Effect of velocity and water cut on water distribution in elbows of petroleum pipelines

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Abstract. As one of the main energy sources, petroleum and natural gas are widely used around the world. Safety of the transportation causes more attentions recently. Currently, since some oil wells are in the late period of the production, water pre-injection is often used to rise the well pressure. Thus, the water cut is usually high in oil gathering pipelines. The inner wall of pipelines without coating would be corroded by contacting with the mixed corrosive medium and water during the long-term running, which may even lead to leakage accidents. Researches about flow pattern of oil-water multiphase flow pipes are mainly about straight pipelines, but few about elbows. In this work, water distributions in elbows of gathering pipelines were studied according to the experimental results and computational fluid dynamics (CFD) simulation results. The water deposited when the fluid velocity was low enough and the water cut is high. According to the simulation results and experimental results, an oil-water phase inversion curve was obtained to be guidance for water distribution analysis in elbows.

1. Introduction

Inner erosion [1-2] and corrosion [3-4] induced wall thinning of pipelines is a main reason of the leakage accidents in oil and gas industry. In order to ensure the operation safety of in-service pipelines, it is necessary for companies to evaluate the situation of pipelines based on inspections. Due to the limitation of the surrounding environment of in-service pipelines, detection for some pipelines are very difficult to carry out and the cost is high. Flow field analysis and evaluation of pipelines are valid methods for key detection areas determination to reduce the detection cost. Water distribution in an important factor in flow field analysis [5-6] and direct evaluation of internal corrosion of oil-water pipelines [7]. It is well known that the corrosion is induced by the presence of water [8-9]. Corrosion behavior is dependent on multiple factors such as the fluid properties, velocity, water cut, phase inversion, flow pattern, material of pipelines and so on [10-11]. A review of internal corrosion mechanism of multiphase flow were discussed which considering the water deposit depends on the maximum droplet diameter and critical droplet diameter of water [12]. Researches are mainly concentrated on flow pattern in straight pipelines, but few about that in elbows. However, erosion and corrosion are more common in gathering and industrial pipelines [13], especially in pipelines with high water cut. Water distributions of elbows were discussed according to experiments and simulations in this work.
2. Multiphase flow experiments

2.1. Experimental loop design
Due to the effect of fluid viscosity, the velocity of fluid in pipelines are various in different positions. The fluid velocity near the wall is lower than it near the center of the pipe. In experiments, the length for fluid fully developed depends on the flow situation and Reynolds number of the fluid shows below [14].

\[
\frac{L_e}{D} \approx 0.06 \text{Re}, \quad \text{Laminar flow} \quad (1)
\]

\[
\frac{L_e}{D} \approx 4.4 \text{Re}^{0.8}, \quad \text{Turbulence flow} \quad (2)
\]

When Reynolds number is 2300, the critical condition for laminar flow transiting to turbulent flow, the necessary length of pipe for flow fully development is 138 times of diameter. The inner diameter of pipelines used in experimental loop is 100 mm, so the length of fully developing straight pipe is designed as 13.8 m. According to the functional requirements of the experiments, the connection diagram of the test loop is designed as shown in Figure 1. Considering that the water is easy to deposit at the bottom of the elbow by gravity, the test elbow was set up on the bottom of the upward pipe in the loop shown in the red circle in Figure 1.

![Connection diagram of test loop.](image)

The 46# hydraulic oil and water were used to obtain effect of velocity and water cut on water distribution in elbow. Different velocities and water cuts were set in experiments. The specific parameters of experiments are shown in Table 1.

![Table 1. Specific parameters of experiments.](table)

2.2. Experimental results
The stable water distributions in the test elbow are shown in Figure 2, when the flow velocity changed from 0.1 m/s to 1.2 m/s and the water cut is 20%. In the test elbow, the yellow part in the elbow is the oil phase and the milky white translucent medium is the water phase. Although, the emulsification of oil-water occurred after long-time operating, the boundary layer of the two phases could be distinguished in the image analysis software.
Water distributions in elbows for various velocities when the water cut was 20%.

