Fluid Dynamics & Materials Processing
DOI:10.32604/fdmp.2020.08896
Article

Tech Science Press

Effect of the Inclination Angle on Slippage Loss in Gas-Liquid Two-Phase Flow

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Received: 22 October 2019; Accepted: 09 March 2020

Abstract: The lifting efficiency and stability of gas lift well are affected by the so-called slippage-loss effect in gas-liquid two-phase flow. The existing studies on this subject have generally been based on vertical and horizontal wells. Only a few of them have considered inclined pipes. In the present work a new focused study is presented along these lines. More specifically, we use the non-slip pressure drop model with Flanigan's fluctuation correction coefficient formula (together with the parameters of slippage density, slippage pressure drop and slippage ratio) to analyze the influence of the inclination angle on slippage loss for different conditions (different gas-liquid superficial velocity and pipe diameters). Moreover, the "standard regression coefficient method" is used for multi-factor sensitivity analysis. The experimental results indicate that slippage loss is affected by multiple factors, and the influence of the inclination angle on slippage loss is less significant than other factors. The change of the slippage pressure drop with the superficial velocity of gas-liquid is similar to that of the total pressure drop. The inclination angles of 45° and 60° have the greatest influence on slippage loss. The correlation between slippage density and slippage ratio is not obvious. Using the so-called slippage ratio seems to be a more accurate option to evaluate the degree of slippage loss.

Keywords: Inclined pipes; gas-liquid flow; slippage loss; pressure drop; gas-liquid ratio

1 Introduction

Gas-liquid two-phase flow exists in the production of oil and gas resources. Flow pattern, pressure drop and liquid holdup are the main parameters to characterize a gas-liquid two-phase flow [1]. With formation pressure decreasing and water cut increasing, liquid slippage loss will have increasingly greater influence on the pressure drop in the process of gas lift, which will further reduce the lift efficiency [2–5]. Therefore, understanding of the effects of inclination angle on the slippage loss is of great importance for calculating the productivity of inclined wells.

It is known that the two-phase flow in an inclined pipe is different from that in a vertical pipe, and that in an inclined pipe, the acceleration pressure drop is often much smaller than the friction pressure drop and gravitational pressure drop [6,7]. Therefore, in this paper, acceleration pressure drop is ignored, and only friction pressure drop and gravitational pressure drop are considered. According to the research on gas-liquid slippage loss effect by Zhong [8], slippage loss can be characterized by slippage density (the difference between the density of gas-liquid two-phase mixture under true liquid holdup and non-slip model), slippage pressure drop (the difference between actual pressure gradient and calculated pressure drop by non-slip model) and slippage ratio (ratio of slippage pressure drop to actual total pressure drop) [9–11].

This paper conducts experimental research on the pressure drop caused by slippage phenomenon under the conditions of different gas-liquid superficial velocities and pipe diameters in inclined pipes. The multi-factor sensitivity analysis is performed to investigate the degree of influence of inclination angle on slippage loss.

2 Theoretical Basis

2.1 Slippage Loss

Slippage is a phenomenon in which gas rises beyond liquid due to the density difference between them in a gas-liquid two-phase flow [12,13]. When no slippage is assumed, a homogeneous flow model is used to assume that gas and liquid flow velocities are equal, where slippage velocity difference Δv is 0, and slippage ratio s is 1.

Simultaneously, it is also assumed that the gas phase and liquid phase have reached a thermodynamic equilibrium state. The pressure and density are single-valued functions. Therefore, without considering slippage, the flow density of a two-phase mixture is given by:

$$\rho' = \frac{G}{Q} = \frac{\rho_g Q_g + \rho_l Q_l}{Q_g + Q_l} = \beta\rho_g + (1-\beta)\rho_l \tag{1}$$

where ρ' is the density of the non-slip mixture, ρ_g is the density of gas, ρ_l is the density of liquid, G is the mass flow rate of the mixture, Q_g is the volume flow rate of gas, Q_l is the volume flow rate of liquid, β represents the volume void fraction, dimensionless.

In this paper, the pressure drop of gas-liquid two-phase flow in inclined pipes is solved by the non-slip model and Flanigan's undulation correction coefficient formula [14]. We have

$$-\frac{dp}{dz} = \frac{\lambda v^2}{2D}\rho' + F_c\rho_l \sin\theta + \rho v\frac{dv}{dz} \approx \frac{\lambda v^2}{2D}\rho' + F_c\rho_l \sin\theta \tag{2}$$

$$\lambda = 0.0056 + \frac{0.5}{\mathrm{Re}^{0.32}} \tag{3}$$

$$\mathrm{Re} = \frac{Dv\rho'}{\mu'} \tag{4}$$

$$\mu' = \beta\mu_g + (1-\beta)\mu_l \tag{5}$$

$$F_c = \frac{1}{1 + 1.0785 v_{sg}^{1.006}} \tag{6}$$

where λ represents the non-slip friction coefficient of gas-liquid mixture, dimensionless, θ represents the inclination angle of the pipeline, D represents the diameter of the pipeline, F_c represents the Flanigan's fluctuation correction coefficient.

In an actual flow process, density difference will occur because gas density is smaller than liquid density, so that the actual flow velocity of gas phase is greater than that of liquid phase [15]. Therefore, actual mixed flow density is greater than ideal mixed flow density (without slippage). ϕ represents the cross-sectional void fraction. The slippage density can be expressed as:

$$\Delta\rho = \rho - \rho' = (\phi - \beta)\rho_g + (\beta - \phi)\rho_l \tag{7}$$

where the actual density of mixed fluid flow can be measured from the actual liquid holdup of two-phase flow [16–18]. As a result, the density with slippage loss can be calculated using the actual pressure drop obtained from experiment, after which we can analyze the change in slippage loss under different conditions.

