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A new model for predicting liquid holdup in two-phase flow under high gas and liquid velocities

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Low liquid holdup.

Abstract. Existing liquid holdup models are generally based on low gas and liquid velocities. To extend the applicable range of existing liquid holdup prediction models and improve their prediction accuracy, a gas-liquid two-phase flow experiment was carried out using a pipe with an inner diameter of 60 mm and a length of 11.5 m. The superficial gas and liquid velocity ranges were 14.07 ~ 56.50 m/s and 0.205 ~ 1.426 m/s, respectively. The results indicate that the liquid holdup decreases with an increase in the superficial gas velocity and increases with an increase in the superficial liquid velocity. A new annular flow model for calculating low liquid holdup in a horizontal pipe was developed and presented, considering the relationships between the friction factor ratio of the liquid phase and the gas-liquid interface as well as the superficial Reynolds number of the gas and liquid. The predictions of the model were found to be accurate with an average absolute error of 4.8%. Further, by combining the approach of the Beggs-Brill model with that of the horizontal pipe model established in this paper, a new liquid holdup model that accounts for different angles was presented. It was observed that the resultant model was also accurate and had an average absolute error of 10%.

1. Introduction

Gas-liquid two-phase flow exists widely in petroleum, chemistry, nuclear power, aerospace, and other industries. In the petroleum industry, gas-liquid two-phase flow often occurs in oil and gas production wells and gathering pipelines, and its flow characteristics have significant influence on the production of reservoirs and the equipment on the ground. Liquid holdup is not only an important parameter for the classification of flow patterns, but also related to the calculation of the existing models of pressure drop.

Gas-liquid two-phase flow is more complicated than single-phase flow. Similarly, the determination of liquid holdup is also complex, because there are many factors that influence liquid holdup. Due to its complexity, most researchers have initially used empirical models to predict liquid holdup [1-3]. However, empirical models are based on experiments and are applicable to experimental data in a certain range of conditions. It is difficult, therefore, to generalize and apply the empirical models to other experimental and operational conditions. With the development of gas-liquid two-phase flow mechanisms and Computational Fluid Dynamics (CFD), several investigators have studied mechanistic models that can predict the liquid

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holdup and subsequent pressure drop for different angles [4-11]. One of the most significant mechanistic models, which is based on the dynamics of slug flow, was carried out by Zhang [8]. By using the entire film zone as the control volume, the momentum exchange between the slug body and the film zone was introduced into the momentum equations for slug flow.

Slug flow shares transition boundaries with all the other flow patterns. The equations of slug flow are used not only to calculate the slug characteristics but also to predict transitions from slug flow to other flow patterns. Slug liquid holdup is a critical slug flow characteristic for predicting average liquid holdup. Wang et al. [12] developed a complex mechanistic model for slug liquid holdup by using an empirical proportionality parameter generated from their data bank as a function of the Froude number and the inclination angle. Al-Safran [13] postulated several mechanisms of gas entrainment and evolution within the slug body and proposed a new simple empirical slug liquid holdup closure relationship valid for different liquid viscosities. Hassanlouei et al. [14] presented a methodology for calculating a slug liquid holdup in a horizontal pipe. The advantage of this method is that the slug unit holdup can be calculated directly based on the solutions of the flow field equations with no need to use correlations. Zuber and Findlay [15] first proposed the drift-flux model to predict the liquid holdup for slug flow, which has been well-researched and applied to gas-liquid two-phase pipe flows [16-21].

Some researchers used the two-fluid model to calculate liquid holdup of stratified and annular flow regimes [22-24]. The two-fluid model was developed by establishing and solving a momentum equation for each phase with corresponding closure relationships, which are often empirical in nature. Khaledi et al. [25] performed experiments with high density gas phase and oils of two different viscosities, and the obtained experimental results were compared with the predictions from a two-fluid gas-liquid model, which was presented by Unander et al. [26]. Dabirian et al. [27] studied the effects of phase velocities and fluid properties on the characteristics of stratified flow and proposed a closure relationship for the interfacial friction factor to predict the liquid holdup.

The mechanistic model is more accurate for liquid holdup prediction; however, it usually incorporates a system of nonlinear equations. In addition, the mechanistic model also relies on some assumptions and empirical constants obtained by experiments. Due to the limitation of such experimental conditions, the superficial gas and liquid velocities for most gas-liquid two-phase flow experiments reported in the literature are generally not very high. Most of the experimental data for liquid holdup based on gas-liquid two-phase flow are derived from the Tulsa University Fluid Flow Projects (TUFFP), where the superficial gas velocity range of the experimental loops in the laboratory is 0∼44.8 m/s, while the superficial liquid velocity range is 0∼1.83 m/s.

Therefore, it is necessary to develop a prediction model for liquid holdup and pressure drop based on experimental data and take advantage of different models. To obtain an accurate model for predicting liquid holdup at higher gas and superficial liquid velocities applicable to different angles, a two-phase flow experiment with higher gas and liquid velocities was carried out on a multi-phase flow experimental platform at Yangtze University where the superficial liquid velocity range was from 0.205 to 1.426 m/s, and the superficial gas velocity range was from 14.07 to 56.50 m/s. The flow patterns in the experiment were observed, and the influence of different factors on the liquid holdup under the experimental conditions was obtained by analyzing the experimental data. Finally, a new model for predicting low liquid holdup ($H_L < 0.1$) in horizontal pipes was presented. In addition, based on the Beggs-Brill model, a model for predicting the holdup at different angles was obtained under the condition of higher superficial gas and liquid velocities.

