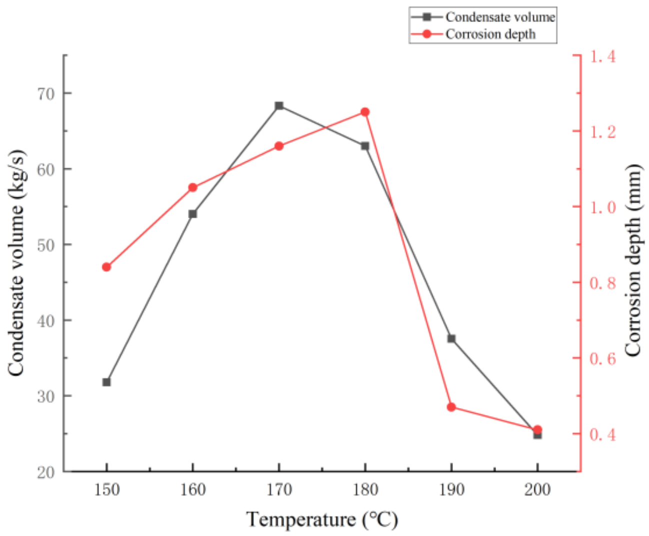


Fig6. Relationship between steam temperature and corrosion depth, condensate volume

As can be seen in Figure 6 with the increasing temperature of steam, the degree of corrosion first increased and then decreased at 180°C to reach the maximum, 200°C when the degree of corrosion is the smallest.

With the increase in temperature, the degree of corrosion increases with the increase in condensation, when the temperature reaches 180°C, although the amount of condensation has decreased, but due to the temperature increases ion activity, so that the ions dissolved in the condensate increased, and thus the degree of corrosion compared to 170°C increased; As the temperature continues to increase, there is a significant decrease in the amount of condensate. Although the temperature increases the ionic activity, the dissolvable ions are reduced and easily saturated, which in turn leads to a reduction in corrosion.

When the pressure flow rate is certain, the temperature varies with the amount of condensate, the larger the amount of condensate, the more dissolved ions and thus the greater the concentration difference, the more intense the diffusion and thus the more intense corrosion. But when the condensate gap is not large, the temperature increases the ion activity, increasing the diffusion flow rate of iron ions at the oxide solution to the main zone flow, steam to take away the mainstream zone iron ions, the diffusion process continues, corrosion intensifies, resulting in continued thinning of the wall thickness. Therefore, the degree of corrosion is mainly related to the amount of condensate followed by the influence of temperature.

4.3. Effect of vapor pressure on corrosion

Table 5 gives the amount of condensation at the elbow when the steam temperature is 150°C, the flow rate is 30m/s, and the pressure is 0.5MPa, 0.6MPa, 0.7MPa, 0.8MPa, 0.9MPa, when the steam flows through the elbow, the amount of condensate shows a ripple type change, with the largest amount of condensate at 0.7MPa and the smallest at 0.6MPa.

As the pressure [22] increases, the steam condenses more readily into droplets, and as the surface area of the droplets continues to increase, the heat exchange increases, which in turn leads to condensate turning into steam, thus decreasing compared to 0.6 MPa at 0.5 MPa; As the pressure continues to increase, the amount of steam condensation is much greater than the amount of liquid droplets into steam, resulting in an increase in the amount of condensate, which reaches a great value at this time; as the pressure continues to increase to 0.8 MPa gas molecular spacing further reduced, condensing into droplets, droplets are more easily brought together, but the surface area increases to further accelerate heat absorption, resulting in a reduction in the amount of condensate. After the pressure continues to increase, the amount of condensed water shows an increasing trend, indicating that the effect of steam pressure is greater than the effect of heat exchange. At a certain flow temperature, as the pressure increases, the condensation temperature gradually increases and the vapor condenses more easily into liquid droplets. The spacing between the molecules of steam gas is reduced, and the gas molecules are more likely to gather together to generate droplets, and when the surface area of the droplets increases the heat exchange gradually increases, which in turn leads to condensate becoming steam again, and the amount of condensate is not only related to the pressure but also to the size of the droplets after condensation.

Tab.5 Condensation water at different wall temperatures

Pressure/MPa	Thermal conductivity	Kinetic viscosity	Volume fraction of water	Condensate volume kg/s
0.5	3.49%	1.61×10^{-5}	3.07×10^{-2}	45.36
0.6	3.54%	1.60×10^{-5}	1.48×10^{-2}	21.87
0.7	3.58%	1.60×10^{-5}	3.57×10^{-2}	53.75
0.8	3.63%	1.59×10^{-5}	2.09×10^{-2}	30.88
0.9	3.67%	1.59×10^{-5}	3.18×10^{-2}	46.99
1.0	3.72%	1.58×10^{-5}	3.48×10^{-2}	51.42

As can be seen from Figure 7, when the flow rate temperature is a certain degree of corrosion with the amount of condensate showing ripple-type changes, when the condensate gap is not large, the impact of pressure is greater than the impact of condensate, in 0.6MPa corrosion depth of the smallest, in 1MPa to reach the maximum.