2.2 Sensitivity Analysis Method

In an actual flow process, density difference will occur because gas density is smaller than liquid density, so that the actual flow velocity of gas phase is greater than that of liquid phase. Therefore, actual mixed flow density is greater than ideal mixed flow density (without slippage). The slippage density can be expressed as:

Slippage loss is usually affected by multiple factors, such as gas-liquid ratio, fluid superficial velocity, and pipe diameter. Since the single factor analysis method cannot accurately analyze the influence of inclination angle on slippage loss, this research adopts the "standard regression coefficient method" [19,20].

For the dependent variable Y, n experiments are conducted, and the independent variables are X_1, X_2, ……X_m, where X_{ik} represents the value of independent variable X_i in the k-th experiment and Y_k represents the result of dependent variable Y in the k-th experiment.

$$\begin{cases} I_{ij} = \sum_{k=1}^{n} (X_{ik} - \bar{X}_i)(X_{jk} - \bar{X}_j) \\ I_{i0} = \sum_{k=1}^{n} (X_{ik} - \bar{X}_i)(Y_k - \overline{Y}) \\ I_{00} = \sum_{k=1}^{n} (Y_k - \overline{Y})^2 \\ i,j = 1, 2, \ldots, n \end{cases} \tag{8}$$

$$\bar{X} = \frac{1}{n}\sum_{k=1}^{n} X_{ik}, (i = 1, 2, \ldots, m) \tag{9}$$

$$\bar{Y} = \frac{1}{n}\sum_{k=1}^{n} Y_k \tag{10}$$

If there is a linear relationship between Y and X_i , the regression equation is expressed as:

$$Y = a + b_1X_1 + b_2X_2 + \ldots + b_mX_m \tag{11}$$

$$\sum_{j=1}^{n} I_{ij}b_j = I_{i0}, (i = 1, 2, \ldots, m) \tag{12}$$

where a is a constant, and $b_i^{'}$ is the standard regression coefficient. They can be expressed by:

$$a = \bar{Y} - \sum_{i=1}^{m} b_1\bar{X}_i \tag{13}$$

$$b_i^{'} = b_i\sqrt{\frac{I_{ii}}{I_{00}}} \tag{14}$$

The standard regression coefficient b_i' is independent of the units of Y and X_i. Therefore, the greater the absolute value of b_i', the greater the influence of X_i on Y.

3 Experimental Setup

The two-phase flow in an inclined wellbore is similar to that in a conventional inclined pipe [21]. The experiment was carried out on the multi-phase flow experimental platform at Yangtze University, as shown in Fig. 1. The parameters of the multi-phase flow were set as follows, inclination angle of 0~90°, temperature of 0~90 °C, and pressure of 0~3.5 MPa. The platform is mainly composed of the gas circuit, the liquid circuit, the test section, and the operation control platform. The liquid flowmeter used the E + H brand with an accuracy of 0.3%. The gas flowmeter used the Brooks brand with an accuracy of 1%. The differential pressure sensor used the Rosemount brand with an accuracy of 0.25%. The accuracy of the pressure signal of the test section was 0.1%. Two quick closing valves installed in the test section were used to measure the liquid holdup, with a resolution of less than 0.1 kPa. The accuracy of the thermometer was 0.5%. The experiment was conducted on the test section with a length of 7 m. The liquid was white oil and the gas was air.

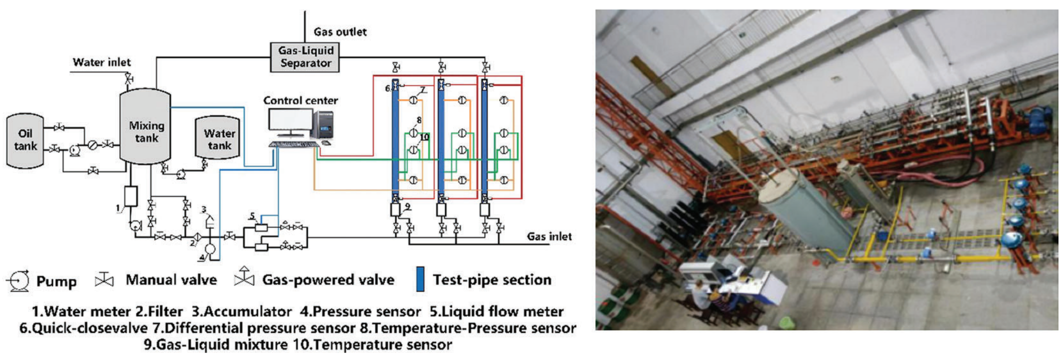

Figure 1: Schematic diagram and picture of the experimental platform

In the experiment, the liquid inlet volume could be changed by adjusting the power of the liquid pump and the ratio of the opening of the regulating valve. The air intake volume could also be changed according to the above method. The volume flow rate of the liquid phase was 10~30 m3/d, and that of the gas phase was 1000~10000 m3/d. The experimental parameters are shown in Tab. 1.

The experiment was carried out at room temperature of 11–14°C. The specific steps are as follows:

(1) Firstly, in each group of experiments, the volume flows of the liquid and gas were set through the experimental platform, and the plunger pump and gas valve under the corresponding flow were opened. The liquid was output from the oil-water mixing tank, followed by the mixing with the compressed gas from the air compressor after boosting, stabilizing and measuring by the liquid pump, and then entered the test section.

