A numerical study of liquid film distribution in wet natural gas pipelines

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Abstract. The software of FLUENT was used to simulate the gas-liquid turbulent flow in wet natural gas pipeline of the Puguang gas field. The RNG k-ε model was used to simulate the turbulent flow, the Mixture model was used to simulate gas-liquid mixed phase, and the Eulerian wall film model was used to simulate the formation and development of liquid film. The gas phase flow field characteristics, the distribution of the axial and circumferential film thickness, and the droplet distribution in the pipeline were studied when the gas Reynolds number is $7.72 \times 10^6$ (10.8 m/s). The results can be concluded as followed: Liquid film distributes unevenly along the circumferential direction and mostly distributes under the pipeline wall because of gravity. The impact of the dean vortex and centrifugal force in the straight section can also influence the liquid film distribution. The wall shear stress distributions in horizontal straight pipeline is concerned with liquid membrane volatility, and consistent with the film volatility period, the wall shear stress reached the maximum value in a certain position of wave front. The influence of the wall shear stress on the film fluctuation in inclined pipeline is weakened by gravity and other factors.

1. Introduction

In wet natural gas pipeline, saturated moisture is easy to produce condensate water in conveying process. Condensate water and the corrosive medium form thin liquid film together which unevenly distributes on the pipe wall. This uneven distribution of liquid film on the metal surface causes the different process of cathode and anode, so metal local corrosion is appeared. There are many kinds of reasons that can influence metal corrosion, such as carbon dioxide, sulfur dioxide, water, corrosion inhibitor, temperature, PH value, medium composition, flow conditions, and so on. Many scholars had gained some good results in this area; however, the study of the distribution of the liquid film is far less for low liquid. The liquid film plays an important role on the corrosion of the pipe, and it lacks further research in this area. So the study of liquid film thickness distribution and how it is changed under the effect of gas fluctuation are very important.

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The gas-liquid flow in the wet natural gas pipelines was simulated using the Fluent software, and the simulation results are verified by theory analysis. This paper mainly studied the distribution of liquid film thickness affected by gas fluctuation.

2. Calculation model
The pipeline structure size of the simulation is shown in figure 1. According to the operation data provided by Puguang gas field, the pipe diameter is 0.4636 m, the angle of two curved section is 30.78 °, and the curvature radius is 2.03 m. In order to ensure the turbulence is fully developed, setting the length of two straight pipes to be 9 m, and the inclined pipe to be 9 m, too. The origin of coordinates is located in the center of output section; y-axis negative direction is the direction of gravity. The zoning grid method is adopted in modeling, and the total grid node is 2792250. The meshing model is shown in figure 2.

3. Calculation method and the boundary conditions
The gas velocity of inlet is 10.8 m/s (7.7×10⁶), thus it belongs to the strong turbulent flow, RNG k-ε model was used in numerical calculation. The Mixture and Eulerian wall film model were used to simulate the gas-liquid two phase in the pipeline. The Mixture model was used to simulate gas-liquid mixed phase, and calculate the volume fraction of each phase. While the Eulerian wall film model was used to simulate the formation and development of liquid film. In pulse injection of diesel engine, Wall Film model was validated in the liquid film thickness and evaporation rate prediction well. Because the formation of the liquid film in the pipeline is similar to the Wall Film model, and satisfies the assumptions and limits as well, therefore, the Wall Film model was used in the simulation.

The inlet boundary condition is ‘VELOCITY_INLET’. In order to guarantee the outputs of exhaust pipe meet fully developed flow conditions, pipe length is supposed to be about 10 times of the pipe diameter. The outlet boundary condition was ‘OUTFLOW’. The outlet simulation conditions and
methods were the same as inlet. Wall boundary conditions was no slip boundary condition and reinforced wall functions was combined in simulation of fluid flow near wall region.

4. The verification of the simulation results
This article respectively verified the influence velocity distribution, wall shear stress and liquid membrane distribution on the circumferential direction in horizontal pipe.

4.1. The verification of velocity
When the gas Reynolds number $Re_g=7.72 \times 10^6$, comparing the simulation results of average velocity distribution with the theoretical results in horizontal pipe.

