Distribution of void fraction for gas-liquid slug flow in an inclined pipe

XIA Guo-Dong[1], ZHOU Fang-De[2], HU Ming-Sheng[2]

([1] *College of Environmental and Energy Engineering, Beijing Polytechnic University, Beijing 100022;*
[2] *State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049*)

Abstract In order to investigate the effect of inclination angle on the spatial distribution of phases, experiments on gas-liquid two-phase slug flow in an inclined pipe were carried out by using the optical probe and an EKTAPRO 1000 high speed motion analyzer. It has been demonstrated that the inclination angle and the mixture velocity are important parameters to influence the distribution of void fraction for upward slug flow in the inclined pipe. At high mixture velocity, the gas phase profile is axial symmetry in the cross-section of the pipe. This is similar to that for vertical slug flow. In contrast, most of the gas phase is located near the upper pipe wall at low mixture velocity. By measuring the axial variation of void fraction along the liquid slug, it can be concluded that there is a high void fraction wake region with length of 3~4D in the front of liquid slug. In the fully developed zone of liquid slug, the peak value of the void fraction is near the upper wall.

Keywords Gas-liquid slug flow, Void fraction, Inclined pipe

CLC numbers O359^{+}.1, V211.1^{+}7, TL334

1 INTRODUCTION

Slug flow is one of the most complicated gas-liquid two-phase flow patterns. It is characterized by a quasi-periodic alteration of long bullet-shaped bubbles (Taylor bubbles) and liquid slugs. In vertical pipe, the Taylor bubble is symmetrical. The liquid around the Taylor bubble moves downstream as a thin falling film. For the case of the inclined slug flow, the interface structure of Taylor bubble will change from annular to stratified flow pattern depending on the gas and liquid flow rates. And the small bubbles are more or less stratified in the liquid slug due to the interaction between buoyancy and turbulence dispersion. The characteristics of inclined slug flow are quite different from those of vertical slug flow.

Many investigations are focused on the void fraction distribution for vertical or horizontal slug flow[1]. Akagawa[2] conducted a detailed investigation on vertical air/water

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slug flow in a pipe of 27.6 mm diameter by the methods of conductance wires. The experimental results demonstrate that more than 30% gas exists in the liquid slugs. Mao and Dukler[3] measured the local holdup in the liquid slug using a high-precision radio-frequency probe. Van Hout *et al*[4] measured the distribution of void fraction in the liquid slug by using optical probes. They gave the reason that high void fraction occurred in the front of liquid slug: Small bubbles are produced due to the tearing from the Taylor bubble tail and dispersed into the liquid slug. Then, the dispersed bubbles are recaptured by the next Taylor bubble. Felizola and Shoham[5] proposed a unified model for slug flow in upward inclined pipes.

The purpose of the present work is to study the spatial distribution of phases for gas-liquid slug flow in an near-vertical inclined pipe and the effect of inclination angle on it. The experiments were carried out by using the optical probe and the EKTAPRO 1000 high speed motion analyzer.

2 EXPERIMENTAL SYSTEM AND TEST PROCEDURES

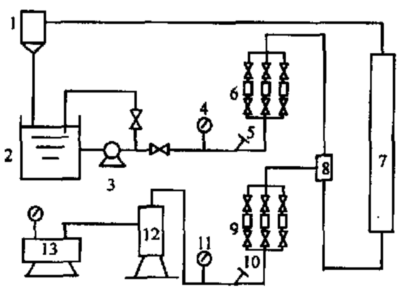

Fig.1 Schematic diagram of the experimental system

1. Filter; 2. Tank; 3. Pump; 4. Pressure gauge; 5. Thermometer; 6. Water flowmeter; 7. Test section; 8. Mixing chamber; 9. Air flowmeter; 10. Thermometer; 11. Pressure gauge 12. Stabilizer 13. Air compressor

The experimental system is schematically shown in Fig.1. Water and air are used as the working fluids. Their flow rates are measured separately by the flow rate meters. The test section is a plexiglass pipe, which has a length of 6 m and a diameter 0.03 m. The measuring point is installed at the location of 4.5 m away from the inlet of the pipe. The U-type optical probe is used to measure the void fraction. The collecting frequency is 3000~5000 Hz. The measuring time is 30~60 s so that each value of void fraction is the average one of about 30 slug units. The radial position of the optical probe can be adjusted easily. Measurements are taken at 13 radial positions in the pipe, namely at coordinate positions of r = 0, ±0.2, ±0.4, ±0.6, ±0.7, ±0.8, ±0.9R relative to the pipe centerline. The threshold value can be obtained in synchronous measurement by using the high speed motion analyzer and the optical probe at the same measuring position[6]. The frame rate of the high speed motion analyzer is 1000 frames per second. Over five slug units are measured each time. By analyzing the pictures recorded by the high speed motion analyzer, the time that each