(2) The gas-liquid distribution was carefully observed until it tended to be stable. Then the gas and liquid volume flow rate, temperature, pressure and pressure difference in the test section were recorded in real time through the experimental platform. The recording time was 3 min, during which time 36 sets of data were finally obtained. After screening out the obviously erroneous data, the average value was adopted.

(3) Turn off instruments after recording. A quick shut-off valve was installed at both ends of the test section. The liquid holdup was measured by the fast-open valve method. After separating the gas through a gas-liquid separator, the fluid in the pipe returned to the mixing tank to subject to a set of cycles.

(4) Change the pipe diameter (40 mm, 60 mm and 75 mm), pipe inclination angle (30°, 45°, 60° and 90°), liquid volume flow, and gas volume flow to obtain the experimental results under different conditions.

This experiment aimed to obtain the parameters including gas-liquid ratio, superficial liquid velocity, liquid holdup and pressure drop under different pipe inclination angles. Finally, we calculated the slippage density and slippage pressure drop.

Table 1: Experimental parameters

Experimental conditions	Values
Pressure (MPa)	0.01~0.12
Temperature (°C)	23.11~30.35
Superficial liquid velocity (m/s)	0.026~0.46
Superficial gas velocity (m/s)	1.3~138.15
Liquid holdup	0.014~0.47
Pipe diameter (mm)	40, 60, 75
Angle of upward inclination (°)	30, 45, 60, 90
Gas-liquid ratio	50, 100, 150, 200, 300

4 Results and Analysis

The flow patterns were recorded using a high-speed camera. There were three flow patterns in the experiment, i.e., slug flow, churn flow and annular flow, as shown in Fig. 2. As a result of gravity, there was a liquid film on the pipe wall in all experiments. The thickness of the liquid film was affected by many factors [22,23]. Taking the slug flow as an example, under the condition of the same superficial liquid velocity (0.026 m/s) at 45°, as the superficial gas velocity increased from 1.3 m/s to 13 m/s, less liquid occupied the cross section of the pipe. Since gas-liquid slippage could affect the liquid holdup which would decrease with the increase in the superficial gas velocity, the liquid at the bottom of the pipe would constantly reduce along the pipe wall, and less liquid would adhere to the upper pipe wall.

Under the condition of the same gas-liquid flow rate, larger inclination angle led to more obvious liquid recirculation due to the influence of gravity. Besides, the liquid holdup was observed to change regularly with the inclination angle, which could explain that the degree of slippage in the gas-liquid two-phase flow also changed accordingly.

Because slippage loss is affected by many factors, the influence of inclination angle on slippage loss cannot be intuitively observed from experimental results. Therefore, slippage density, slippage pressure drop and slippage ratio were used to characterize the slippage loss of the two-phase flow in the inclined pipe. Sensitivity analysis was performed on four main factors including inclination angle, gas-liquid ratio, superficial liquid velocity and pipe diameter. The results of sensitivity analysis are shown in Fig. 3.

The results indicated that the slippage loss was affected by four factors. Among the four factors, inclination angle had the smallest influence while pipe diameter had the largest influence. Among the three parameters of slippage loss, slippage ratio was most affected by the four factors.

In order to more intuitively exhibit the influence of inclination angle on the slippage loss, analysis was performed about how the inclination angles affected the slippage loss under different gas-liquid superficial velocities and pipe diameters.

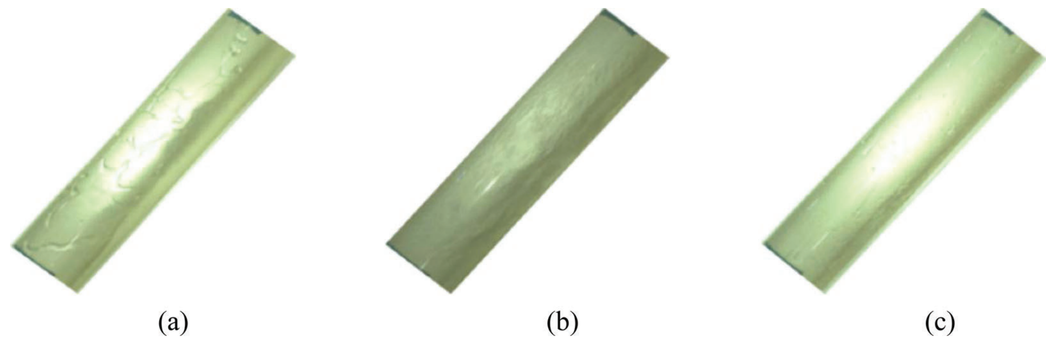

Figure 2: Pictures of different flow patterns at a 60° inclination angle: slug flow (a); churn flow (b); and annular flow (c)

