NUMERICAL SIMULATION AND EXPERIMENT ANALYSIS ON EROSION LAW OF FRACTURED ELBOW PIPE

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ABSTRACT: In order to study the erosion law of elbow pipe in the working process under the high-pressure fluid, three kinds of elbow pipe model are established based on the theory of computational fluid mechanics, combined with the actual working condition, numerical simulation of the internal flow field of elbow pipe, and erosion experiments were carried out according to the three kinds of installation angles and selection of three kinds of pipe materials, and draws the following conclusions: with the velocity increasing, the outlet velocity of the fluid will occur in any angles, so it would cause serious erosion for the elbows; in the state of turbulent flow, the erosion rate of inside and outside wall surface of elbow pipe is not uniform, the velocity of elbow pipe is greater than the velocity of straight pipe wall surface. The material of 42CrMo has the ability of resistance to erosion, it helps to prolong the service life of the pipeline when selecting 42CrMo of transporting piping.

KEYWORDS: elbow pipe, installation angles, erosion law, numerical simulation

1 INTRODUCTION

In recent years, with the increasing demand for petroleum and natural gas resources, the use of high-pressure fluid pipelines for exploitation of natural gas is also increasing gradually [1,2]. However, the fractured elbow pipelines will erode and cause fatigue damage in the process of transporting high-pressure fluid, which is accompanied by the technical problems of pipeline manufacturing and installation.

Therefore, scholars have studied the installation technology and material selection of field pipelines. Wu Xing et al. [3] found elbow is the most vulnerable place for erosion and fatigue damage of high-pressure manifold, and the outer and inner wall of elbow is the most dangerous area based on the existing erosion and wear theory of high-pressure manifold. Sun Bingcai et al. [4] mainly analyzed the strength and erosion resistance of elbows under different materials by composition test. The erosion wear rate of 40CrMo increased and the erosion resistance decreased. Song Xiaojin et al. used computational fluid dynamics software to simulate gas-solid two-phase flow in pipe to predict wall wear. The variation trend of wear with different influencing factors was similar to that of boundary angle. It was proved that boundary angle was a parameter which could comprehensively evaluate erosion wear characteristics of elbow. Based on the corrosion mechanism of metal pipelines[5-7]. Sun Ruqi et al. established the erosion model of double elbow elbow based on the liquid-solid two-phase flow model and erosion theory, and studied the influence of typical working conditions and structural parameters of double elbow elbow on the erosion rate of double elbow elbow [8-10]. Barbara Zardin has studied the pressure loss of the hydraulic system, and analyzed the pressure loss prediction of the divergent branch pipe in the hydraulic system, especially the expansion/contraction of 90 degree elbow and the intersection of the channel with computational fluid dynamics, which is helpful to optimize the design process of the channel [12]. A. Mansouri et al. studied the resistance characteristics of heavy oil flowing through horizontal pipeline in detail combined CFD with experiments, and obtained the rule of fluid erosion in horizontal pipeline [13, 14].

In this paper, the flow field research of three angle erosion laws of elbow installation in space has been carried out based on the previous research results. The flow field state of elbow under different matching angles in the installation process has been calculated. The erosion experiment of the test piece under the field environment has been simulated to determine the impact of fluid erosion loss in elbow. The main factors and laws of effectiveness provide a theoretical basis for designing elbow.

2 NUMERICAL CALCULATION EQUATIONS

2.1 Computational fluid dynamics controlling equations

The laws of conservation of mass, momentum, and energy control the flow of fluids. If the flow is
in a turbulent state, and the system also follows the additional turbulent transport equation. The control equation is a mathematical description of these conservation laws, the mathematical description of the physical model of the flow problem is given, which is the basic equation of flow (control equation) and its boundary conditions are given, which is known as mathematical model. The establishment of mathematical model is based on the physical model, in the study of the hydraulic end of the plunger pump. In addition, a three-dimensional model models the geometry of internal fluid of hydraulic end, flow state is in turbulent flow. Therefore, the mathematical model obtained is as follows [15,16]:

