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A Criterion of Negative Frictional Pressure Drop in Vertical Two- Phase Flow

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Pressure drop is an important parameter in the study of gas-liquid two-phase flow (Beggs and Brill, 1973). The phenomenon of negative frictional pressure drop is observed in an experiment. In the process of the experiment, it is necessary to research the law of negative pressure drop. In this paper, the two-phase flow experiment is carried out in a vertical pipe of 60mm in diameter and 8m in length. The apparent liquid velocity is from 0.08 to 0.20 m/s, the apparent gas velocity is from 1 to 19 m/s. Air and mineral oil are used as the working fluids, and the viscosities of the oil are 25, 50, 70, 150, and 200 cp, respectively. The multiphase flow test platform is used to research the negative pressure drop. A criterion is given to judge the phenomenon of negative frictional pressure drop; the smaller the apparent gas-liquid velocity, the greater the influence of viscosity on the negative frictional pressure drop.

1. Introduction

Gas-liquid two-phase flow in pipes is common in the petroleum industry (Gokcal et al., 2008). In the course of practical research, the phenomenon of negative frictional pressure drop was found. Accordingly, the negative frictional pressure drop is considered to be unrealistic in pipe flow (Zhang et al., 2012).

Some research is aimed at the study of friction resistance in pressure drop, mainly due to the phenomenon of negative frictional pressure drop in oil gas flow. D.T. Akhiyarov (Akhiyarov et al., 2010) studied the highly viscous oil-gas two-phase flow in vertical pipes and found that the negative frictional pressure drop influences the prediction results. Lei Liu (2014) studied the vertical gas-liquid two-phase pipe flow, and concluded that the falling of liquid film in the Taylor bubble segment resulted in the occurrence of negative frictional pressure drop, and introduced the buoyancy-like term from the energy conservation equation analysis, which proved the phenomenon of negative frictional pressure drop. A. Al-Sarkhi (Al-Sarkhi et al., 2016) studied the phenomenon of negative frictional pressure drop of high-viscous oil and gas slugs in vertical tubes. In the experimental section of 50.8 mm, the phenomenon of negative frictional pressure drop was analyzed qualitatively from the shear stress. A criterion for judging the appearance of negative frictional pressure drop is given.

At present, the mechanism of the negative frictional pressure drop phenomenon has not been studied thoroughly and there is a lack of research data on negative pressure drop. In this paper, a criterion is given to judge the phenomenon of negative frictional pressure drop.

2. Experimental apparatus

This experiment was conducted at the Yangtze University Multiphase Flow Experimental Platform. The platform can carry out many kinds of fluids such as oil, gas, and water. The dynamics of multiphase flow can be studied in the range of 0~90° inclination, 0~90°C temperature, and 0~3.5MPa pressure.

As shown in Figure 1, it mainly includes the gas circuit, liquid circuit, test section, and operation control platform. The accuracy of the liquid flowmeter is 0.3%, the accuracy of the gas flowmeter is 1%, the accuracy

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of the pressure signal of the test section is 0.1%, and the accuracy of the differential pressure signal of the test section is 0.03%. Resolution is less than 0.1kpa; thermometer accuracy 0.5%. This study was conducted on a test section with an inner diameter of 60mm and a length of 8m. The liquid was oil and the gas was air. According to the viscosity-temperature characteristics, oils of different viscosities were available, and the densities did not change so much that they were ignored. The scope of the experiment is shown in Table 1.

