Numerical investigation on the sealing performance of pipeline inspection gauge (PIG) Crossing Elbows

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Abstract. The pipeline inspection gauge (PIG) is one of the most popular pigging equipment. In recent years, blocking and stagnation accidents during PIG’s operation process seriously affect the safe operation of energy pipelines. In order to investigate the sealing performance of the PIG’s rubber cup, a four cup drain PIG's movement in elbow was considered as a prototype in this study. Based on a validated finite element model, the contact stress between sealing cups and the pipe wall and pressure relief area of cup are obtained. The results indicate that when the PIG is operated in a small curvature elbow, the sealing performance of the cup is obviously weakened. Increasing the sealing cup interference and the differential pressure of the sealing cup surface can enhance the sealing performance of PIG cup. When the PIG's sealing cup is detached from the inner wall of the pipe, reducing the elastic modulus of the pig's cup material can be a reasonable measure to enhance the sealing performance of PIG cups.

1.Introduction
As the most safety and economical transportation method for oil and gas, long distance pipelines are widely used in the energy industry. The PIG are mainly used for removal of fouling inside the pipeline, improving the pipeline’s transportation efficiency. During the pigging operation, due to the unknown internal conditions of the pipeline, blocking and failure accidents of the PIG may occur, threatening the transportation safety of pipelines.

Thus, in recent decades, numerous experimental and numerical investigations on the pigging process have been carried out. Liu et al. [1] adopted numerical simulation methods to study the contact performance between the rubber cup and the pipe wall under different pigging conditions. Souza et al. [2] considered the PIG material to be linear and the finite element method (FEM) was developed to simulate the friction between the rubber cup and the pipe wall. Zhu et al. [3-4] compared numerical simulation results when the material of cup is linear and non-linear. The friction between the sealing discs and the pipeline is small, when the material is set to linear. Based on the 2D nonlinear numerical simulation model, the effects of parameters (including chamfer dimension, interference, thickness and clamping rate of the sealing disc) on the contact stress between the cup and the pipe wall were
investigated. Wang et al. [5] studied the contact stress state of sealing cups when the PIG was running in elbow. M.H.W. Hendrixa et al. [6] investigated the effect of thickness, interference and elastic modulus of sealing cups on the friction between the PIG and the pipe wall by experimental tests and numerical simulation methods. Xue et al. [7] analyzed the influence of thickness and hardness of cups on the contact performance of the PIG by numerical simulation method.

As mentioned above, documented investigations were mainly carried out via laboratory testing and numerical simulation methods. To a certain extent, the factors influencing the contact performance between the PIG cup and the pipe wall were investigated. While most numerical simulation researches were based on a 2D model with relatively small curvature radius, making the simulation process unable to reflect the actual operating state of the PIG accurately. Meanwhile, influence factors of PIG cup’s sealing performance was not sufficiently investigated. In this study, the operation process of a PIG in a straight pipe and elbow were simulated by finite element method. Extensive parametric analysis was conducted based on the main factors that influence the sealing performance of the PIG, i.e. sealing cup interference, elastic modulus of the sealing cup material and surface pressure difference of the sealing cup.

2. Finite element model

2.1. Geometric model

The PIG model is composed of a mandrel and rubber cups. In this study, a PIG used for a DN 508 mm pipe was considered. The four sealing cups as shown in Figure 2 are numbered Cup 1-4 from left to right respectively. In order to consider the operation of a PIG in a small curvature elbow. The curvature radius of the elbow is set to 2D, 4D and 6D respectively. The elements modelling the PIG cups, PIG mandrel and pipeline are three solid elements developed by ABAQUS, i.e. C3D8RH, C3D8R, R3D4. Based on the results of a preliminary mesh sensitivity analysis, the PIG is divided into 90721 elements as shown in Figure 2, the elbow is divided into 6336 elements as shown in Figure 3.

2.2. Material model

The material of the PIG mandrel is 20# steel. The flange and the anti-collision head plate are both made by Q345 steel. The PIG cups are made of polyurethane rubber. The elastic modulus and the Poisson ratio of both Q345 and 20# steel are 206 GPa and 0.3. In order to investigate the effects of the elastic modulus of cup material on the sealing performance of the PIG, the elastic modulus of the polyurethane material is set to four possible values, i.e. 2 MPa, 4 MPa, 6 MPa, 8 MPa. The Poisson ratio of rubber is set to 0.48 to consider its incompressibility.

2.3. Boundary conditions

The deformation of pipeline during the pigging process is negligible, thus the elbow was modeled with discrete rigid body. In order to avoid the rigid body displacement of the pipeline, all the degrees of freedom of the pipeline are constrained by a reference point. The reference point of the PIG is coupled with the inner surface of the anti-collision head mounting plate, and the PIG can be running in the pipeline by applying suitable displacement boundaries to the reference point. The friction coefficient between the rubber cup and the pipeline wall is 0.3 according to field investigation.
2.4. **FE model verification**

The FE model developed in this study is validated by a documented numerical result. The inner diameter of the pipe is 496 mm, the interference of PIG cups is 2%, and the friction coefficient between the cup and the inner wall of the pipe is set to 0.3. It can be observed from Figure 4 that with the increase in the number of sealing cups in contact with the pipeline wall, the maximum friction between cups and the pipe wall increases continuously. When the PIG is running in a straight pipe, the friction between cups and the pipe wall keeps invariant. Comparing the finite element analysis (FEA) results with the existing research results, we can find that the trends of the two numerical simulation results are basically identical, and the maximum friction forces derived is also almost the same. The correlation error is due to the fact that it is unable to obtain the accurate values of all parameters used in the literature. Generally, the FE model developed in this study is validated by this comparison.