1) Mass conservation equation
\[ \frac{\partial \rho}{\partial t} + \frac{\partial (\rho v_x)}{\partial x} + \frac{\partial (\rho v_y)}{\partial y} + \frac{\partial (\rho v_z)}{\partial z} = 0 \quad (1) \]

2) Momentum conservation equation
\[ \frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \eta \frac{\partial u_i}{\partial x_j} - \rho u_i u_j \right) \quad (2) \]

3) Energy-balance equation
\[ \frac{\partial (\rho T)}{\partial t} + \frac{\partial (\rho v_i T)}{\partial x_i} + \frac{\partial (\rho v_i v_j)}{\partial x_j} = \frac{\partial}{\partial x_i} \left( \eta \frac{\partial T}{\partial x_i} \right) - S_r \quad (3) \]

Where \( c_p \) is the specific heat capacity. This the temperature, \( k \) is the fluid heat transfer coefficient, \( S_r \) is the internal heat source of fluid and mechanical energy of fluid is converted into heat energy by viscous action, also it is known as viscous dissipation phase.

2.2 Turbulence equations

According to the theory of advanced fluid mechanics, division basis of the fluid flow state is \( R_e \), when \( R_e \) is less than 2150, fluid flow is laminar motion, when \( R_e \) is over 4000, fluid flow is turbulent. The formula of \( R_e \) is as follows [16,17]:
\[ R_e = \frac{\rho V D}{\mu} \quad (4) \]

Which \( \rho \) is the fluid density; \( V \) is the fluid velocity; \( D \) is the characteristic scale of the flow; \( \mu \) is the fluid viscosity.

For the fractured media, fracturing fluid is an incompressible fluid, \( R_e \) is far greater than 4000, so it select the standard \( k - \varepsilon \) model, and this equation corresponds to the two equation model in fluid mechanics, which is the continuity equation, Reynolds equation, turbulent kinetic energy equation (\( k \) equation) and the dissipation rate equation [17].

The most widely used and the most basic two equations model in engineering is \( k - \varepsilon \) model, which is the equations of turbulent flow energy and dissipation rate:
\[ \frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \frac{\mu}{\sigma_k} \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \varepsilon \quad (5) \]
\[ \frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \frac{\mu}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right) + \frac{\varepsilon}{k} (c_k G_k - c_\varepsilon \rho \varepsilon) \quad (6) \]

In the equation:
\[ G_k = \mu \left\{ 2 \left( \frac{\partial u_i}{\partial x_i} \right)^2 + 2 \left( \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial u_i}{\partial x_i} + \frac{\partial v}{\partial y} \right)^2 \right\} \quad (7) \]
\[ G_b = -\beta \rho \left( \frac{\partial u_i}{\partial x_i} + \frac{\partial v}{\partial y} \right) \quad (8) \]
\[ \mu_\varepsilon = \mu + \mu_\varepsilon \quad (9) \]
\[ \mu_\varepsilon = C_\mu \frac{k^2}{\varepsilon} \quad (10) \]

Where \( k \) is the turbulent kinetic energy; \( \varepsilon \) is the turbulent dissipation rate; \( G_k \) indicates the turbulent kinetic energy caused by the average velocity gradient; \( G_b \) indicates the turbulent kinetic energy caused by buoyancy; \( c_i \) and \( c_\varepsilon \) are the constant; \( x, y, Z \) are the coordinates. The general data model often desirable for computing experience,
\[ C_\mu = 0.09, c_i = 1.44, c_\varepsilon = 1.92, \sigma_k = 1, \sigma_\varepsilon = 1.3 \quad (11) \]

In the equation, \( \rho \) is the fluid density, \( kg / m^3 \); \( p \) is the pressure, \( Pa \); \( u \) is the fluid velocity vector, \( m / s \); \( \eta \) is the turbulent viscosity coefficient, \( kg / (m \cdot s) \); \( \varepsilon \) is the dissipation rate, \( m^2 / s^3 \); \( k \) is the turbulent kinetic energy, \( m^2 / s^2 \).