2. Experimental facility and measurement methods

2.1. Experimental facility

The experiment was carried out on the multi-phase flow experimental platform, which is the platform of the gas lift test base of CNPC located at the School of Petroleum Engineering, Yangtze University. The diagram of the experimental device is shown in Figure 1.

Liquid from the mixing tank is pressurized by a pump. After pressure stabilization and measurement, the liquid is mixed with measured compressed gas, and the mixed media are introduced together into the test section. The liquid returns to the mixing tank after separation from the gas as they pass through the gas-liquid separator. The inner diameter of the test section used in the experiment is 60 mm. The length of the plexiglass pipe used to observe the flow pattern is 7 m. The test section can be adjusted at an angle of $0 \sim 90°$. Pressure, temperature, and pressure differential sensors, as well as quick closing valves and other devices, are installed on the pipe section. The distance between the two quickly closing valves is 9.5 m, including the 7-m Plexiglas tube and 2.5-m-long stainless steel tube. Control of the devices and extraction of data are done directly online at the control center. The test section is shown in Figure 2.

To ensure the reliability of the experimental data, high-precision instruments are used. The liquid flowmeters installed include Endress+Hauser/80E25

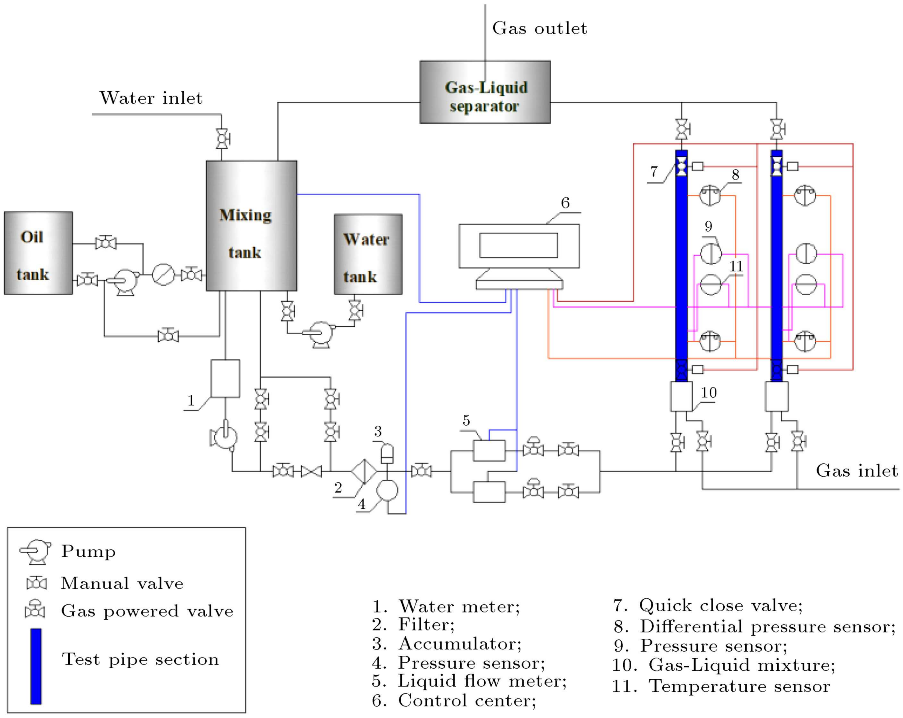


Figure 1. Multiphase flow test device.

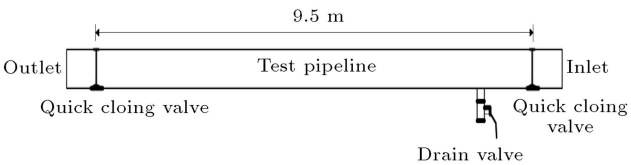


Figure 2. Liquid holdup test section.

and Endress+Hauser/80E50, while the gas flowmeter employed is Endress+Hauser/65F1H. All flowmeters measure the volume flow rate during the experiment. The response time of the quick-closing valve is 0.3 $\sim$ 0.5 s. The pressure and temperature sensors installed behind the quick-closing valve are used to measure the temperature and pressure in the test section. The measurement parameters and errors of each device are shown in Table 1.

Air is the gas phase, while water constitutes the liquid phase. The surface tension of the water is 0.071 Nm^{-1} (23.58°C). The densities of water and air are 1000 kg/m^3 and 1.205 kg/m^3 (0.101 MPa), respectively, while their respective viscosities are 1 mPa.s and 0.0181 mPa.s (20°C).

