Numerical Analysis of Erosion Wear of Water with Particles in Elbows

Chaojie Li¹,a, Yanqin Mao¹, Xiaoyue Wang¹, Zhixing Zhan¹, Liang Cai¹,b*

¹College of Energy and Environment, Southeast University, Nanjing 210096, China
¹,aemail: 220190526@seu.edu.cn , ¹,b*email: Cailiang@seu.edu.cn

Abstract—In this paper, the numerical analysis of erosion wear of water with particles in elbow is carried out based on fluent. The influence of different inlet velocity and bending angle on pipeline erosion, and the distribution of pressure field and velocity field in the pipeline are studied. The main conclusions are as follows: the erosion of elbow section is more serious than that of inlet section and outlet section of pipeline. With the increase of inlet velocity, the maximum erosion rate of elbow section gradually increases, and the maximum velocity and maximum pressure inside the elbow section also increase. When other conditions are certain, different bending angles make the elbow receive different erosion effects. When the bending angle is larger, the pipeline erosion rate is relatively more uniform. Study on erosion helps to reduce the impact of fluid on the wall and improve the safety and reliability of engineering.

1. Introduction

When the fluid with particles flows in the elbow, the elbow changes the velocity direction of the fluid medium. The solid particles in the fluid repeatedly impact on the surface, resulting in material loss and erosion[1]. Erosion may lead to thinning or even rupture of pipe walls such as gas pipelines and water pipelines for residents, and this may lead to leakage of natural gas pipelines and industrial water pipelines, so it is very important to study the erosion of elbows. It is of great significance for natural gas pipelines and industrial water pipelines to minimize erosion, thereby improving the safety and reliability of pipelines.

In recent years, many scholars have studied erosion. Li Cang [2] conducted a simulation study on the erosion of the gas transport process containing solid particles, and analyzed the influence of the gas inlet flow rate and particle diameter on the erosion rate. When Wang Hongjun [3] studied the impact of particles on the erosion wear of double 90° elbow, it was found that the area outside the elbow and near the entrance was more serious, and the wear away from the entrance was less. Li Fangmiao [4] studied the influence of installation angle, fluid inlet velocity, and mass flow of solid particles on the erosion rate of movable elbows and provided references for further optimization design of movable elbows. Lai Jiaxiang [5] simulated the erosion characteristics of the ash conveyance of the vortex pipeline by the shrinkage angle of the pipeline under the condition of swirling transportation of fly ash-air two-phase flow, and studied the erosion effect of the shrinkage tube on the pipeline at different shrinkage angles. Bitter [6] proposed single crystal deformation and wear theory and corrosion resistance mechanism. Yapyj [7] proposed a reasonable pipe diameter ratio to reduce the erosion effect of particles on the pipeline.

The simulation analysis of the erosion effect is helpful to detect and weaken the erosion effect, and reduce or avoid pipeline wear and fracture. This paper mainly studies the erosion effect of water with particles on elbows with different angles and different fluid inlet velocities, and analyzes the internal
flow field, which helps to improve the reliability of the pipeline.

2. Numerical model

The flow of water with particles in the pipeline should meet the conservation laws of mass, energy and momentum. For incompressible fluid continuity equation is as follows:

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0$$

Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = S_m$$

Momentum conservation equation:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial}{\partial x_i}(\rho u_i) + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i$$

In this paper, the continuous phase is water, the particle diameter in the discrete phase is 10^{-4}m, and the particle mass flow rate is 10^{-16}kg/s. The selected turbulence model is k-epsilon Standard, the extensible wall function. The turbulence k equation is as follows:

$$\frac{\partial}{\partial x_j}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[(\mu + \mu_t)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho \varepsilon - Y_M + S_k$$

The turbulence $\varepsilon$ equation is as follows:

$$\frac{\partial}{\partial x_j}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[(\mu + \mu_t)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\epsilon}\frac{\varepsilon}{k}(G_k + C_{3\epsilon}G_b) - C_{2\epsilon}\frac{\rho}{k} + S_\varepsilon$$

Where $G_k$ represents the turbulent kinetic energy generated by the laminar flow velocity gradient, $G_b$ is the turbulent kinetic energy generated by buoyancy, and $Y_M$ is the fluctuation generated by transitional diffusion in compressible turbulent flow. $C_{1\epsilon}$ and $C_{2\epsilon}$ and $C_{3\epsilon}$ are constants, $\sigma_k$ and $\sigma_\varepsilon$ are the turbulent Prandtl numbers of the k equation and the $\varepsilon$ equation, $S_k$ and $S_\varepsilon$ are custom parameters.