According to the general structural design drawing of fracturing elbow and considering the actual installation angle of pipeline, the fluid models of three kinds of installation angles are established. They are the design structures with 0°, 45° and 90° in the direction of elbow and vertical plane respectively. As shown in figure 1, the feasibility of actual numerical simulation is shown, and the calculation model of fracturing elbow is reasonably simplified. Taking the angle sphere opening of the pipeline as an example, the three-dimensional flow field grid of fracturing elbow is
established, and the parameters of inlet and outlet fluids are set up. The fluid movement path of the upper wall is a-b-c, and the fluid path of the lower wall is d-e-f, as shown in figure 2.

Figure 1. Solid Model of fracturing elbow

Figure 2. 3-D flow field mesh model

Aiming at the safety accidents of bursting and cracking in field fracturing pipeline (as shown in figure 3 and figure 4), the movement state of fluid field for active elbow under different matching angles in installation process is calculated, and the erosion experiment of test pieces under field environment is simulated, in order to determine the main factors affecting the fluid erosion failure in elbow pipe and to determine the main factors affecting the fluid erosion failure in elbow pipe.

Figure 3. Fracture accident of high pressure elbow pipe on-site

Figure 4. Erosion piercing photograph of movable elbow

3 NUMERICAL CALCULATION AND RESULTS ANALYSIS OF FLUID MOTION

The parameters (pressure, velocity, etc.) in the flow field in the fracturing elbow change continuously and irregularly with time. Therefore, the following assumptions need to be put forward for the numerical simulation of the flow field [18,19]:

1) Fluid as Newtonian Fluid (along with the velocity gradient change, dynamic viscosity $\mu$ unchanged)

2) Through the calculation, the Reynolds number Re of the model far outweigh the critical Reynolds number Re (2000-3000), so the flow model state was mainly on the turbulent flow, which fulfilled $k-\varepsilon$ turbulence model.

3) To solve discrete equations, numerical calculation in common used the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm of the finite volume method.

4) The wall boundary was no slip condition, namely $u_{wall}=0$, $v_{wall}=0$, $w_{wall}=0$, $k_{wall}=0$, $\varepsilon_{wall}=0$.

Model boundary conditions: In order to further explore the relationship between flow velocity distribution and installation angle of elbow and pipe flow field, the inhalation process under the maximum impulse is obtained by calculating. The values of the parameters of the discharge process of high-pressure plunger pump are shown in table 1.

4 CALCULATION RESULTS ANALYSIS

The results are obtained by flow field simulations shown in figure 5. It can be seen that velocity vector contour of fluid flow inside the fracturing elbow under three angles in figure 5, because the direction of fluid flow is constantly changing, the velocity will change greatly in the position of direction change, the flow area will decrease abruptly, and the fluid will flow through the upper part of the fracturing elbow at a high velocity, especially in the inflection. There will be a great pressure drop at the corner and a great increase in velocity, which will produce a large local impact force. In this condition, the energy loss will be great and the erosion phenomenon of the inner wall will be serious, which will seriously affect the service life of the elbow.
Table 1 The parameters of the discharge process of plunger pump

<table>
<thead>
<tr>
<th>Gear</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
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<tbody>
<tr>
<td>Transmission ratio of gearbox</td>
<td>3.75</td>
<td>2.69</td>
<td>2.2</td>
<td>1.77</td>
<td>1.58</td>
<td>1.27</td>
<td>1</td>
</tr>
<tr>
<td>Stroke/(r/min)</td>
<td>79</td>
<td>111</td>
<td>135</td>
<td>169</td>
<td>189</td>
<td>235</td>
<td>29</td>
</tr>
<tr>
<td>output volume (L/min)</td>
<td>657</td>
<td>915</td>
<td>1119</td>
<td>139</td>
<td>155</td>
<td>193</td>
<td>24</td>
</tr>
<tr>
<td>Pressure/MPa</td>
<td>105</td>
<td>105</td>
<td>87</td>
<td>60</td>
<td>63</td>
<td>50</td>
<td>40</td>
</tr>
</tbody>
</table>