2.2. Experimental measurements

Numerous researchers have reported various development lengths (L/D ratios) for fully developed flow. Omebere et al. [28] demonstrated that $L/D = 40$ was sufficient for a reasonably well-developed churn-turbulent flow using probability density functions of the void fraction that showed the same shapes for this value and higher. In addition, some of the reported experimental observations are temporary or developing flow patterns, as described by Brennen [29]. Aliyu et al. [30] observed fully developed flow in a pipe position with $L/D = 46$ for annular flow in upward vertical pipes. In the literature, no previous study provides conclusive experimental evidence or estimates of the minimum required length for the flow development section. This study provides approximately 2.4 m for the flow to develop, $L/D = 40$, and our observations show that flow almost reaches development in this stage; therefore, the liquid holdup measurements could proceed.

In the experiment, a constant liquid flow rate was maintained, while the gas flow rate was adjusted.

Table 1. Measurement parameters and errors of the experimental devices.

Equipment	Measuring range	Measurement error
Pressure	0~3.5 MPa	±0.1%
Temperature	0-90°C	±0.5%
Liquid flow rate	$2 \sim 20$ m^3/h	±0.3%
Gas flow rate	$160 \sim 2000$ m^3/h	±1%

Table 2. Range of parameters under the experimental conditions.

Experimental conditions								
Superficial liquid velocity (m/s)	0.205 ~ 1.426							
Superficial gas velocity (m/s)	14.07 ~ 56.50							
Pressure (MPa)	0.03 ~ 0.46							
Temperature (°C)	4.0 ~ 20.83							
Liquid holdup	0.007 ~ 0.329							
Angle of upward inclination (°)	0	15	30	45	60	75	90	Total
Number of data points	92	91	85	68	72	69	71	548

When the system was steady, the data were recorded, and the experimental flow pattern was observed. The experimental data were recorded every 5 seconds for 3 minutes; finally, the average value of each measurement parameter was obtained. After completing the data recording, the quick-closing valve was closed, and the liquid holdup was measured. The measurement method of liquid holdup was used to test the volume of residual liquid in the test section, and the ratio of the volume of the residual liquid to the volume of the whole pipe was used as the average liquid holdup of the experiment. The range of measurement parameters in the experiment is shown in Table 2.

3. Experimental results and analysis

3.1. Experimental flow pattern

Under the experimental conditions, the flow patterns observed in the horizontal pipe were slug and annular flow, attributed to the high superficial gas and liquid velocities. Experimental data points, indicating the observed flow patterns, plotted on the flow pattern maps presented by Mandhane et al. [31], Taitel and Dukler [32] and Zhang are shown in Figure 3. It can be observed that when the superficial gas velocity is approximately 12 m/s, the slug flow is transited to annular flow. With the increase of the superficial liquid velocity, the superficial gas velocity is required when the slug flow changing into annular flow increases gradually. It can also be observed that the experimental data fall near the transition boundary between slug flow and annular flow in the three flow pattern maps. It is found that the Mandhane flow pattern map is in excellent agreement with the experimental data.

In addition, slug flow, churn flow, and annular flow were observed in the inclined and vertical pipe sections. The experimental data points plotted on the flow pattern map of Kaya [33] for vertical pipes are presented in Figure 4. It can be seen from Figure 4 that the area of churn flow decreases with increasing superficial liquid velocity. It can also be observed that the flow pattern map of Kaya is consistent with the experimental data.

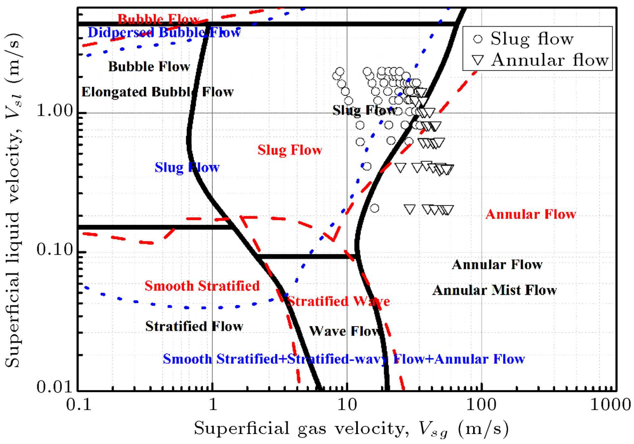


Figure 3. Test points on different horizontal flow pattern maps (black represents the Mandhane flow pattern map; blue color represents the Taitel-Dukler flow pattern map; and red represents the Zhang flow pattern map).

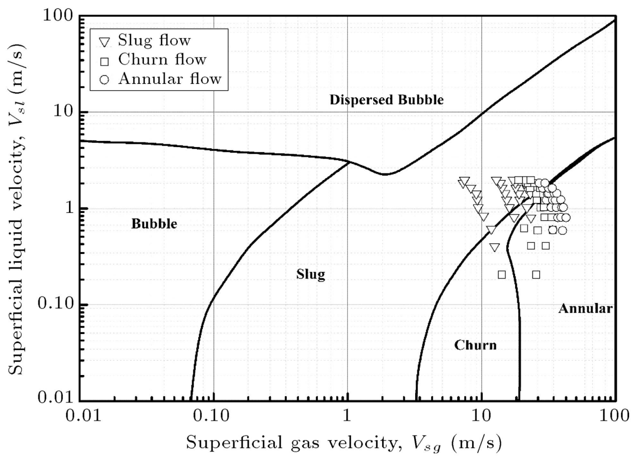


Figure 4. Test points on the Kaya flow pattern map.