In this paper, the McLaury model is used to study the erosion effect of water with particles on the pipeline. The McLaury erosion rate influence equation is as follows. $E = AV^n f(\gamma)$, where $A = FBh^x$, $f_1(\gamma) = by^2 + c_y$, $f_2(\gamma) = x\cos^2 y\sin(w) + vsin^2 y + z$, Bh is determined by the hardness of the material.

3. Grid independence verification and simulation materials

The elbow model used in the simulation includes inlet section, elbow section, and outlet section. The length of the inlet section is 350mm, the curvature radius of the elbow section is 30mm, the length of the outlet section is 350mm, and the pipe diameter is 60mm, as shown in Fig.1 below. The grid is divided according to the structure of the pipeline, and the grid accuracy is above 0.45, as shown in Fig.2 below.
Numerical simulation of erosion in this paper is based on fluent. Before the formal simulation, the maximum erosion rate is used as the monitoring quantity to verify the grid independence and reduce the error factor of the number of grids on the simulation results, and make the simulation results more accurate. In the Fluent simulation, water is used as the continuous phase, particles are used as the discrete phase, the viscosity model is k-epsilon, the wall function is expandable, and the particle type is inertia. The inlet boundary is the velocity inlet, the BC type of the discrete phase is escape; the outlet boundary is the pressure outlet, the BC type of the discrete phase is escape, and the wall is reflected boundary. The McLaury erosion model is mainly considered. The boundary conditions are set as follows.

### Table 1. Fluent boundary condition settings

| Boundary   | Continuous phase | Discrete phase |
|------------|------------------|----------------|
| model      | k-epsilon        | dpm model      |
| inlet      | velocity inlet   | escape         |
| outlet     | pressure outlet   | escape         |
| wall       | no slip boundary | reflect        |

Fig. 3 shows the maximum erosion rate of the elbow with granular water when the flow inlet velocity is 1 m/s, the bending angle is 90° and the mesh number is 5w, 35w, 68w, 91w, 126w, 158w. When the mesh quality is above 90w, the maximum erosion rate is less affected by the mesh number. Therefore, in order to ensure the accuracy of simulation and less use of computing resources, the following simulation analysis grid number is about 1 million.

![Fig.3 Maximum erosion rate corresponding to different grid numbers](image)

4. **Pipeline erosion simulation analysis**

4.1. **Analysis of Internal Flow Field of Pipeline Erosion**

Fig. 4 and Fig. 5 are the pressure distribution and velocity distribution of the central axis of 90° elbow with the inlet velocity of 1 m/s. The pressure and velocity of granular water are evenly distributed at the inlet section and far from the elbow section, and there is a trend of pressure decrease and velocity increase near the elbow. There is an obvious pressure gradient between the inside and outside of the elbow section. The inside pressure is small and the velocity is large, while the outside pressure is large and the velocity is small. Due to the change of water flow velocity, there is a large centrifugal force at the elbow. The pressure and velocity of the outlet section are relatively uniform.
Fig. 4 Pressure cloud diagram of pipeline axis

Fig. 5 Velocity cloud diagram of pipeline axis

Fig. 6 and Fig. 7 are the corresponding streamlines and erosion rate contours in the pipeline respectively. When the flow passes through the elbow section, the velocity vector changes, resulting in the erosion effect of particles repeatedly impacting on the elbow surface. Due to the relatively flat flow in the inlet section, the erosion effect is small. The number and intensity of collisions between solid particles and pipe wall in elbow section become larger, which is greatly affected by erosion. Some pipe sections in outlet section are also eroded due to the change of fluid velocity.

4.2. The effect of flow velocity on pipeline erosion

The flow velocity affects the strength of the particle impacting the elbow surface, and has a great influence on the internal pressure field, velocity field and erosion rate of the pipeline. In order to study the influence of flow inlet velocity on pipeline erosion, the bent pipe with 90° bend angle is selected as the calculation model. Eight different initial conditions are taken respectively, such as inlet velocity of 1m/s, 1.5m/s, 2m/s, 2.5m/s, 3m/s, 3.5m/s, 4m/s and 4.5m/s. Each use case ensures that the particle diameter is $10^{-4}$ m and the flow rate is $10^{-18}$ kg/s. Because the change of pressure field and velocity field in inlet section and outlet section is relatively small and the erosion effect is not obvious, the simulation results of elbow section are mainly analyzed. Fig. 8 shows that when the inlet velocity increases, the maximum pressure of the elbow section increases gradually. At the lateral position of the elbow, due to the enhancement of the centrifugal effect, the negative pressure inside the elbow is also gradually increased, and the pressure at the same position is generally increased. The elbow sections corresponding to different inlet velocities have obvious pressure gradients.
Fig. 8 The axial pressure field of the elbow with different inlet flow rates

Fig. 9 is the velocity cloud map of the middle axis of the elbow corresponding to different inlet velocities. The calculation results show that the velocity of the middle axis of the elbow section has obvious gradient change. With the increase of the inlet velocity, the maximum velocity of the elbow section increases significantly.