Based on a lot of experimental results [1], the distribution of turbulent velocity in circular tube can be calculated as Eq. (4-1).

$$u = u_m \left( \frac{y}{r} \right)^n$$

(4-1)

Where $u$ is average velocity of the fluid; $u_m$ is the maximum velocity of the fluid in the tube axis; $r$ is the radius of the pipe; $y$ is radial distance from the wall; $n$ is the index, for the hydraulic smooth tube, when $Re < 10^5$, $n = 1/7$. When $10^5 < Re < 4 \times 10^5$, $n = 1/8$. and for rough tube, $n = 1/10$.

Figure 3 shows the velocity comparison between simulation and the theory in horizontal pipe. Simulation result shows a good agreement with the theoretical data, and the maximum error is 10.7%.

4.2. The verification of wall shear stress
When the gas Reynolds number $Re_g=7.72 \times 10^6$, the wall shear stress of simulation compared with the theoretical in horizontal pipe.

The original work shows [2, 3] that when $Re_g$ is more than $10^6$, the wall shear stress is as follows:

$$\tau_w = \frac{0.0296 \rho U^2}{Re_i^{0.2}}$$

(3-8)
where \( \text{Re}_x \) is the local Reynolds number, \( U \) is the velocity in the center of pipe, \( \tau_w \) is wall shear stress, \( \rho \) is the gas density under the condition.

Figure 4 is the comparison of wall shear stress between simulation and theoretical values. The conclusion is present that the simulation results agree well with the theory data. The maximum error is 4.0%.

![Figure 4. The wall shear stress between simulation theory](image)

### 5. Phase flow field analysis
The gas phase flow field distribution in wet natural gas pipeline is done to set the foundation of further study of liquid film distribution in the pipeline. Cross sections of the pipe are chosen to be analyzed, which is shown in Figure 5.

![Figure 5. The distribution of the cross section](image)

#### 5.1. Gas streamlines
In this paper, the pipeline bending angles were all set to be 30.78°. The velocity distribution of bend section is chosen to be studied because the flow in bending pipe is complex.
As can be seen from above streamline distribution, there are a pair of dean vortex at the bending section of entrance, and the vortex move to the inside gradually. There are two pairs of dean vortex at the bending section of output, one pair at lateral, and other at inner side. The outside vortex moves to the side wall gradually, and the inner side vortex moves close to the center gradually, in the meantime, they became smaller gradually. Dean vortex is a common physical phenomenon [4]. Due to the effects of centrifugal force, viscous fluid produced a pair of symmetric vortex under the mainstream velocity in the bending pipe, and in contrast to the mainstream direction of cross section.

5.2. Velocity distribution curved line

In order to study the speed changes with the Reynolds number, three typical sections in the pipe are analyzed, which are the straight pipe 1-3, bending pipe 1-2, inclined pipe 5 (as shown in figure 6).

Figure 6 represents speed curve of straight pipe 1-3, the cross section location of fully turbulent area in straight pipe. There is boundary layer near the wall, and velocity distribution of the boundary layer is more complex. The speed tends to increase along with the increase of radial distance. Velocity is close to the entrance speed in fully turbulent area, and in line with turbulent velocity distribution of the straight pipe.

Figure 9 is speed curve of bending pipe 1-2 (the section of up bend 20°). The speed change is bigger at bending pipe, the velocity decreases from inner side to lateral outside in bending pipe. The fluid is squeezed to lateral wall side of pipeline because of the centrifugal factor, in the meantime, the diffusion effects on the outside lateral of bending pipe are generated, and the acceleration channel on inner side is appear.

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Figure 10 shows speed curve of inclined pipe 5. The speed has a tendency to increase from down wall side to up wall side in the fully turbulent area. Because of dean vortex moving to down wall side under gravity, fluid is squeezed to the lateral wall, diffusion effect on the outside lateral of bending pipe is generated, and the acceleration channel is formed on inner side. So the velocity near the up wall side is faster than the velocity near the down wall side. Y is radial distance away from the down wall side on diagram.