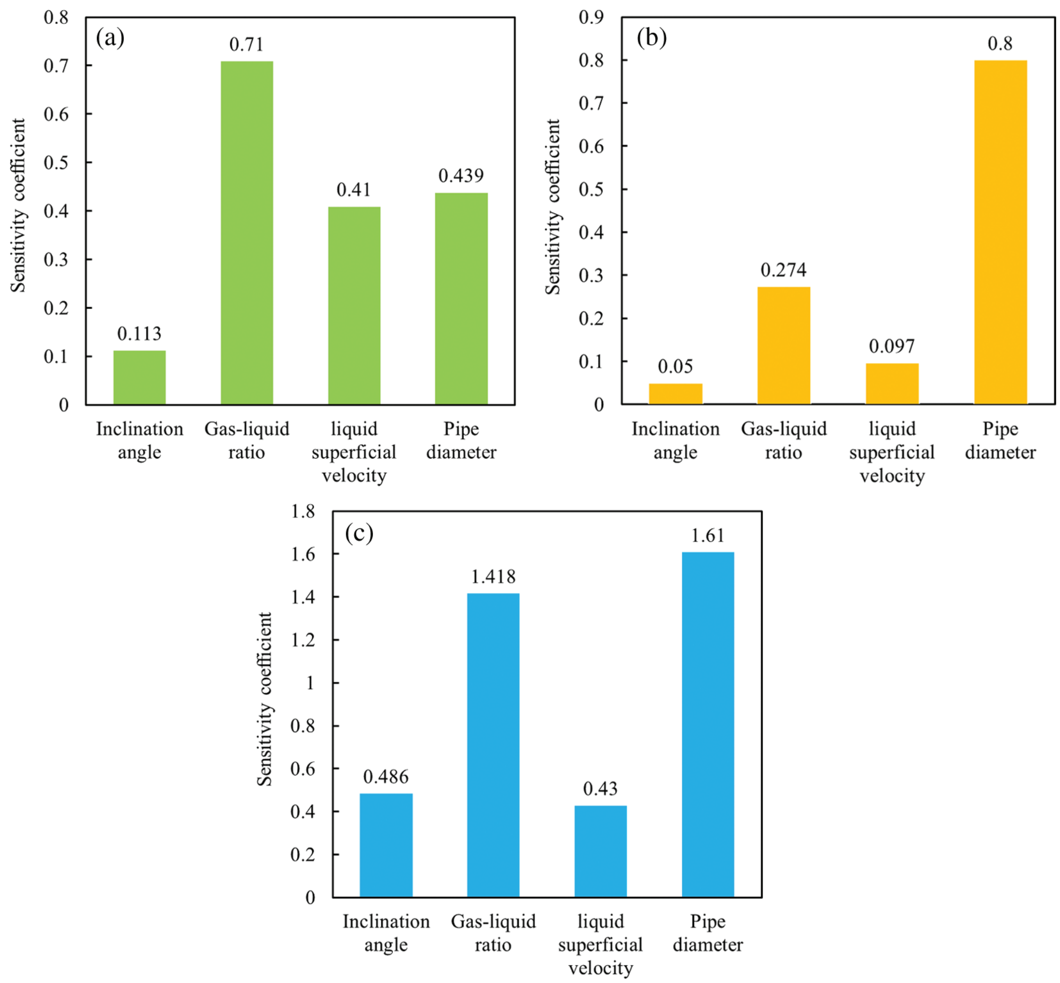

Figure 3: Influences of the factors on slippage loss: (a) Sensitivity analysis of slippage density; (b) Sensitivity analysis of slippage pressure drop; (c) Sensitivity analysis of slippage ratio

4.1 Different Gas-Liquid Superficial Velocities

With the pipe diameter kept at 60 mm, the inclination angle was changed (30°, 45°, 60°, and 90°) under different gas-liquid ratios, to observe the influence of inclination angle on the slippage density, slippage pressure drop, and slippage ratio. The experimental results are shown in Figs. 4–6.