Taylor bubble passes by the measuring point is obtained. Therefore, n corresponding values F_i (i=1, 2, $\cdots$ n) can be gained by comparing to the signals measured by the optical probe. The average value can be referred as the threshold value of the probe in this flow condition, which is as following

$$F = \frac{1}{n}\sum_{i=1}^{n} F_i \tag{1}$$

3 EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Radial profiles of void fraction for slug flow

The following nomenclature is used for the analysis.

D-diameter/m	Subscripts used are:
r-radius/m	G-gas phase
R-radial position/m	L-liquid phase
U-velocity/m·s^{-1}	LS-liquid slug
x-axial position/m	SG-superficial gas velocity
α-void fraction	SL-superficial liquid velocity
θ-inclination angle/rad	SU-slug unit
< >-average value	

When U_{SL} is constant, as shown in Fig.2, the peak location of void fraction gradually moves to the pipe centerline with the increase of U_{SG}. The void fraction profile is approximately axial symmetry in the condition of U_{SL}=0.472m·s^{-1} and U_{SG}=1.156m·s^{-1}. It demonstrates that the profile of void fraction for slug flow in the inclined pipe is greatly affected by the mixture velocity. When the mixture velocity exceeds a certain value, the two phases distribute symmetrically in the cross section of the pipe.

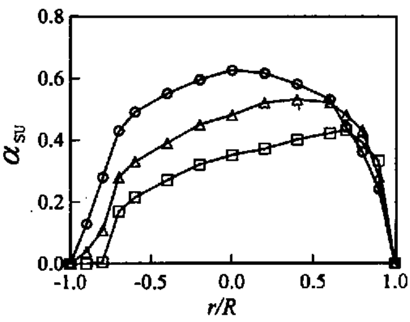

Fig.2 Influences of gas and liquid velocities on void fraction (θ=80°)
U_{SL}=0.472 m·s^{-1}, U_{SG}/m·s^{-1}:
□ 0.360, △ 0.742, ○ 1.156

The effect of the inclination angle on void fraction is shown in Fig.3. For upward vertical slug flow, the profile of void fraction is a parabolic type and the maximum value appears at the position of pipe centerline. More and more dispersed bubbles move towards the upper wall with the decrease of inclination angle. Gas phase can hardly be detected in about 0.2 R distance from the lower pipe wall in the certain range of mixture velocity. And the smaller is the inclination angle, the more gas can be detected near the upper wall.

Fig.4 shows the influence of inclination angle on the average void fraction. The average values of void fraction in vertical slug flow are a little bigger than those in inclined ones. This is partly due to the liquid slug void fraction decreases as the pipe deviates from vertical[7].

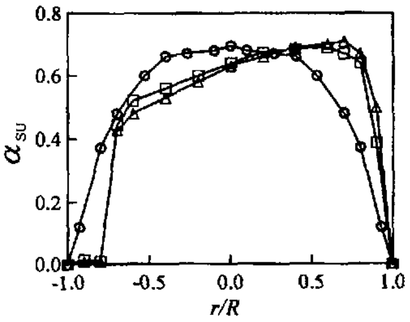

Fig.3 Influence of inclination angle on local void fraction
θ: ○ 90°, □ 85°, △ 80°;
U_{SG}=0.742m·s^{-1}, U_{SL}=0.157m·s^{-1}

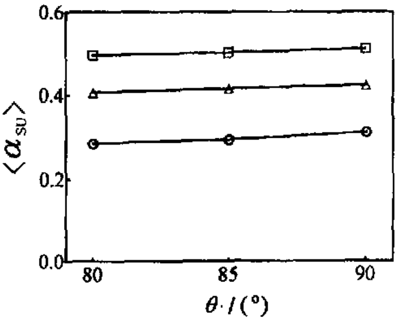

Fig.4 Influence of inclination angle on average void fraction
U_{SL}=0.787m·s^{-1}, U_{SG}/m·s^{-1}:
○ 0.742, △ 1.156, □ 1.792

3.2 Radial profiles of liquid slug void fraction

Fig.5 shows the radial profiles of liquid slug void fraction. When U_{SL} is constant, there are three kinds of void fraction profiles with the increase of U_{SG}. Under the condition of lower U_{SG}, such as U_{SG}=0.360 m·s^{-1}, the peak value of liquid slug void fraction only occurs near the upper pipe wall. With the increase of U_{SG}, void fraction peak can occur either near the pipe centerline or near the upper wall. To keep the increase of U_{SG}, the saddle shape profile of void fraction occurs (U_{SG}=1.156 m·s^{-1}). This is similar to that for vertical slug flow.