The curves of water layer thickness under various velocities and water cuts are as shown in Figure 3. The water layer thickness is expressed by \( h/D \), where \( h \) is the actual thickness of water layer measured from the surface to the bottom, \( D \) is the inner diameter of the pipeline. When the water cut is low, small amount of water flowed near the bottom of the test elbow, the water layer thickness is small. The water carrying capacity of the fluid became better as the velocity increased, and there was almost no water in the bottom of the test elbow. The water layer thickness became higher obviously as the water cut increased. When the water cut increased to a certain value, even the fluid velocity was high, there was still some water which could not be carried to the downstream. Corrosion would occur in this kind of stagnant water area possibly. A suggestion of operation velocity range in industry could be proposed based on this curve. Due to the fluctuation of the test results, the water phase distribution at the bottom of the test elbow was analyzed combining with the numerical simulation.

3. Numerical simulations of the elbow

3.1. Simulation model

The pipe geometry is shown as Figure 4 with tetrahedral meshes according to the size of pipelines in test loop [15]. The length of horizontal part of the pipe was 5 m to ensure the flow fully developed. The boundary conditions of the model were set according to the velocity and water cut in experiments.
The temperature was set as 25 °C neglecting the effect of temperature fluctuation. There will be a slip between the two phases for the densities of oil and water are different, the volume of fluid (VOF) model were used in simulation.

![Figure 4. The mesh of the text elbow.](image)

3.2. Comparison between simulation results and experimental results
Effect of velocity and water cut on water phase distributions were analysed according to the simulation results obtained from the model shown in Part 3.1. The water layer situation and flow track in experiments and simulations are shown in Figure 5, when the water cut is 20% and velocity is 0.1 m/s. The water layer in the elbow are similar in both experimental and simulation results. Because of the slight fluctuations in experiments, the thickness of the water layer is a little bit higher in Figure 5(a) than that in Figure 5(b). The backflow occurred in the downstream upward pipe under the effect of gravity, especially under low velocity.

![Figure 5. Water layer situation and flow track in experiments and simulations (when the water cut is 20% and velocity is 0.1 m/s).](image)

3.3. Effect of velocity and water cut on water distribution
The water distributions at the bottom of elbows under different velocities are shown in Figure 6, when the water cut was set as 20%. The water carrying capacity of the medium could be improved by increasing the velocity. So that corrosion possibilities would be reduced by this method. Water would fall back in elbows under the effect of the gravity and further form a stagnant water area. The water could not be carried completely and even induced corrosion on the wall of elbows.
The thickness values were obtained from simulating results at the bottom of the upstream pipe as shown in Figure 7 (in the position of the red line). The calculating values were obtained by inserting a central line in the connection interface between the elbow and the straight pipe. Relations between the water layer thickness and velocities in elbows are shown in Figure 7. The water layer thickness was determined when the local water cut equal to 80%. The water layer thickness decreased faster as the velocity increased while the water cut of the medium is high. Relations between water layer thickness and water cut are shown in Figure 8. The water layer thickness increased more obvious as the water cut became larger while the fluid velocity is low. The curve tends to a linear growth when the fluid velocity is 0.3 m/s, and the value of the water layer thickness \((h/D)\) is close to the water cut of the medium.

Figure 6. Water layer situations in elbows under various velocities when the water cut is 20%.

Figure 7. Relations between water layer thickness and velocity at the bottom of elbows.
4. Analysis of oil-water stratification based on simulations and experiments

The similar fitted curve [16] of oil-water stratification for elbows with the same size in experiments was obtained according to the simulation results, which is shown in Figure 9. Relations amount water cut, velocity and water deposition were obtained by this method which provide a simple method for water accumulation prediction of elbows. Generally, the size and parameters pipelines are uniform in the same area. An oil-water phase transition curve can be fitted for a company. The blue triangle points represent water occurring in elbows. The possibility of water deposition can be simply predicted by comparing the operating conditions with the curves.