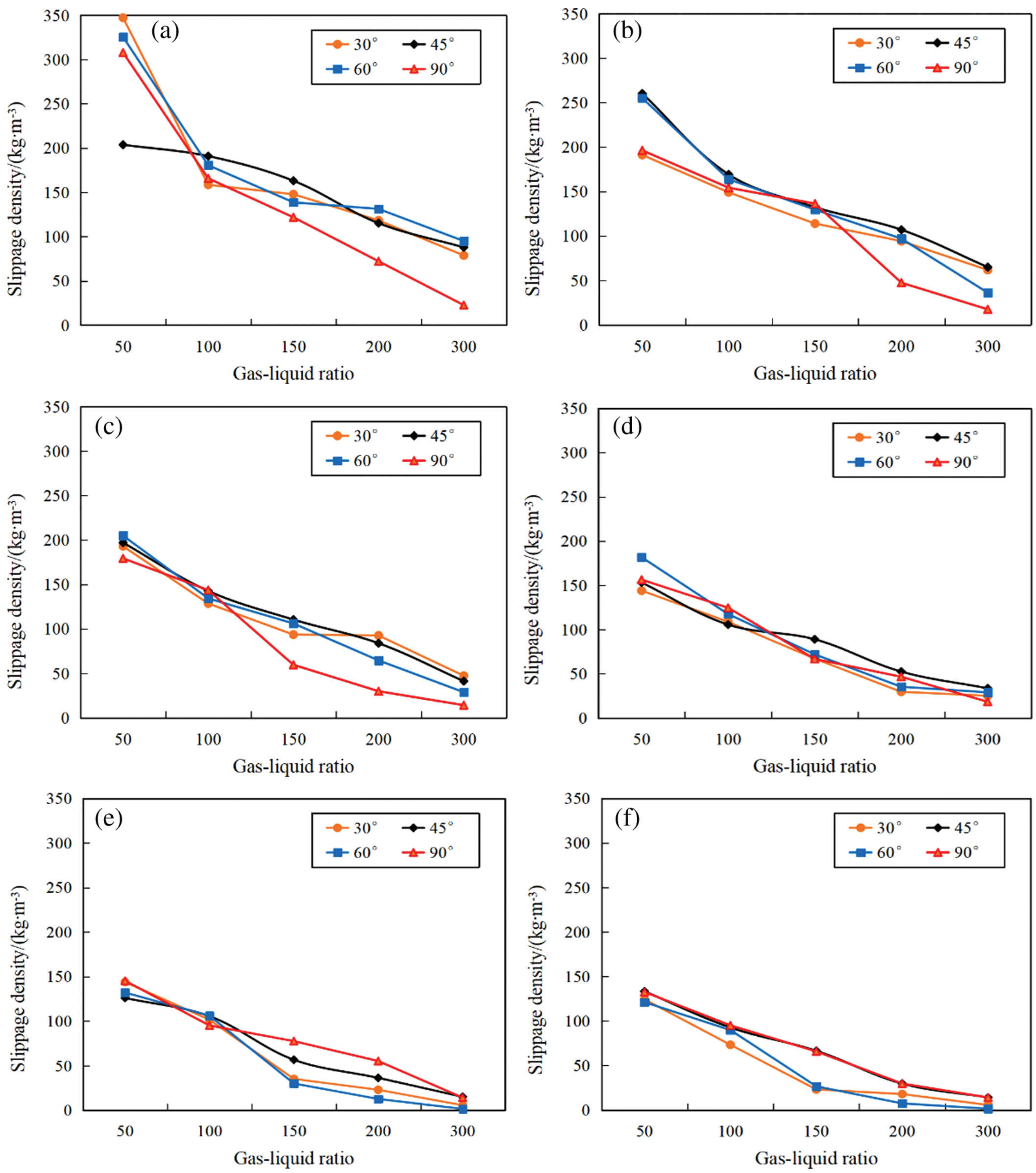

Figure 4: Slippage density *vs.* gas-liquid ratio at the superficial liquid velocity of (a) $v_{sl} = 0.041\ m/s$; (b) $v_{sl} = 0.061\ m/s$; (c) $v_{sl} = 0.082\ m/s$; (d) $v_{sl} = 0.122\ m/s$; (e) $v_{sl} = 0.164\ m/s$; (f) $v_{sl} = 0.205\ m/s$

According to Figs. 4–6, under the same superficial liquid velocity, with the increase of the gas-liquid ratio, the slippage density decreased and the slippage pressure drop and slippage ratio first decreased and then increased. According to the experimental flow patterns, it could be observed that the slippage pressure drop during the slug flow was greater than that during the annular flow. But after the flow pattern entered the annular flow, the loss in slip pressure drop increased, which was similar to the change