Figure 5. Vector charts of fluid flow velocity at three angles

Figure 6. Fluid velocity variation along paths of a-b-c and d-e-f with installation angle of 0°

Figure 7. Fluid velocity variation along paths of a-b-c and d-e-f with installation angle of 45°

Figure 8. Fluid velocity variation along paths of a-b-c and d-e-f with installation angle of 90°

It shows that the maximum velocity is 14.1 m/s that cause the most serious erosion in this location when the stroke is 299 r/min and the installation angle is 90° in figure 5. The maximum velocity followed by 13.8 m/s under the 0° of installation angle, the maximum velocity is 13.7 m/s under the 45° of installation angle, so when the installation angle is 0° and 45°, the impact velocity of the fluid will be smaller.
It shows the process of velocity change at 0° of installation angle in figure 6. In the elbow section, the velocity changes greatly. The maximum and minimum velocities fluctuate jumpily. For the flow path a-b-c on the wall of the pipe, the overall trend of velocity change is that in the 0-400 section (i.e., elbow section), the velocity changes greatly. At b-c, it decreases and then remains stable. In the d-e segment of the lower wall, there is a sudden change at the corner of the middle pipeline, and in the elbow section, there are two sections where the velocity transits smoothly (for example, between 50-200 mm and 300-450 mm), then decreases in the e-f, and then remains stable.

It shows the process of velocity change at 45° of installation angle in figure 7. The overall trend of velocity is as follows: the greater the number of impulses inside and outside the pipe wall, the greater the velocity of fluid outlet, and the greater the impact velocity of fluid path a-b-c on the pipe wall at section a-b. Firstly, there is a smooth transition zone from the exit to the corner, and then there is a large velocity fluctuation at the corner of 45° with the maximum velocity exceeding 13 m/s. The overall velocity first increases, and there is no stable transition stage in the middle. There is a sudden change at the corner of the middle pipeline, then decreases at b-c, and then remains stable. The fluid path on the lower wall is d-e-f. Along the pipeline path, there is a smooth transition zone from the exit to the corner, and then there is a large velocity fluctuation at the 45° corner. There is a smooth transition zone with a smaller width in the middle (for example, between 900 and 1100 mm). At last, it becomes stable again after a steep increase, and then remains stable.

We can get the process of velocity change at 90° from figure 8. For the flow path a-b-c on the wall of the pipe, the greater the overall trend of velocity change is, the greater the velocity of the fluid outlet is. First, the fluid enters the pipe smoothly between 0-250 mm, then there is a process of rapid increase, and then suddenly decreases between 300-700 mm. There are fluctuation changes, one section is smooth transition (such as between 500-700 mm), then it tends to be stable again after steep increase; and the fluid path on the lower wall is d-e-f, between 0-200 mm, when the fluid flows out from the outlet of the reciprocating pump, there will be a greater impact velocity on the pipe wall, and there will be a sudden change at the corner of the middle pipeline, and one section is. A smooth transition (e.g., between 400 and 600 mm), followed by a steep increase in velocity, then a sudden decline, it becomes smaller in the e-f segment, and then maintain stability.

The maximum velocity of a-b-c and d-e-f along the pipeline path varies with different installation angles and rotational velocities as shown in figure 9. At the same installation angle, the maximum velocity increases with the increase of rotational velocity. At the same rotational velocity, when the installation angle is 45°, the velocity contour obtained from other angles also corrodes the pipeline.

![Figure 9. The maximum velocity curve at different rotary speed](image)