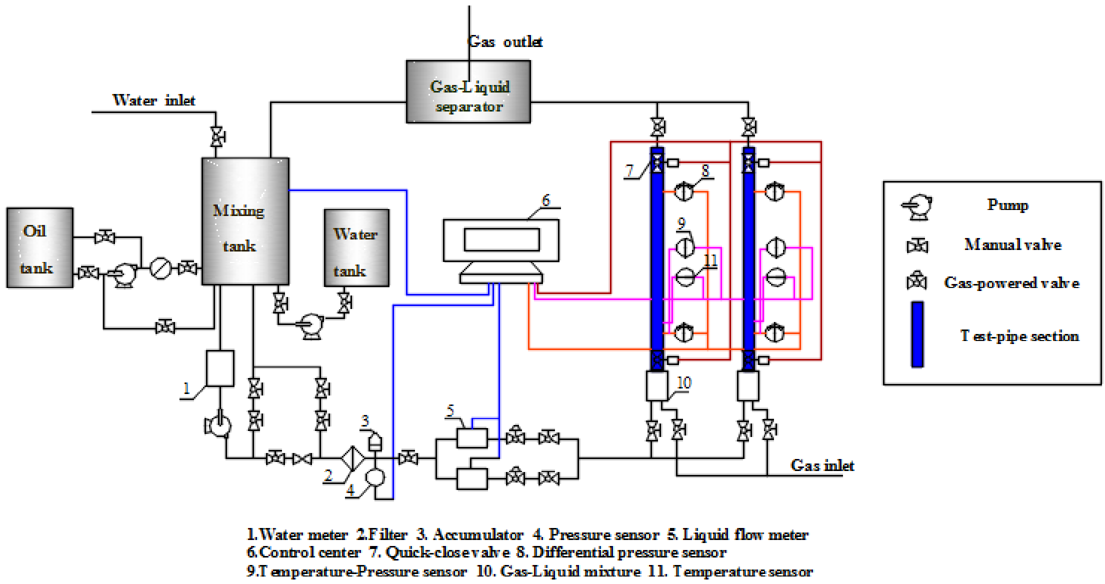

Figure 1: Multi-phase flow test device

Table 1: Paramatric ranges in the test

Working conditions	
Oil viscosity (cp)	25,50,70,150,200
Liquid flux (m^3/h)	0.83,1.25,1.67,2.08
Gas flux (m^3/h)	30~370
Gas liquid ratio	25~200

3. Experiment results

The phenomenon of negative frictional pressure drop was observed in experiments. The study by Lei Liu (Liu, 2014) shows that the phenomenon of negative frictional pressure drop mainly occurs in intermittent flow such as slug flow (Liapidevskii and Tikhonov, 2016), churn flow, and semi-annular flow. According to Figure 2, the slug unit is composed of a bubble region and a liquid slug region, in which the liquid slug and the bubble flow upward, the generated shear force is downward, and the liquid film in the bubble region flows downward, and thus the generated shear force is upward. In the pressure drop calculation, the upward direction is positive. According to the momentum equation, the negative friction is caused by the upward shear force. Therefore, the negative frictional pressure drop is caused by the downward flow of the liquid film. A. Al-Sarkhi (Al-Sarkhi et al., 2016) also gave a judgment criterion, but simplified it in the derivation process. Assuming that the liquid slug segment does not contain small bubbles, the liquid plug density is approximately equal to the liquid density, and it is assumed that the liquid slug length is equal to the length of the bubble section. Then a rough determination relation is obtained. This paper gives a more accurate standard by derivation (Nan et al., 2007). According to the momentum conservation equation in the liquid film area and the liquid slug area, the liquid and gas momentum equations (Raghunathan et al., 2003) in the liquid film area are as follows:

$$AH_{LF}\frac{\Delta p_F}{L_{LF}} = \tau_{LF} S_{LF} - \tau_{iF} S_{iF} + \rho_L g A H_{LF} \tag{1}$$

$$A(1-H_{LF})\frac{\Delta p_F}{L_{LF}} = \tau_{GF} S_{GF} + \tau_{iF} S_{iF} + \rho_G gA(1-H_{LF}) \tag{2}$$