3. **Sealing performance analysis of the rubber cup**

The sealing performance of rubber cups is one of the most important factors that influence the traveling ability of PIG. Especially, during the running process of the PIG in elbow, the separation of the rubber cup from the inner wall of pipelines leads to the insufficient driving force, which significantly increases the risk of blocking failure. The differential pressure at the front and end surfaces of the PIG was set to 0.02 MPa. In order to ensure that the PIG cup has good sealing performance, the contact stress between the rubber cup and the inner wall of the pipeline must be greater than the fluid pressure. In this study, the contact stress of 4 feature locations of the cup was obtained to monitor the sealing performance of the cups. As shown in Figure 5, four locations were marked as 0°, 90°, 180°, 270°, respectively. For each sealing cup, four nodes located along the radial direction at each location were selected. The sum value of the contact stresses on four nodes were adopted to evaluate the sealing performance at each location.

![Figure 4 Comparative analysis of numerical simulation results and existing research results](image)

![Figure 5 The distribution of feature locations of the rubber cup](image)

The curves presented in Figure 6 indicate the variation of the contact stresses during the pigging process. When the sealing cup interference is 2% and the differential pressure is 0.02 MPa, the contact stress of the sealing cup 1 and the sealing cup 4 in the location marked as 0° is less than fluid pressure. During PIG’s operation in elbow, the pressure relief phenomenon will occur in cup 1 and cup 4. On the contrary, cup 2 and cup 3 have better sealing performance.
In order to evaluate the sealing performance of considered rubber cups accurately, an evaluation index of the sealing performance of cups was defined as follows: If the sealing cup separates from pipe wall, the area where the contact stress is less than the fluid pressure is defined as the pressure relief area of the cup. The ratio of the pressure relief area to the contact area between the sealing cup and the pipe wall is defined as the evaluation index of the rubber cup sealing performance. If the cup is always in good contact with the inner wall of the pipe, the maximum value of the contact stress is selected as the evaluation index of the cup sealing performance.

4. Results and discussion

4.1. Effect of the sealing cup interference

The sealing cup interference plays an important role in pigging process. Increasing the cup interference can enhance the sealing performance of PIG. At the same time, the increase of interference will also accelerate the wear of the rubber cups. In this study, the interference of sealing cups varies from 2% to 5%. The sealing performance of the PIG is investigated, when the PIG is running in different curvature radius elbows. The pressure relief ratio and the contact stress are plotted against the sealing cup interference in Figure 7. The results presented in the figure indicate that when the curvature radius of the elbow is $2D$ and the sealing cup interference is less than 4%, different degrees of pressure relief phenomena occur in four cups. As the curvature radius of the elbow increases, the sealing performance of the rubber cup is observed to be enhanced. When the curvature radius of the elbow is $6D$, pressure relief phenomenon only occurs in the cup 4.
4.2. Effect of the elastic modulus of cup material

In the presented study, four elastic modulus values of PIG cups are considered, i.e. 2 MPa, 4 MPa, 6 MPa, 8 MPa. Figure 8 illustrates the effect of cup material’s elastic modulus on the contact stress and pressure relief ratio. It can be seen from the figure that when the curvature radius of the elbow is 2D, pressure relief phenomenon occurs in all the four sealing rubber cups. Once the PIG cup is separated from the pipe wall, increasing the elastic modulus of the cup material may significantly weaken the sealing performance of the rubber cups. If the PIG is running in a small curvature elbow, proper reduction of the elastic modulus of the cup material can reduce blockage risk of the PIG effectively. On the other hand, if the sealing cup is always in good contact with pipe wall, a generally linear positive relationship exists between the cup material’s elastic modulus and contact stress.

4.3. Effect of the differential pressure

The differential pressure of the cup surface is set as 0.02 MPa, 0.04 MPa, 0.06 MPa, 0.08 MPa, which may induce by reference 3. Effect of the differential pressure on the sealing performance of the PIG is depicted in Figure 9. The plots in the figure illustrate that when the curvature radius of the elbow is constant, the sealing performance of the PIG cup can be enhanced effectively by increasing the differential pressure of the sealing cup surface. This is due to the increase of the pressure difference on the surface of the cup will increase the contact area between the cup and the pipe wall, and reduce the possibility of the detachment between PIG’s rubber cups and pipe inner surfaces.
5. Conclusions
The pigging process of PIG in elbows was analyzed numerically in the presented study. A 3D numerical model was established by nonlinear finite element software ABAQUS. The actual operating states with various elbow radiiuses, differential pressure, cup materials and interferences of rubber cups were considered. The accuracy of the numerical model was verified by existing research results. Results show that: (1) PIG sealing cups may be detached from the pipe wall more easily, when the PIG is running in a small curvature radius elbow. With the decrease of the curvature radius of pipe elbow, the sealing performance of the PIG cup is significantly weakened, which obviously increases the blockage risk of the PIG. (2) With a determined curvature radius elbow, increasing the sealing cup interference and the surface pressure difference of the sealing cup can enhance the sealing performance of the PIG cups. (3) Once the PIG cup is separated from the pipe wall, reducing the elastic modulus of the cup material can enhance the sealing performance of the PIG cup.

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