5 EROSION ANALYSIS OF FRACTURING ELBOW WITH DIFFERENT MATERIALS

5.1 Experimental study on erosion wear of different materials

For typical plastic metal materials, the erosion wear at low impact angle is more serious than that at frontal impact. The set test conditions are as follows: According to the installation angle of high pressure manifold and the choice of material, the corresponding erosion wear test scheme is designed. In the test, the high pressure liquid is water and sand, and the sand is ceramsite proppant. The eroded materials are 30CrMo, 40CrNiMo, and 42CrMo used for manufacturing high pressure manifolds. The corrosion resistance of the sample alloys is improved by adding elements such as Cr, Ni and Mo, and the erosion medium is water and sand. Therefore, the surface loss caused by fluid corrosion in a short time (less than 1 hour) is very small. It is the wear effect of proppant particles on the surface of the sample. At room temperature, the jet velocity is 20 m/s, the sand concentration is 8%, the sand concentration is 145 kg/m³, the erosion angle is set to 0°, 45° and 90°, and the erosion angle is different. Under the same conditions of other working conditions, the macroscopical morphology and alloys of several high-pressure manifold materials after erosion test for one hour are eroded at three different angles. The erosion wear morphologies of the materials are shown in figure10-figure12, respectively. The test results
show that under the same working condition, under the action of cutting and chipping, the erosion wear of materials is the largest, the length of erosion pit is the largest, and the depth of erosion pit reaches 2.588 mm. At 45°, the macroscopical morphology of erosion is circular plastic deformation pit, the average size of length, width and height are 12.411 mm, 12.409 mm and 0.622 mm respectively, and the weight loss of erosion wear is small. The morphology of the three materials after erosion wear shows that the erosion wear of the uncarburized 30CrMo and 40CrNiMo materials is significantly worse than that of 42CrMo at any erosion angle, and the erosion wear of 42CrMo is the smallest.

Figure 10. Erosion pit morphology of three kinds of materials after erosion for 1 hour at 0°

Figure 11. Erosion pit morphology of three kinds of materials after erosion for 1 hour at 45°

Figure 12. Erosion pit morphology of three kinds of materials after erosion for 1 hour at 90°

5.2 Analysis of erosion and wear of material in 1h

Because the sand is recycled in this test device, the longer the test time is, the more serious the particle loss is. Therefore, in order to ensure the stability of the test results, it is necessary to carry out further erosion time test and test the performance of proppant particles. According to the same test conditions, the erosion time is set to be 0-60 minutes, and the erosion wear loss weight is calculated to calculate the erosion wear rate. Three repeated tests are conducted for each group of specimens. The average values of three repeated tests are obtained. The test results are shown in figure 13. The relationship between erosion time and erosion weight loss is shown in figure 13(a). From figure 13(a), it can be seen that when the erosion time is less than 5 minutes, there is almost no mass loss of the erosion sample. It is the incubation period of erosion wear. After more than 5 minutes, the erosion weight loss of the material increases with the erosion time. It is also increasing.

It shows the relationship between erosion time and erosion wear rate in figure 13(b). As a typical plastic material, the curve of erosion wear rate and time can be divided into three regions: incubation zone, maximum erosion rate zone and stable zone.

The length of incubation period indicates that the material can withstand the external energy from elastic deformation to plastic failure, which is related to the properties of material itself and the impact kinetic energy of particles. It is an important reference value for evaluating the erosion resistance of materials. Under the experimental conditions, the incubation period of material erosion is about 0-5 minutes, and the erosion time is large. After 10 minutes, it enters the erosion acceleration zone. The maximum erosion rate occurs between 10 minutes and 20 minutes. After 20 minutes, the erosion rate of the material tends to stabilize gradually and reaches the stable zone.

6 CONCLUSIONS

Based on the hydrodynamic analysis of the actual installation position of elbow and the experimental study of high pressure manifolds with different materials, the following conclusions can be drawn:

(1) Under different installation angles, the overall trend of flow velocity changes on the upper and lower walls of pipe wall is as follows: with the increase of impulse times, the outlet velocity of fluid increases. At any installation angle, the elbow will have greater velocity fluctuation, so the elbow will have serious erosion.

(2) In the bend section of elbow, the velocity on the upper wall is smaller than that on the lower wall, and the velocity on the upper and lower walls of the straight section is equal, and the velocity is basically stable.

(3) It causes the most serious erosion in this location when the installation angle is 90°. When the installation angle is 0° and 45°, the impact velocity of the fluid will be smaller.
(4) Compared with 30CrMo and 40CrNiMo, 42CrMo has the strongest anti-erosion ability. The choice of 42CrMo is helpful to prolong the service life of pipelines.

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8 REFERENCES