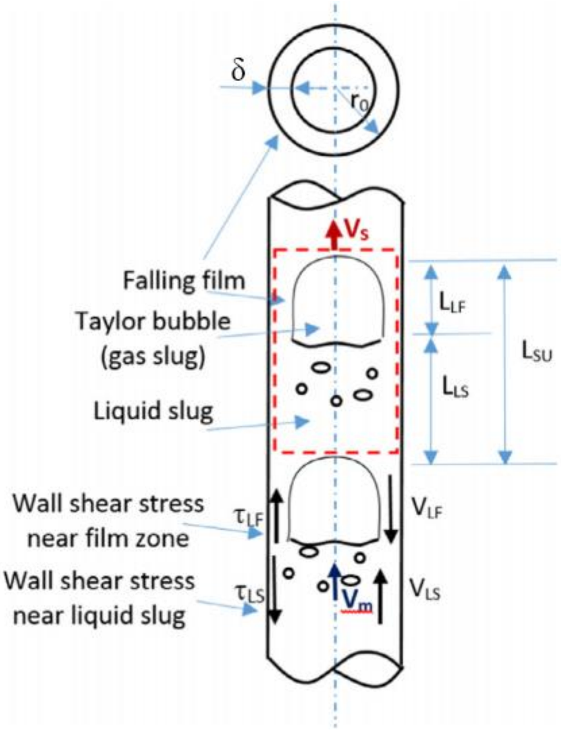

Figure 2: Typical slug flow in vertical tubes

The liquid slug area momentum equation (Zhang et al.,2003) is as follows:

$$A\frac{\Delta p_{LS}}{L_{LS}} = \tau_{LS}\pi D + \rho_{LS} gA \tag{3}$$

The liquid and wall shear stresses (Morgado et al.,2016) are as follows:

$$\tau_{LF} = \frac{1}{2}\rho_L f_{LF} v_{LF} |v_{LF}| \tag{4}$$

$$\tau_{LS} = \frac{1}{2}\rho_S f_{LS} v_{LS} |v_{LS}| \tag{5}$$

Derived from the momentum equation to obtain the frictional pressure drop of the slug unit,

$$\Delta P_{fr} = \frac{1}{2} f_{LF}\rho_L v_{LF}|v_{LF}|S_{LF} L_{LF} + \frac{1}{2} f_{LS}\rho_S v_{LS}|v_{LS}|\pi D L_{LS} \tag{6}$$

The slug unit length is calculated as follows:

$$L_{SU} = L_{LF} + L_{LS} \tag{7}$$

Simplify equation (6) so that the pressure drop

$$P_{fr} = \left[|\tau_{LS}|\frac{L_{LS}}{L_{SU}} - |\tau_{LF}|\frac{L_{LF}}{L_{SU}}\right]\pi D \tag{8}$$

From equations (6) and (7), it can be seen whether the phenomenon of negative frictional pressure drop occurs depends on whether the above two equations are negative or not. There is as follows:

$$\rho_S f_{LS} v_{LS}^2 L_{LS} < \rho_L f_{LF} v_{LF}^2 L_{LF} \tag{9}$$

$$\rho_S = H_S \rho_L + (1 - H_S)\rho_G \tag{10}$$

According to Gregory's liquid holdup of liquid slug (Gregory et al., 1978),

$$H_S = \frac{1}{1 + (\frac{v_m}{8.66})^{1.39}} \tag{11}$$

Schmidt's study (Schmidt et al., 1981) found that the slug velocity is a linear function of the mixed velocity. As this experiment is similar to the Schmidt test conditions, we use the following formula:

$$v_{LS} = 0.92 v_m \tag{12}$$

According to A. Al-Sarkhi (Al-Sarkhi et al., 2016), the liquid film velocity is calculated using the following formula:

$$v_{LF} = \frac{(H_{LF} - H_S)(c_0 v_m + v_D) + v_{sl}}{H_{LF}} \tag{13}$$

Where c_0 is the flow coefficient. If the flow regime is laminar flow, c_0 is 2. If it is turbulent flow, c_0 is 1.2.

$$v_D = -2.67\frac{\mu_L}{\rho_L D} + \sqrt{0.222gD + 7.111(\frac{\mu_L}{\rho_L D})^2} - 0.121\sqrt{gD} \tag{14}$$

$$H_{LF} = \frac{\pi r_0^2 - \pi(r_0 - \delta)^2}{\pi r_0^2} = \frac{2\delta}{r_0} - \frac{\delta^2}{r_0^2} \tag{15}$$

$$\mathrm{Re}_{LS} = \frac{v_{LS}\rho_S D}{\mu_S} \tag{16}$$

$$\mathrm{Re}_{LF} = \frac{v_{LF}\rho_L(4\delta - \frac{2\delta^2}{r_0})}{\mu_L} \tag{17}$$