3.2. Liquid holdup versus superficial velocity and inclination

The variation in liquid holdup with the superficial gas and liquid velocities is shown in Figure 5. From the horizontal to vertical orientation, the liquid holdup decreases with the increase of superficial gas velocity. When the superficial gas velocity is greater than

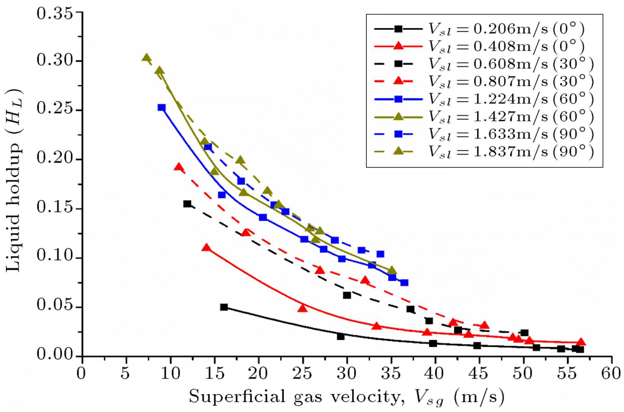


Figure 5. Liquid holdup versus superficial gas velocity with different inclinations (from horizontal to vertical).

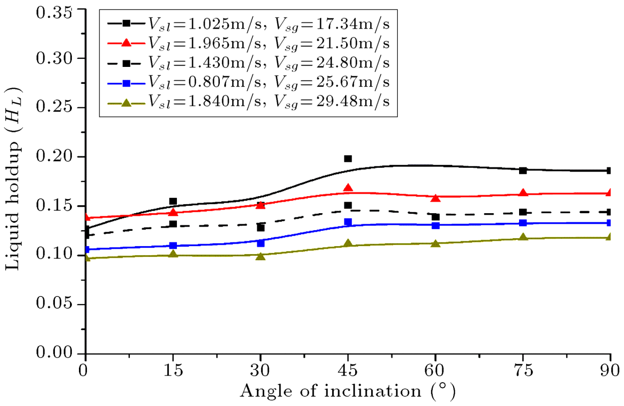


Figure 6. Liquid holdup versus angle of inclination.

35 m/s, with an increase in superficial gas velocity, the liquid holdup decreases a little. When the superficial gas velocity is high enough, the flow pattern changes into annular flow, the liquid holdup is very low, and the influence of increasing gas velocity on liquid holdup is not obvious. The figure also shows that the liquid holdup increases with the increase of the superficial liquid velocity at the same superficial gas velocity.

The variation in liquid holdup with the inclination angle is shown in Figure 6. The liquid holdup increases with the increase of the angle at the same superficial gas and liquid velocity and reaches the maximum value when the inclination angle is 45°. The liquid holdup decreases slightly; however, the change is small with the increase of the angle. This effect may result from the influence of gravity and viscosity, which can be seen in the literature study of Beggs [1]. When the inclination angle is less than 45°, the influence of angle on the liquid holdup decreases with the increase of the superficial gas velocity.

3.3. Prediction of liquid holdup by empirical and mechanistic models

The Beggs-Brill (B-B) empirical model and the Kaya mechanistic model were used to predict the experimental liquid holdup data. The Kaya model was applicable to deviated pipes and not suitable for horizontal pipes. Therefore, the Kaya model was used to predict the liquid holdup at the angle from 15° to 90°, while the B-B model was used to predict the liquid holdup at the angle from 0° to 90°. The results of the comparison between the predicted values of the two different models and the experimental data of the liquid holdup are shown in Figure 7. When the liquid holdup is low, the prediction of the liquid holdup from these two models is not accurate.

The prediction average relative error and the average absolute error are determined as follows:

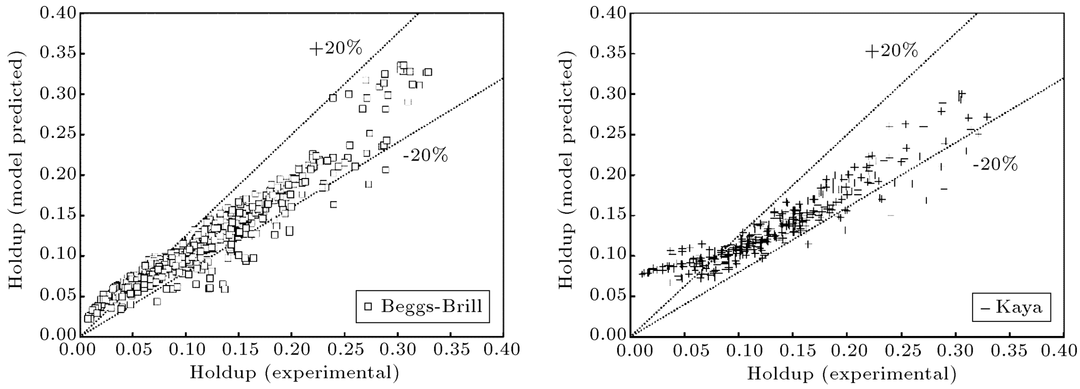
Average relative error:

$$E_1=\left(\frac{1}{n}\sum_{1}^{n}\frac{H_{Lcal}-H_{L\,\exp}}{H_{L\,\exp}}\right)\times 100. \quad (1)$$

Average absolute error:

$$E_2=\left(\frac{1}{n}\sum_{1}^{n}\left|\frac{H_{Lcal}-H_{L\,\exp}}{H_{L\,\exp}}\right|\right)\times 100, \quad (2)$$

where H_{Lcal} is the liquid holdup predicted by the model, and H_{Lexp} is the liquid holdup measured in the experiment.