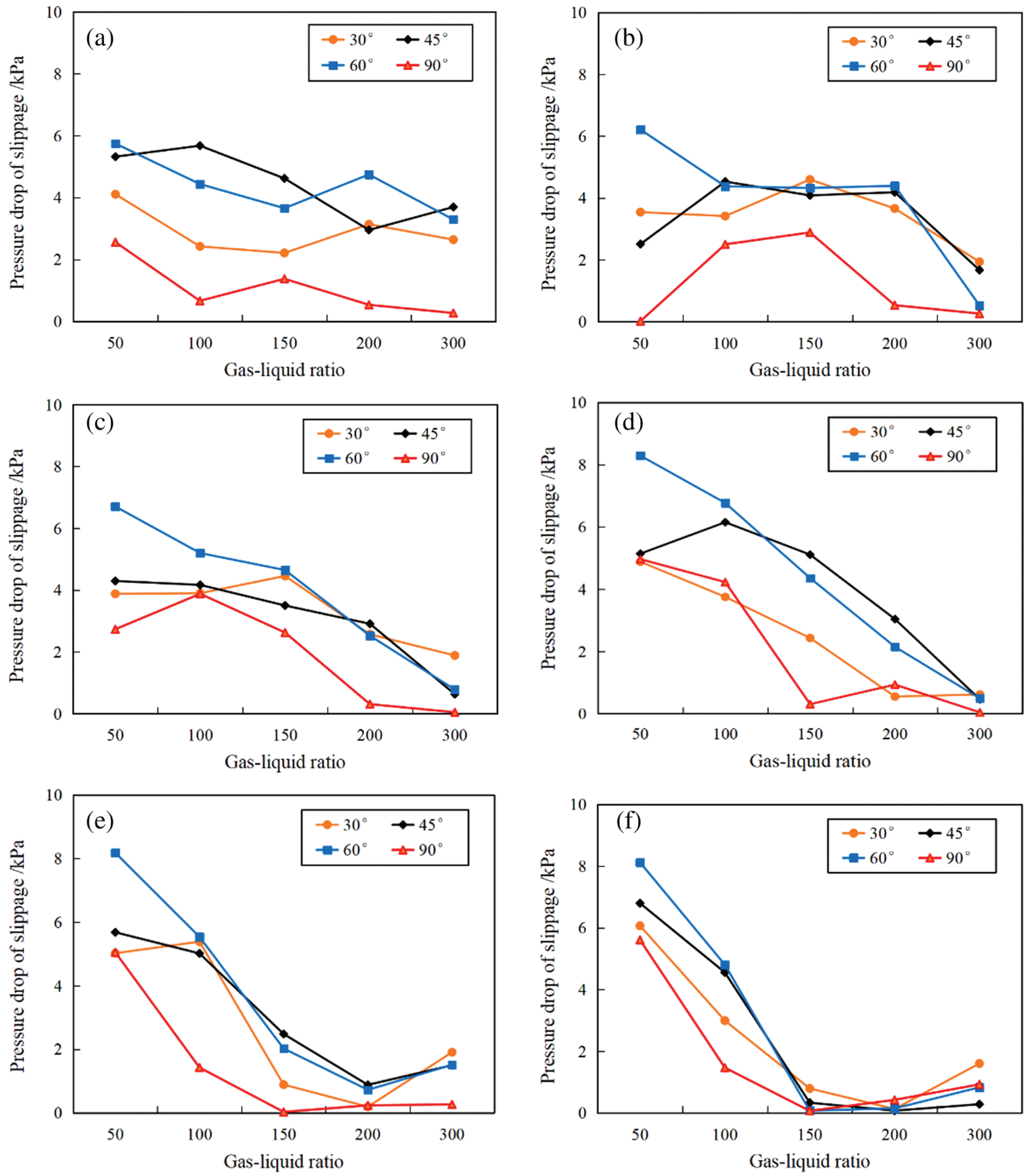

Figure 5: Slippage pressure drop *vs.* gas-liquid ratio at the superficial liquid velocity of (a) $v_{sl} = 0.041\ m/s$; (b) $v_{sl} = 0.061\ m/s$; (c) $v_{sl} = 0.082\ m/s$; (d) $v_{sl} = 0.122\ m/s$; (e) $v_{sl} = 0.164\ m/s$; (f) $v_{sl} = 0.205\ m/s$

of the total pressure drop in the pipe. When increasing the superficial liquid velocity, the slippage loss would increase due to the increase in the liquid holdup and the liquid film thickness. Besides, the backflow phenomenon and the slippage effect between the gas and liquid became significant.

In order to analyze the effect of inclination angle on slippage loss more clearly, analysis was performed on the slippage density, slippage pressure drop and slippage ratio at different inclination angles. The superficial liquid velocity was kept at 0.122 m/s. The results are shown in Figs. 7–9.

At a small gas-liquid ratio, the slippage loss was greatly affected by the inclination angle, and as the gas-liquid ratio increased, the inclination angle had decreasing influence on the slippage loss. When the

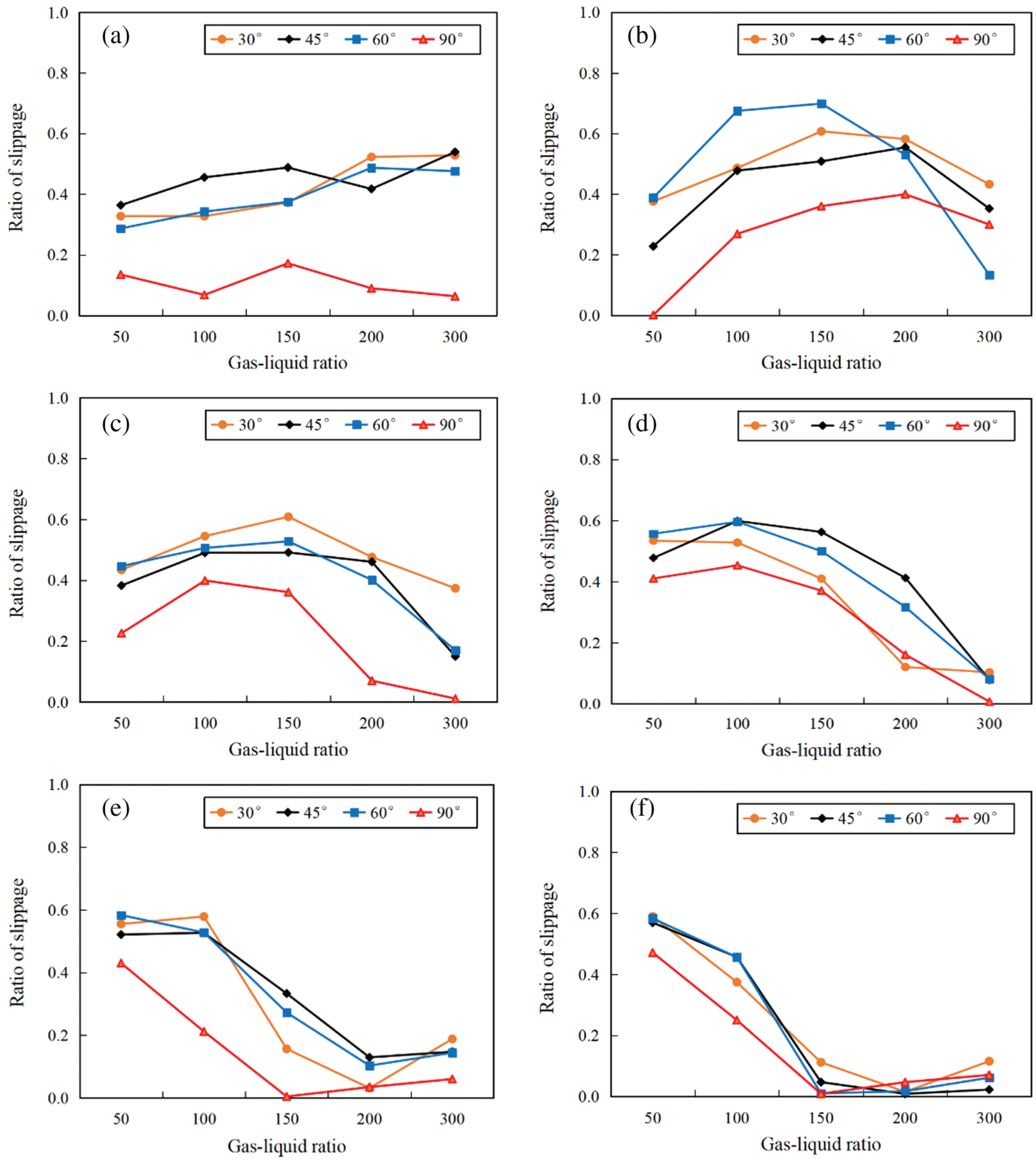

Figure 6: Slippage ratio *vs.* gas-liquid ratio at the superficial liquid velocity of (a) $v_{sl} = 0.041\ m/s$; (b) $v_{sl} = 0.061\ m/s$; (c) $v_{sl} = 0.082\ m/s$; (d) $v_{sl} = 0.122\ m/s$; (e) $v_{sl} = 0.164\ m/s$; (f) $v_{sl} = 0.205\ m/s$

gas-liquid ratio reached 300, the slippage loss no longer depended on the inclination angle. It also showed that larger superficial liquid velocity led to greater influence of inclination angle on the slippage loss, which was consistent with the previously-observed results.