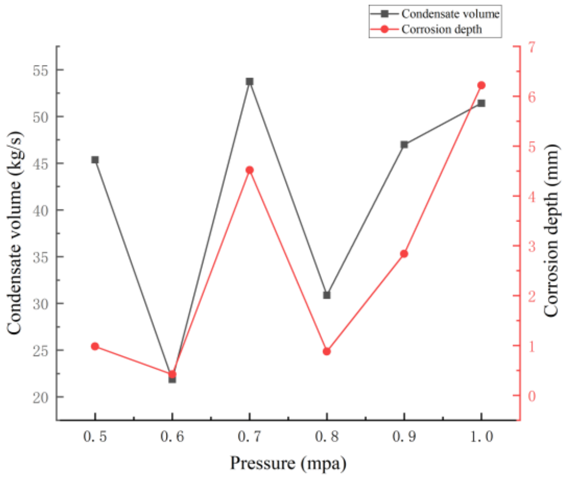


Fig7.The relationship between steam pressure and corrosion depth, condensation water

As the amount of condensation decreases, although the pressure increases to speed up the process of reaction, but the amount of reduction in the amount of reactants, eventually leading to a decrease in the degree of corrosion; when the pressure continues to increase to 0.7 MPa, the amount of condensate continues to increase, the reactants increase, the pressure also increases, leading to an obvious increase in the degree of corrosion; The pressure increases to 0.8 MPa, although the pressure increases, but the condensate volume decreases sharply, resulting in a significant reduction in the degree of corrosion, so the condensate volume has a greater impact on corrosion compared to the pressure; When continuing to increase the pressure to 1MPa, the condensate volume also increased, the condensate volume and 0.7MPa compared to the reduction, but the reaction rate of increased pressure is significantly greater than the effect of the concentration of reactants, and then to the maximum degree of corrosion.

With the increasing pressure, accelerating the reaction between the wall iron ions and the aqueous solution, so that the concentration of iron ions at the interface of the oxide film solution increases compared to the very high concentration of iron ions in the steam, under the effect of the concentration difference, the diffusion of iron ions at the oxide solution to the main zone flow, the steam takes away the iron ions in the mainstream zone, the diffusion process continues, the corrosion intensifies, resulting in continuous thinning of the wall thickness; Although condensate can react with iron ions on the wall, but when the pressure increases to a certain extent, compared to the amount of reactants (condensate) to speed up the reaction and greater impact on the degree of corrosion.

4.4. Experimental verification

In order to verify the accuracy of the simulated maximum corrosion depth of the pipe, and the experimental data in references[23-29] were compared, the experimental material used in the literature was selected to use one year of high temperature and high pressure high flow rate steam pipeline elbow components, the following figure is a picture of some samples of elbow corrosion.

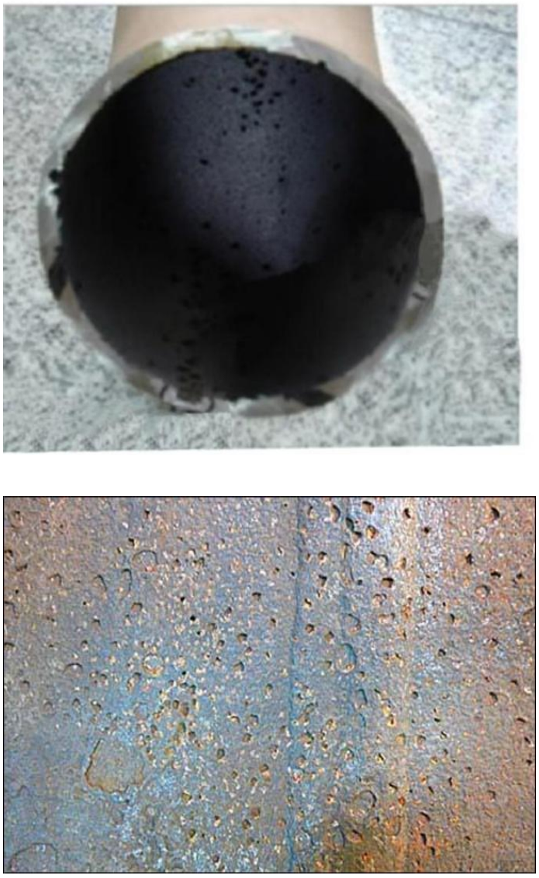


Fig8.Elbow corrosion sample diagram

By measuring the pitting corrosion depth in Figure 8 and some data collected from references, it was finally concluded that the corrosion depth range in the temperature range of 150-200°C, flow rate of 20-40m/s and pressure between 0.5-1.0MPa is generally 0.01mm-0.70mm.

5 Conclusion

(1) Steam condensation depends mainly on the heat transfer between the steam and the wall and the surface area of the droplets. As the heat transfer increases, the amount of condensed water increases, followed by a gradual increase in the surface area of the droplets, which in turn leads to the vaporization of the droplets into steam and a decrease in the amount of condensed water; Corrosion of the elbow is further affected by changes in steam flow rate, temperature and pressure through changes in condensate volume.

(2) Steam entrained with liquid droplets washing elbow, so that the inner surface of the steam pipeline is difficult to form an effective protective film, and the concentration of iron ions at the interface of condensate droplets compared to the concentration of iron ions in steam is very low, causing the pipe wall iron ions to move to the steam mainstream area, causing corrosion of the pipe wall.

(3) In the pipe network should control the inflow of steam temperature and pressure at 200°C and 0.6 MPa or so, control the degree of valve opening, control the flow rate at 30 m / s, reduce the impact of flow rate on the elbow corrosion, extend the life of the pipe network and reduce economic losses.

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