(a) Beggs-Brill model (b) Kaya model

Figure 7. Comparison of different models predicting liquid holdup with experimental data.

Table 3. Errors of the B-B model and Kaya model.

	$H_L < 0.1$		$H_L > 0.1$		All data	
Model	E_1 (%)	E_2 (%)	E_1 (%)	E_2 (%)	E_1 (%)	E_2 (%)
B-B	43.6	46.7	-5.2	10.2	15.6	25.8
Kaya	66.4	67.1	-3.9	8.9	19.7	28.5

Table 4. The errors of B-B and Kaya models at different angles.

Model	Angle (°)	0	15	30	45	60	70	90
B-B	E_1 (%)	38.5	35.2	33.2	-4.0	-0.8	-5.5	-4.5
	E_2 (%)	41.9	41.7	40.1	11.6	13.4	10.0	8.7
Kaya	E_1 (%)	–	50.1	31.6	6.0	13.1	5.5	6.9
	E_2 (%)	–	60.0	40.2	21.7	17.6	13.4	13.2

The liquid holdup errors of $H_L < 0.1$ and $H_L > 0.1$ are shown in Table 3. Accordingly, when $H_L < 0.1$, the prediction values of the two models are greater than the experimental value. The average absolute error shows that the errors of the two models are high and more than 40%. When $H_L > 0.1$, the errors of the two models are lower, and the predicted values are lower than the experimental value. Based on the error of all the data, it can be seen that the errors of the two models are relatively high. However, the performance of the B-B model is better than that of the Kaya model; the errors of the B-B model are 15.6% and 25.8%.

The errors of the two models at different angles are shown in Table 4. It can be observed that the errors of the two models decrease with the increase of the angle. The performance of the B-B model is relatively better. When the angle is greater than 45°, the B-B model is more accurate and the error is approximately 10%. However, the error is high; when the angle is less than 45°, all the errors are greater than 40%.

4. Model development and evaluation

According to the error analysis, the error of the B-B model is high when the liquid holdup is less than 0.1. However, the liquid holdup prediction at different angles of the B-B model is based on the calculation of the liquid holdup of the horizontal pipe. Therefore, the development of a low liquid holdup correlation capable of predicting values less than 0.1 in the horizontal pipe is necessary. When the liquid holdup is low, the flow pattern of the horizontal pipe is either stratified or annular. However, no stratified flow was observed in this experiment. Therefore, the low liquid holdup ($H_L < 0.1$) model was developed based on annular flow.

Hart et al. [34] proposed the "Apparent Rough Surface" (ARS) model. Badie et al. [35] validated the two models by using the experimental data and attached the importance of liquid holdup prediction to the accuracy of pressure drop prediction. Meng et al. [22] added the concept of droplet entrainment on the basis of the "double-circle" model that was developed by Chen [36] and presented a new model. Fan [23] presented a two-fluid model that requires the initial value calculated by the ARS model proposed by Hart. Xu [24] combined the research results of Meng and Fan and presented a new model for calculating the low holdup and verifying it with the laboratory data from the experiments of Meng and Fan.

4.1. Development of a liquid holdup model for the horizontal pipe

The liquid phase in annular flow exists in two forms: a liquid film flowing along the pipe wall and the droplets entrained in the gas core. The shape of the liquid in annular flow is shown in Figure 8.

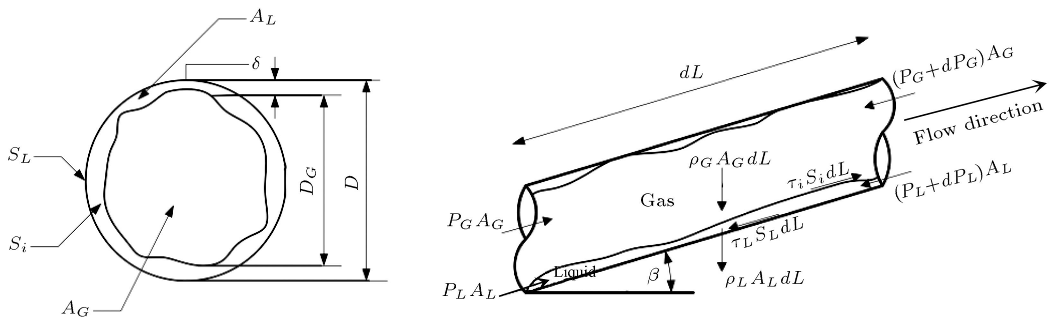


Figure 8. The morphology of gas-liquid two-phase flow in the pipe.

The study follows the approach of Xiao [5], who presented an annular flow model with an average liquid film thickness around the pipe wall. The model was developed based on the momentum equation in the liquid film and the gas core.