**Figure 8.** The velocity curve of straight pipe 1-3 (Y is radial distance away from the down wall side on diagram)

**Figure 9.** The velocity curve of bending pipe 1-2 (Y is radial distance away from the down wall side on diagram)
6. Phase flow field analysis

6.1. Liquid Film Distribution
Since the liquid film is very thin in the pipe, the liquid film thickness is magnified 1000 times in this article in order to clearly show the liquid film. There are nine characteristic sections (Figure 6) to be studied. They respectively are straight pipe 1-3, bending pipe 1-1, bending pipe 1-2, bending pipe 1-3, inclined pipe 3, inclined pipe 6, bending pipe 2-1, bending pipe 2-2 and bending pipe 2-3.

Figure 12 shows the distribution of liquid film thickness of characteristics section. Liquid film distributed on the circumference of tube wall, because it was influenced by the mechanism of the gas secondary flow, the principle of disturbance wave suction, droplets carrying and settlement mechanism. Figure (a) shows that liquid film is mainly distributed in the under part of pipe because of the influence of the gas phase flow field and the gravity. The liquid film in the upper part of pipe is very thin. The location in Figure (b), (c), (d) is up bending 10°, 20° and 30.78° of cross section. The liquid film is thinner at this time according Figure (b), (c), and there is a big bump in Figure (d). Because of the centrifugal force, liquid moved from inner side to lateral side in bending pipe. In addition, the gas phase flow field driven liquid flow, and the movement of gas fluid squeezed liquid, lead to the liquid film bulged. Fluid went through a tilt angle when the liquid moved from straight pipe to bending pipe. In F.Maroteaux’s [5] article, there is a part of the liquid film peeled and forming droplets when the liquid film flows through a certain angle. The droplets made a horizontal cast exercise in bending pipe, and landing in the under part of pipe after peeling off position. Therefore, the liquid film thickness before part of the bending pipe is thinner than the straight pipe. Figure (e) and (f) shows the liquid film thickness in the bending pipe. The liquid film concentrated on the down part of the wall under gravity, and the thickness increases gradually. The location in Figure (g), (h), (i) is down bending 10°, 20° and 30.78° of cross section. The distribution is similar to the up bending pipe. Under the accelerated speed of inclined pipe, the inlet’s velocity was much bigger than the one on the up bending pipe. Therefore the liquid film thickness increased gradually.
6.2. The effects of wall shear stress on liquid film distribution

The wall shear stress was used to verify the simulation results in former part. The conclusion was presented that the wall shear stress increased with the gas Reynolds number. In this section, the relationship between wall shear stress and the distribution of the liquid film was mainly explored.

The curve of wall shear stress and liquid film thickness of straight pipe and inclined pipe were drawn as it is seen in ‘Figure 12’.
Figure 12. Intercepted section of the straight pipe and inclined pipe.

Figure 13 and Figure 14 are curve of the wall shear stress and the liquid film thickness along the axial direction. Z is the horizontal distance away from the entrance. Figure 13 shows the simulation results is similar to analysis of Xuehu Ma [6] professor, that is the wall shear stress affected the liquid film thickness. The fluctuation curve of liquid film was connected with distribution of wall in straight pipe, and is cyclical. Wall shear stress reached peak in front of wave crest of the liquid film, and then fell rapidly. Figure 14 shows wall shear stress fluctuation in inclined pipe. It hasn’t caused too much influence to liquid film thickness. Liquid flow was affected by gas-liquid interface shear stress, weight component along the inclined tube, and wall shear stress.

Figure 13. The changing curve of the wall shear stress and the liquid film thickness on axial direction in straight pipe (Z is the horizontal distance away from the entrance)

Figure 14. The changing curve of the wall shear stress and the liquid film thickness on axial direction in inclined pipe (Z is the horizontal distance away from the entrance)
7. Conclusion
The main conclusions are as follows:
(1) The dean vortex was caused by centrifugal force in the bending pipe, and gradually moved to the outside with the increase of bend angle.
(2) Liquid film distributed unevenly on circumferential direction of pipe wall. The distribution of liquid film was effected by gravity, the movement of the gas phase flow field, and centrifugal force.
(3) The fluctuation curve of liquid film had some relationship with distribution of wall in straight pipe, and appeared cyclically. Wall shear stress reached peak in front of wave crest of the liquid film. The shear stress didn’t cause too much influence on the fluctuation curve of liquid film.
(4) This paper successfully simulated the distribution of the liquid film in large diameter pipe which contained low liquid, supporting the next step of pipeline corrosion research.

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