The slippage loss at 45° and 60° was generally greater than that at 30° and 90°, indicating that the inclination angle of 45–60° had a high degree of influence on the slippage loss. The liquid holdup was high between 45° and 60° as well, and the influence of inclination angle on the liquid holdup had a certain symmetry, which was similar to the total pressure drop in the pipe.

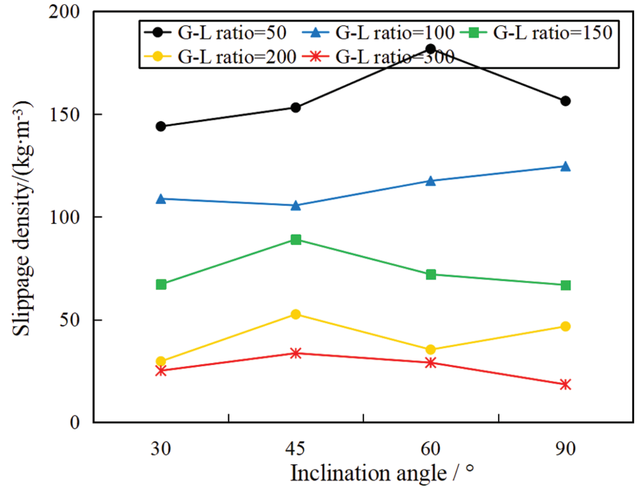

Figure 7: Effect of inclination angle on slippage density at different gas-liquid ratios

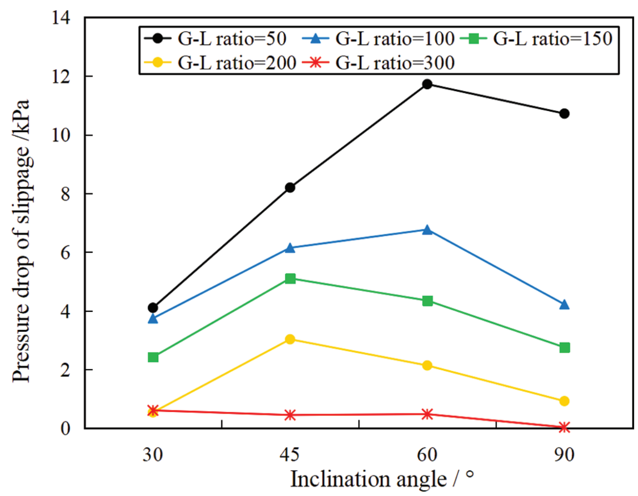

Figure 8: Effect of inclination angle on slippage pressure drop at different gas-liquid ratios

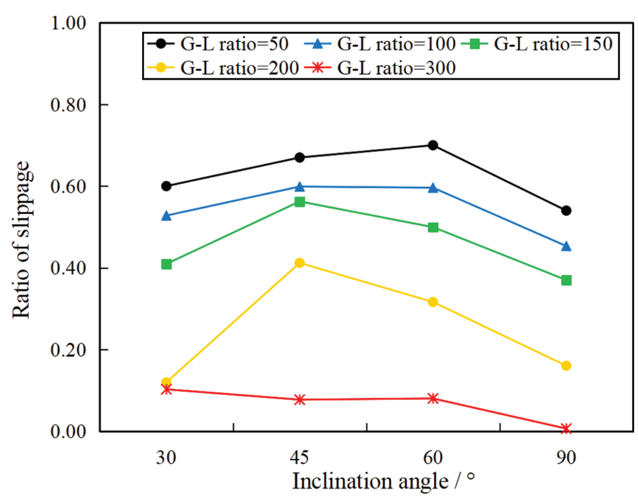

Figure 9: Effect of inclination angle on slippage ratio at different gas-liquid ratios

4.2 Different Pipe Diameters

The superficial liquid velocity was kept at 0.082 m/s and the superficial gas velocity at 4.1 m/s, while the pipe diameters were set to 40 mm, 60 mm and 75 mm. Experimental results are shown in Figs. 10–12. As seen from the figures, slippage density was positively correlated with the liquid holdup, so that at the same gas-liquid ratio, a pipe with a larger diameter exhibits a higher liquid holdup. Fig. 10 shows that the slippage density increased as the pipe diameter increased. The experimental results are consistent with the theoretical analysis.

Figs. 11–12 show that the slippage loss at the pipe diameter of 60 mm was less than that at the pipe diameters of 40 mm and 70 mm. That was because when the pipe diameter changed, the flow pattern and the actual gas-liquid velocity would change accordingly. Under the current experimental conditions, the slippage loss at the pipe diameter of 60 mm was the smallest at the gas-liquid ratio of 50~300.