Momentum equation of gas core:

$$-A_G\left(\frac{dp}{dL}\right)_G - \tau_i S_i - \rho_G A_G g sin\beta = 0, \quad (3)$$

where:

$\left(\frac{dp}{dL}\right)_G$ The pressure gradient of the gas phase, Pa;

A_G The cross-sectional area inside the pipe of the gas phase, m^2;

τ_i The shear stress of the interface, N/m;

S_i The perimeter of the interface, m;

ρ_G Density of the gas, kg/m^3;

g The gravity acceleration, m/s^2;

β The inclination angle, °.

The momentum equation of the liquid film:

$$-A_L\left(\frac{dp}{dL}\right)_L - \tau_L S_L + \tau_i S_i - \rho_L A_L g sin\beta = 0, \quad (4)$$

where:

$\left(\frac{dp}{dL}\right)_L$ The pressure gradient of the liquid phase, Pa;

A_L The cross-sectional area inside the pipe of the liquid phase, m^2;

τ_L The shear stress of liquid film and wall, N/m;

ρ_L The density of the liquid, kg/m^3.

If the pressure drop gradient in the gas is equal to that in the liquid, Eqs. (3) and (4) can be combined to obtain the following combined momentum equation:

$$\tau_i S_i A_p - \tau_L S_L A_G - A_L A_G(\rho_L - \rho_G) g sin\beta = 0, \quad (5)$$

where A_L (m^2) is the cross-sectional area inside the pipe of the liquid phase.

The shear stresses are:

$$\tau_L = f_L \frac{\rho_L {v_L}^2}{2}, \quad (6)$$

$$\tau_i = f_i \frac{\rho_G (v_G - v_i)^2}{2}, \quad (7)$$

where:

f_L, f_i The liquid phase friction factor and the interfacial friction factor, m^2;

v_L The average liquid velocity, m/s;

v_L The average gas velocity, m/s;

v_i The gas-liquid interface velocity, m/s.

The area of each phase can be expressed approximately as functions of pipe cross-sectional area and liquid holdup:

$$A_L = A_p H_L, \quad (8)$$

$$A_G = A_p(1 - H_L), \quad (9)$$

where H_L is the liquid holdup.

Then, we can obtain that:

$$f_L \frac{\rho_L {v_L}^2}{2} S_L A_p(1 - H_L) - f_i \frac{\rho_G (v_G - v_L)^2}{2} S_i A_p + A_p H_L A_p (1 - H_L)(\rho_L - \rho_G) g sin\beta = 0. \quad (10)$$

When the pipe is horizontal, Eq. (10) can be simplified as:

$$\left(\frac{v_L}{v_G}\right)^2 - \frac{1}{1 - H_L}\frac{f_i \rho_G S_i}{f_L \rho_L S_L}(1 - \frac{v_L}{v_G})^2 = 0. \quad (11)$$

The average gas and liquid velocities are:

$$v_G = \frac{v_{sg}}{1 - H_L}, \quad (12)$$

$$v_L = \frac{v_{sl}}{H_L}, \quad (13)$$

where v_{sg} (m/s) is the superficial gas velocity, and v_{sl} (m/s) is the superficial liquid velocity.

The gas-liquid interface velocity is difficult to obtain. Many researchers assume that the gas-liquid interface velocity equals the average liquid velocity, $v_i \approx v_L$.

We define the parameter $a = \frac{H_L}{1-H_L}$, where $H_L = \frac{a}{1+a}$. Eq. (11) can be transformed into:

$$\left(\frac{v_{sl}}{v_{sg}}\right)^2 - (1 + a)\frac{f_i \rho_G S_i}{f_L \rho_L S_L}(a - \frac{v_{sl}}{v_{sg}})^2 = 0. \quad (14)$$

According to the geometry of the flow pattern, the following equations can be obtained:

$$S_L = \pi D, \quad (15)$$

$$S_i = \pi(D - 2\delta), \quad (16)$$

where D (m) is the internal diameter, and δ (m) is the liquid film thickness.

According to the assumption that the liquid film thickness on the wall of the annular flow is the same, the following relation between the liquid film thickness and the liquid holdup is given by Fan [23]:

$$\delta = \frac{D(1-\sqrt{1-H_L})}{2}. \tag{17}$$

By substituting Eq. (15) to (17) into Eq. (14), a can be calculated as follows (Eq. 18):

$$a = \frac{v_{sl}}{v_{sg}}\left(\sqrt{\frac{f_L\rho_L}{f_i\rho_G}}(1-H_L)^{0.25}+1\right). \tag{18}$$

Finally, the implicit equations of liquid holdup are obtained as follows:

$$H_L = \frac{v_{sl}}{v_{sg}}\left(\sqrt{\frac{f_L\rho_L}{f_i\rho_G}}(1-H_L)^{0.25}+1\right)(1-H_L). \tag{19}$$

Eq. (19) shows that the key to calculating the liquid holdup is to calculate the friction coefficient ratio between the liquid phase and the gas-liquid interface $\frac{f_L}{f_i}$. Hart et al. (1989) [34] reported the relationship between $\frac{f_L}{f_i}$ and the superficial liquid Reynolds number. According to the experimental results,

$$\frac{f_L}{f_i} = 108\mathrm{R}_{esl}{}^{-0.726}. \tag{20}$$

According to the experimental data, $\frac{f_L}{f_i}$ can be calculated by Eq. (19); then, the corresponding superficial gas and liquid Reynolds number can also be calculated. The ratio of the friction coefficient between the liquid phase and the gas-liquid interface $\frac{f_L}{f_i}$ of different superficial gas and liquid Reynolds number is shown in Figure 9. It can be seen from the figure that $\frac{f_L}{f_i}$ changes not only with the superficial liquid Reynolds number, but also with the superficial gas Reynolds number.