The influence of inclination angle on the local liquid slug void fraction is shown in Fig.6. The profile of liquid slug void fraction presents the saddle shape for vertical slug flow. For inclined slug flow, the superficial gas and liquid velocities greatly affect both the average value and profile of void fraction. The lower is the mixture velocity, the more gas is close to the upper wall. There is only a little difference between liquid slug void fractions at the inclination angles of 80° and 85° under the present experimental conditions.

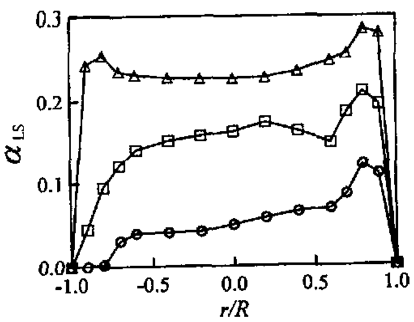

Fig.5 Radial profiles of liquid slug void fraction (θ=80°)
U_{SL}=0.472 m·s^{-1}, U_{SG}/m·s^{-1}:
○ 0.360, □ 0.742, △ 1.156

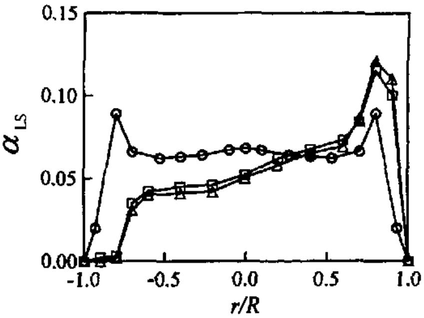

Fig.6 Influence of inclination angle on local liquid slug void fraction
U_{SG}=0.360 m·s^{-1}, U_{SL}=0.472 m·s^{-1},
θ: ○ 90°, □ 85°, △ 80°

3.3 Axial variation of void fraction along the liquid slug

The liquid slugs are divided into several sub-units with length of 1D during data reduction. The average void fraction for each sub-unit can be calculated with the signals collected by the optical probe. The variation of void fraction along the liquid slugs can be obtained by averaging the void fraction values in the corresponding units of more than 30 liquid slugs at each experiment.

In the fully developed zone of liquid slug, as shown in Fig.7, the local void fractions at position of x=0.8R are higher than those of at the centerline of the pipe while the local void fractions at x=−0.8R are lower than those at the centerline of the pipe. It can be seen that there is a high void fraction wake region with length of 3∼4D in the front of liquid slug. It is very important for predicting the pressure drop in the slug flow[8]. In the wake region, the radial distribution of void fraction is uniform from −0.6R to 0.6R due to the effect of the turbulence dispersion.

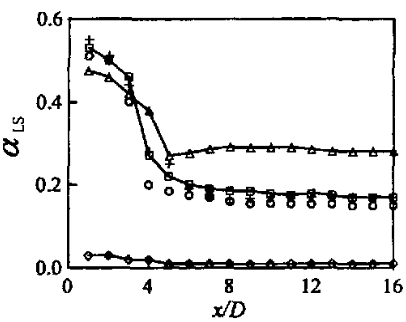

Fig.7 Influence of inclination angle on distribution of void fraction along liquid slugs
□ 0, + 0.6R, △ 0.8R, ○ −0.6R, ◇ -0.8R,
U_{SG}=0.742 m·s^{-1}, U_{SL}=0.157 m·s^{-1}

4 CONCLUSIONS

The inclination angle and the mixture velocity are important parameters to influence the distribution of void fraction for upward slug flow in the inclined pipe. At high mixture velocity, large bubbles are located in the central zone of the pipe. Simultaneously, small bubbles distribute symmetrically along the cross-section of the pipe by the action of strong turbulent dispersion in liquid slug. The gas phase distribution is axial symmetry, which is similar to that for vertical slug flow. In contrast, most of gas phase gathers near the upper wall by the action of buoyancy at the low mixture velocity. By measuring the distribution of void fraction along liquid slug, it can be concluded that there is a high void fraction wake region with length of 3~4D long in the front of liquid slug and the void fraction in this region is uniform along the radial direction. In the fully developed zone of liquid slug, the peak value of void fraction occurs near the upper wall. In general, the average value of void fraction for slug flow slightly decreases when the pipe line deviates from vertical.

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