It can also be observed that at the same gas-liquid superficial velocity, greater inclination angle led to greater slippage pressure drop and slippage ratio. It can be indicated that there was no significant effect

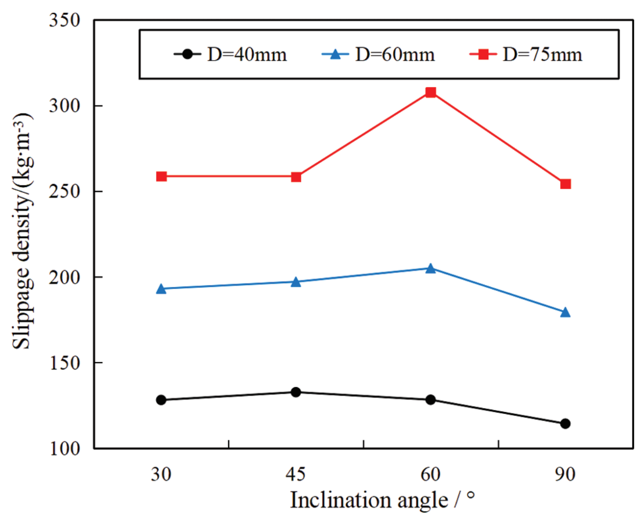

Figure 10: Effect of inclination angle on slippage density at different pipe diameters

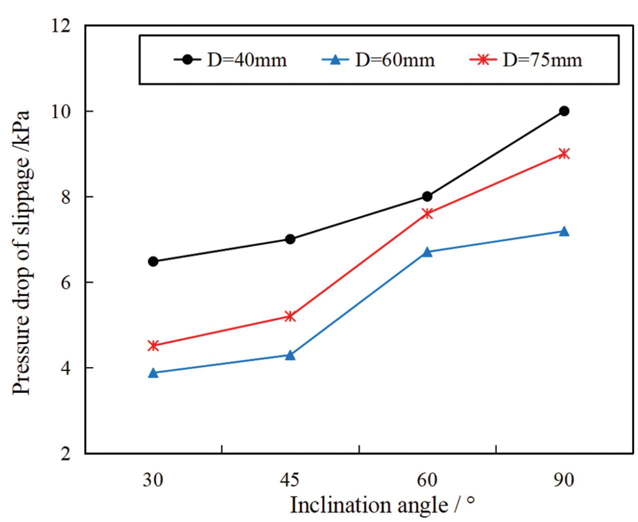

Figure 11: Effect of inclination angle on slippage pressure drop at different pipe diameters

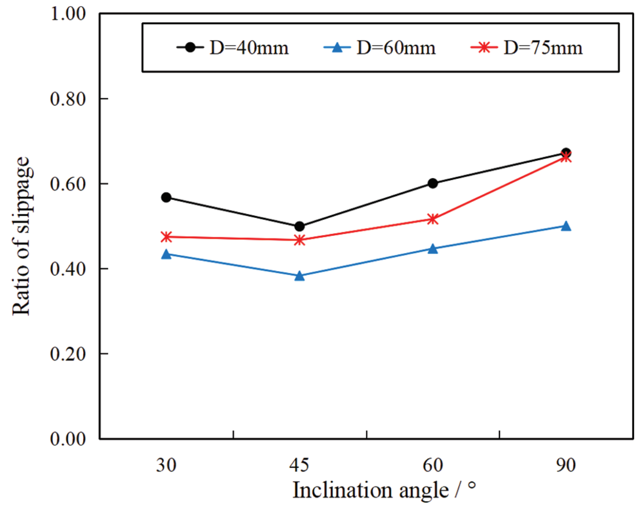

Figure 12: Effect of inclination angle on slippage ratio at different pipe diameters

between inclination angle and slippage density. Experimental results indicate that among the three parameters that characterize the slippage loss, slippage ratio is the best one to measure the degree of slippage loss in the gas-liquid two-phase flow.

5 Conclusion

The main conclusions of this research are summarized as follows.

(1) Slippage loss is affected by multiple factors, including inclination angle, gas-liquid superficial velocity, and pipe diameter. According to the multi-factor sensitivity analysis of slippage loss, it can be obtained that the inclination angle has the smallest influence on slippage loss, and the pipe diameter has the largest influence on slippage loss.

(2) With the other conditions kept unchanged, the slippage density gradually decreases as the gas-liquid ratio increases, and the slippage pressure drop decreases first and then increases. When the superficial liquid velocity is increased, the slippage loss tends to increase. This is similar to the change law of the total pressure drop of the pipe.

(3) The influence of the inclination angle on slippage loss decreases with the increase of the gas-liquid ratio. When the gas-liquid ratio reaches 300, the slippage loss no longer changes with the inclination angle.

(4) The slippage loss at the inclination angle of 45°and 60° is generally greater than that at 30° and 90°. As with the change in liquid holdup, the inclination angle has a symmetrical effect on the slippage loss.

(5) With gas-liquid ratio in 50 ~ 300, the slippage loss at the pipe diameter of 60 mm is smaller than that at the pipe diameter of 40 mm and 75 mm.

(6) The influence of the inclination angle on the slippage density is not significant. Experimental results show that among the three parameters that characterize the slippage loss, slippage ratio is the best one to measure the degree of slippage loss in the gas-liquid two-phase flow.

Acknowledgement: Gratitude is extended to Ruiquan Liao, the corresponding author for the article. The authors would also like to acknowledge the support provided by the National Natural Science Fund Project (61572084) and major national projects (2017ZX05030-005, 2019D-4413).

Funding Statement: This work was supported by National Natural Science Foundation of China (No. 61572084) and the National Key Research and Development Program of China (2017ZX05030-005, 2019D-4413).

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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