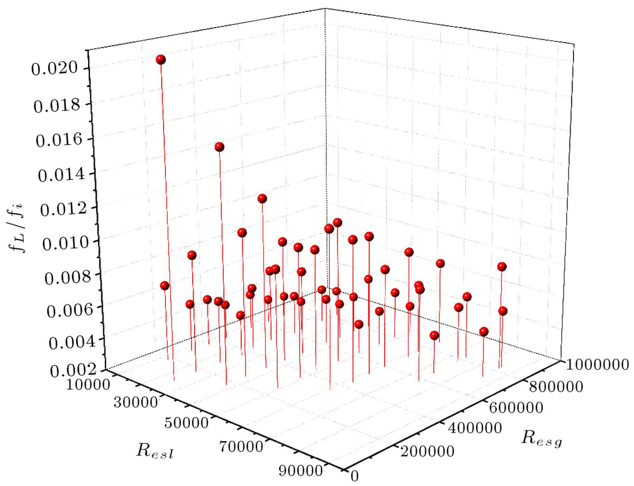


Figure 9. The ratio of friction coefficient between the liquid phase and the gas-liquid interface ($\frac{f_L}{f_i}$) versus superficial gas Reynold number (R_{esg}) and superficial liquid Reynold number (R_{esl}).

Therefore, in the reference form of Eq. (20), the following equations are presented:

$$\frac{f_L}{f_i} = xR_{esl}{}^{y}R_{esg}{}^{z}, \tag{21}$$

where:

$R_{esl} = \frac{\rho_L v_{sl} D}{\mu_L}$ The superficial liquid Reynolds number;

$R_{esg} = \frac{\rho_g v_{sg} D}{\mu_G}$ The superficial gas Reynolds number;

μ_G The gas viscosity, mPa.s;

μ_L The liquid viscosity, mPa.s.

By fitting the experimental data, the obtained parameters are as follows: $x = 0.5756$, $y = 0.5372$, and $z = -0.7734$.

4.2. Evaluation of the new horizontal low liquid holdup model

The calculation procedure for the new horizontal low liquid holdup model is as follows:

1. Select an initial value for the liquid holdup ($H_L = 0.1$);
2. Use Eq. (19) to calculate a new liquid holdup H_{Lnew};
3. If $|H_{Lnew} - H_L| > 0.0001$, then $H_L = H_{Lnew}$. Repeat step (2), until $|H_{Lnew} - H_L| < 0.0001$.

There are 49 groups of data for which the liquid holdup is $H_L < 0.1$ in the horizontal pipe. The results of a comparison between the predictions of 6 existing models (presented by B-B, M-B, Hart, Xiao, Chen, and Fan) and those of the present model and experimental data are shown in Figure 10. The figure shows that the B-B, Xiao, Fan, Chen and Hart models over-predict the experimental values. The average relative error and the average absolute error are all greater than 70%. The performance of the M-B model is good, and the average relative error is 17.8%. The average absolute error is 19.3%; however, the error is relatively high. On the other hand, the present model gives better predictions than the existing models. The absolute error of the present model is within 20%, the average absolute error is 4.8%, and the average relative error is 0.62%.

4.3. Prediction and evaluation of the new liquid holdup model with different inclination angles at high velocity

The presented model modifies the B-B model when the angle is less than 45° and the liquid holdup is less than 0.1. The procedure for predicting the liquid holdup with the modified B-B model is presented in Figure 11.