According to A. O. Morgado (Morgado et al., 2016), liquid film thickness can be calculated by the following formula:

$$\delta = \left[\frac{3v_l}{2g(r_0 - \delta)}((r_0 - \delta)^2 v_{LS} - r_0^2 u_L\right]^{1/3} \tag{18}$$

Fanning friction coefficients f_{LS} and f_{LF} are the function of Re_{LS} and Re_{LF}. In this study, when the viscosity was 150 and 200 cp, it was calculated that the liquid slug and the liquid film area were in a laminar flow state. Then,

$$f_{LS} = \frac{16}{\mathrm{Re}_{LS}},\quad f_{LF} = \frac{16}{\mathrm{Re}_{LF}} \tag{19}$$

When the viscosity is at other values, the liquid slug and the liquid film area are in a turbulent state. Then,

$$f_{LS} = \frac{0.0791}{(\mathrm{Re}_{LS})^{0.25}}, \quad f_{LF} = \frac{0.0791}{(\mathrm{Re}_{LF})^{0.25}} \tag{20}$$

When the viscosity is 150 and 200 cp, the above formula is substituted into equation (9) and simplified, then the negative pressure drop judgment criterion is as follows:

$$\frac{\mu_S v_{LS}}{2r_0} < \frac{\mu_L v_{LF}}{(4\delta - \frac{2\delta^2}{r_0})} \frac{L_{LF}}{L_{LS}} \tag{21}$$

When the viscosity is at other values, the criteria for determining negative pressure drop by simplification are as follows:

$$\frac{\rho_S^{0.75} \mu_S^{0.75} v_{LS}^{1.75}}{(2r_0)^{0.25}} < \frac{\rho_L^{0.75} \mu_L^{0.75} v_{LF}^{1.75}}{(4\delta - \frac{2\delta^2}{r_0})^{0.25}} \frac{L_{LF}}{L_{LS}} \tag{22}$$

The above formula shows that the phenomenon of negative frictional pressure drop is mainly related to superficial gas velocity, superficial liquid velocity, and viscosity.
Taking (21) as an example to calculate the viscosity curve of the friction coefficient of negative friction at 200 cp, as shown in Figure 3, it can be seen that the boundary prediction agrees well with the experiment. Therefore, this standard is applicable to the determination of the negative frictional pressure drop phenomenon under different viscosities.

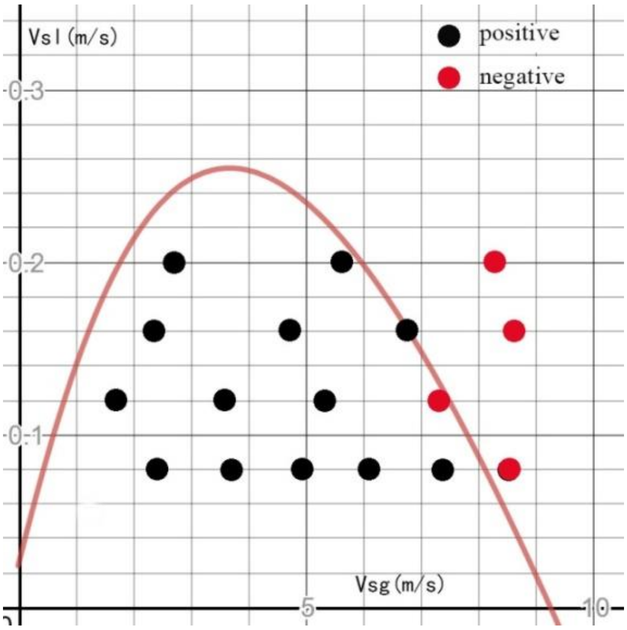

Figure 3: Judgment on boundary of negative frictional pressure drop

4. Conclusion

By modeling and analyzing the negative frictional pressure drop, a criterion for the occurrence of negative frictional resistance pressure drop is given. When the negative frictional pressure drop occurs is associated with the apparent gas-liquid velocity. With the increase of liquid viscosity, the value of negative frictional pressure drop is smaller. Especially in the case of small superficial gas velocity, the effect of viscosity on negative frictional pressure drop is more obvious. When the viscosity increases, the negative frictional pressure drop phenomenon is more common.

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