5. Conclusions

The water distribution in multiphase flow elbows were obtained based on experimental results and CFD simulation results. Effect of velocity and water cut on water layer in elbows was discussed also. The main conclusions are shown as follows,

1) Because of the backflow in elbows, the flow is more complex under low fluid velocity. The water carrying capacity of the multiphase flow becomes stronger as the velocity increases.

2) The water layer thickness increases when the water cut is larger. When the value of water cut increases to a certain value, there is still water deposition at the bottom of the elbow even the velocity is high in experiments of this work.

3) When the velocity is 0.3 m/s, the thickness of the water layer thickness (h/D) at the bottom of the elbow is basically consistent with the water cut under the experimental conditions in this paper. The curve of relation between water layer thickness and water cut tends to be linear.

4) The oil-water stratification curve of multiphase in the elbow can be fitted according to the numerical analysis. It can be a theoretical basis for assessing the possibility of water deposition in elbows.
5) Further study on water distributions in other components of pipelines are necessary for corrosion predictions in the future work.

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References
[1] Wang B, Kang K, Kuai C T, Xu X and Wang L 2019 Numerical simulation of the erosion wear of pipes with a low concentration of particles and multiphase flow Journal of Beijing University of Chemical Technology (Natural Science) 46(02) 24-32
[2] Nan L, Arabnejad H, Shirazi S A, McLaury B S and Huiqing L 2018 Experimental study of particle size, shape and particle flow rate on erosion of stainless steel Powder Technology 336 70-79
[3] Barker RJ, Hu X, Neville A and Cushman R S 2014 Empirical prediction of carbon-steel degradation rates on an offshore oil and gas facility: predicting CO2 erosion-corrosion pipeline failures before they occur SPE J 19 425–436
[4] Nešić S, Wang S, Fang H, Sun W and Lee J 2008 A new updated model of CO2/H2S corrosion in multiphase flow. In: Corrosion Conference and Expo, NACE International, New Orleans
[5] Becerra H Q, Retamoso C, Macdonald D D 2000 The corrosion of carbon steel in oil-in-water emulsions under controlled hydrodynamic conditions Corrosion Sci 42(3) 561-575
[6] Zhu S D, Fu A Q, Miao J, Yin Z F, Zhou G S and Wei J F 2011 Corrosion of N80 carbon steel in oil field formation water containing CO2 in the absence and presence of acetic acid Corrosion Sci 53(10) 3156-3165
[7] Yu B, Li C, Zhang Z and Liu X 2008 Numerical simulation of a buried hot crude oil pipeline under normal operation Aool Therm Eng 30(17) 2670-2679
[8] NACE, Internal Corrosion Direct Assessment Methodology for Liquid Petroleum Pipelines, NACE SP02082008 2008
[9] NACE, Multiphase Flow Internal Corrosion Direct Assessment (MP-ICDA) Methodology for Pipelines, NACE SP0116 2016
[10] Nešić S 2007 Key issues related to modelling of internal corrosion of oil and gas pipelines – a review. Corros Sci 49 4308–4338
[11] Taitel Y and Dukler A 1976 A model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow AIChE J 22 47–55
[12] Zhang H and Lan H Q 2017 A review of internal corrosion mechanistic and experimental study for pipelines based on multiphase flow Corrosion Reviews 35
[13] Huang H, Ma H L, He R Y and Chen L Q 2015 Analysis on the internal corrosion cause of typical pipe fitting in the pipeline of a natural gas gathering station Physical Testing and Chemical Analysis (Part A: Physical Testing) 51(9) 653-656
[14] Zhang H 2020 Location prediction of internal corrosion induced by water wetting in the water-containing crude oil pipeline, Beijing, Beijing Jiaotong University
[15] Moyle K R, Antiga L and Steinman D A 2006 Inlet conditions for image-based CFD models of the carotid bifurcation: is it reasonable to assume fully developed flow? J Biomech Eng 128(3) 371-9
[16] Kee K E, Richter S, Bobic M and Nesic S 2015 Experimental Study of Oil-Water Flow Patterns in a Large Diameter Flow Loop - The Effects on Water Wetting and Corrosion. Corrosion 72(4) 569-582