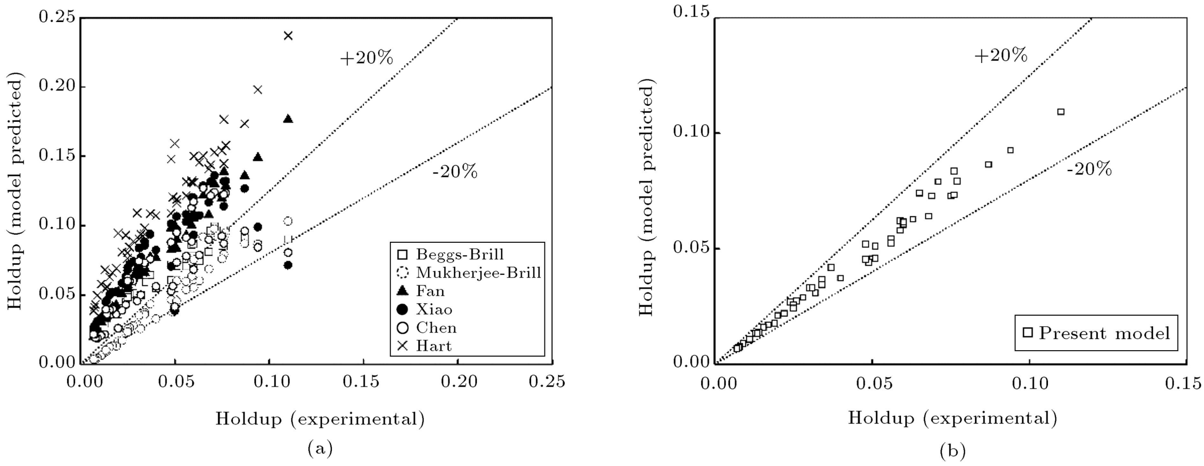


Figure 10. Comparison of predictions of liquid holdup in different models and experimental values: (a) B-B, M-B, Fan, Xiao, Chen, and Hart models, and (b) the present model.

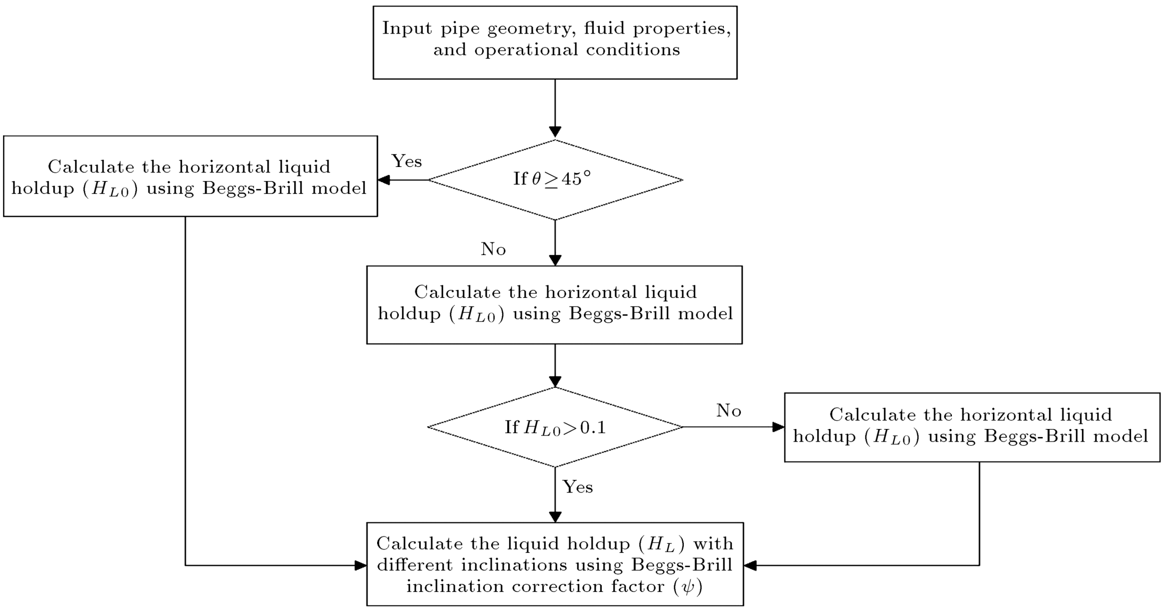


Figure 11. Calculation flow chart for the new model.

Table 5. B-B model errors for different angles.

Angle of inclination (°)	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**0 ∼ 90**
E_1 (%)	-2.2	-0.7	-0.5	-0.4	-0.8	-5.5	-4.5	-2.0
E_2 (%)	7.2	9.3	11.2	11.6	13.3	10.0	8.7	10.0

The average relative error and average absolute error of the new model are shown in Table 5. The table shows that, compared with the B-B model, the error of the new model in $0 \sim 30°$ is clearly reduced, and the average absolute error is approximately 10%. Overall, the predicted average relative error and average absolute error of the new model are 2% and 10%, respectively. In addition, the prediction accuracy is improved compared with those of the B-B model and the Kaya model. The new model is useful for predicting the liquid holdup of gas and liquid at high velocities.

5. Conclusions

To obtain an accurate two-fluid model for the prediction of liquid holdup for all inclinations at high gas and liquid velocities, 548 liquid holdup data points were obtained from the multi-phase flow experimental laboratory of the Yangtze University from the study. The following conclusions can be reached:

1. Under a certain superficial liquid velocity, the liquid holdup decreased with the increase of superficial gas velocity, while the liquid holdup increased gradually with the increase of superficial liquid velocity. The liquid holdup increased with the increase of the angle and reached the maximum value at the angle of 45°. Then, with the increase of the angle, the liquid holdup changed a little and slightly decreased. With the insignificant increase of gas velocity, the effect of angle on liquid holdup decreased when the inclination of angle was less than 45°.
2. A new two-fluid model for predicting liquid holdup for annular flow in horizontal pipes was presented. Predictions of the model were found to be accurate and in agreement with experimental data. The average absolute error was 4.8%. In addition, a modified B-B model for calculating the liquid holdup at different angles was also presented. The error of the new model was lower, and the average absolute error was 10%. Both models were applicable to high gas and liquid velocities.

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