Fig. 9 The velocity field of the axial surface of the elbow with different inlet flow rates

Fig. 10 shows the distribution of erosion rate corresponding to different inlet velocities, and Fig. 11 shows the maximum erosion rate corresponding to different inlet velocities. The calculation results show that with the increase of inlet velocity, the maximum erosion rate increases gradually. The increase of inlet velocity will lead to the increase of the impact strength of particles on the pipe wall in the elbow section, and the number of particles impacting on the wall is more, thus the wear of the pipe
wall material is more serious. As the velocity increases, the centrifugal effect of water flow increases when it passes through the elbow, resulting in stronger erosion on the inner wall of the elbow. When the velocity is large, the erosion intensity on the inner wall is higher than that on the outer wall.

![Erosion rate of elbows with different inlet flow rates](image)

**Fig. 10** Erosion rate of elbows with different inlet flow rates

![Maximum erosion rate corresponding to different inlet velocities](image)

**Fig. 11** The maximum erosion rate corresponding to different inlet velocities

4.3. *The influence of bend angle on pipeline erosion*

The bend angle affects the direction and size of the water flow velocity in the outlet section, and affects the impact strength and erosion rate of the particles on the pipe wall. In order to study the influence of the bend angle on the erosion of the pipeline and ensure that the water inlet flow rate is 2.5m/s, the particle diameter is $10^{-4}$m, the particle flow rate is $10^{-18}$kg/s unchanged, and the bends with bend angles of 60°, 90°, 120° and 150° are simulated and analyzed. The results are shown in Fig. 12, and the maximum erosion rate of the pipeline decreases in turn. The maximum erosion rate of the pipeline at 60° bending angle is the highest, because the impact of centrifugal particles on the pipeline is the strongest, and the inside of the pipeline is relatively more vulnerable to erosion. With the increase of the angle, the maximum erosion rate of the pipeline gradually decreases, and the erosion part of the pipeline at 150° elbow is relatively uniform compared with that at small angle, accompanied by low distribution velocity and erosion rate.
5. Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

1. The erosion of elbow section is more serious than that of inlet section and outlet section of pipeline. With the increase of inlet velocity, the maximum erosion rate of elbow section gradually increases, and the maximum velocity and maximum pressure inside the elbow section also increase. The velocity field and pressure field inside the elbow section have obvious gradients.

2. When other conditions are certain, different bending angles make the elbow receive different erosion effects. When the bending angle is larger, the pipeline erosion rate is relatively more uniform.

3. If time and conditions permit, it is necessary to do further research on the flow field in the elbow, and the research on the elbow with different angles can be more detailed. This paper mainly studies and analyzes the influence of inlet velocity and bending angle on erosion strength, which helps to reduce the erosion of engineering pipelines and improve the safety and reliability of pipelines.

References

[1] Li Shizhuo, Dong Xianglin. Erosion wear and fretting wear of materials. Beijing: Machinery Industry Press.

[2] Li Cang, Sun Baocai. Study on erosion simulation of gas-solid two-phase flow in elbows[J]. Journal of Lanzhou University of Technology, 2020, 46(04): 79-83.

[3] Wang Hongjun. Research on the influence of particle characteristics on the erosion and wear of oil and gas pipeline double 90° elbow[J]. Petrochemical Industry Application, 2020, 39(06): 78-83.

[4] Li Fangmiao, Li Meiqiu, Song Yang, Feng Ling, Feng Zhicheng. Research on the erosion of movable elbows by liquid-solid two-phase flow[J]. Petroleum Machinery, 2019, 47(10): 107-111.

[5] Lai Jiaxiang, Lai Yongbin, Wang Long, Zhang Wenlong. Research on the erosion characteristics of pipe swirling ash transport by pipe shrinkage angle[J]. Electronic Testing, 2021(17): 53-54.

[6] Bitter J.G. Solid particle erosion and erosion-corrosion of materials[M]. Asm International, 1995.

[7] YAPYJ. CFD study of sand erosion in pipeline[J]. Journal of Petroleum Science and Engineering, 2019, 13(17): 269-278.