Two-phase slug flow in vertical and inclined tubes*

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Abstract Gas-liquid slug flow is investigated experimentally in vertical and inclined tubes. The non-invasive measurements of the gas-liquid slug flow are taken by using the EKTAPRO 1000 High Speed Motion Analyzer. The information on the velocity of the Taylor bubble, the size distribution of the dispersed bubbles in the liquid slugs and some characteristics of the liquid film around the Taylor bubble are obtained. The experimental results are in good agreement with the available data.

Keywords Gas-liquid two-phase flow, Vertical tubes, Inclined tubes, Taylor bubble

1 Introduction

Slug flow is one of the most basic flow patterns and occurs over a broad range of gas and liquid flow rate in small and medium size tube. It is characterized by large bullet-shape bubbles (referred to as a Taylor bubble), almost filling up the tube, which are separated by liquid slugs. One may or may not find small bubbles in slug following the Taylor bubble.

Slug flow is a highly complex type of flow with an unsteady nature. A great deal of experimental and theoretical work have been done on slug flow in vertical tubes[1−4]. For the inclined case with a circular tube, only a few studies[5−7] have been presented, and the previous results appear greatly scattered.

The purpose of the present investigation is to obtain some high quality experimental data of slug flow in vertical and near-vertical tubes by using high speed motion analyzer. The non-invasive measurements are in sharp contrast to such commonly used methods as conductance and optical probe in which the data are obtained by insertion of the probe into the flow field at a given point. The proposed data of the bubble velocity, the dispersed bubble size and the characteristics of the liquid film are in good agreement with available results.

2 Experimental facility

2.1 Test loop

The experiments were carried out in an air water flow loop (see Fig.1). The test section is made of a 6 m-long plexiglass tube with i.d. of 30 mm. The measuring station is installed 4.5 m above the inlet, which can eliminate the effects of inlet and outlet. A transparent, water-filled, rectangular box is fitted onto the measuring station to allow undistorted videographic measurements. The experimental conditions are as follows: system pressure 0.1∼ 0.3 MPa, superficial velocity of water 0.032∼1.2 m/s, superficial velocity of air 0.1∼1.6 m/s.

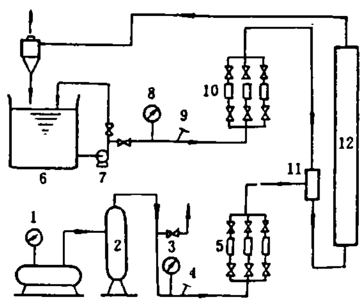

Fig.1 Sketch of the experimental system

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

2.2 High speed motion analyzer

The EKTAPRO 1000 high speed motion analyzer made by Kodak Company of USA was

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used to perform the non-invasive measurement of the gas-liquid slug flow. Light enters the imager through the lens and is converted into a video signal. The video signal correponds precisely to the variation in intensity and spatial relationships of the image captured by the lens. The variation in intensity of light coming from different objects in the image represents the spatial relationship among objects. The video signal created in the imager is amplified and processed so that it can be transmitted through the imager cable to the processor. Once the user is satisfied that the picture will provide the necessary data, a recording of the object of interest is made. In the Record mode the Tape Transport is commonded to move tape at the selected speed and the Modulator and Record boards are turned on, sending the video signal to the Record Head. The frame rate selected in the experiment is 1000 frames per second.

2.3 Image analysis

The image frames describing the two-phase flow field were recorded and stored in the special cassettes. In order to obtain the information on slug flow, a series of image analysis steps must be further undertaken. Motion program is a menu-driven software package designed to facilitate the digitizing object motion recorded with high speed video systems. Using motion program, collecting points, line segments and velocities all are very simple and the data collected are directly stored in the computer.

The first step of datum collection is to determine the scale factor. Such a factor is obtained by dividing the actual distance between two landmarks in the object-space by the measured image distance between them on the screen. The resulting actual/image ratio can be used to convert image into actual coordinates. The outside diameter of the tube was used to accomplish this task.

The second step of datum collection is to measure the velocity of the bubbles and such required parameters as the size of small bubbles and the thickness of falling film. In order to obtain these information, quick measurement is the perfect choice. By using quick measurements, the size of the bubbles, the falling film thickness and the location of the Taylor bubble nose can be obtained easily. The length of the Taylor bubble must be determined by means of the velocity of the corresponding bubble and the known temporal separation because the two landmarks that are used to determine the separation distance may usually not lie in the same frame.

The desired velocity vectors may be determined by dividing the separation distance between corresponding bubble images in successive image frames ($\sqrt{\Delta x_i^2 + \Delta y_i^2}$) by the known temporal separation Δt. Because the time separation between image captures is very small (0.001 s), the instantaneous velocity obtained is defined as:

$$V_i = \frac{\sqrt{\Delta x_i^2 + \Delta y_i^2}}{\Delta t} \quad (1)$$

where Δx_i=horizontal (x) displacement of bubble i between successive images, Δy_i = vertical (y) displacement of bubble i between successive images, Δt = time separation between successive image captures, V_i = instantaneous velocity of bubble i.

The third step of datum collection is to determine the shape of Taylor bubble. Making use of the object data collection, the shape of the Taylor bubble may be drawn by measuring the coordinates of different points on the gas-liquid interface. The data shown in this paper were collected and averaged over ten blocks to ensure accurate results. The relative measurement error of the high speed motion analyzer is within 0.0052.

3 Experimental results and discussion

The present paper is focused in an experimental investigation of the fully developed slug flow in vertical and inclined tubes. The experiments were carried out over the velocity range of slug flow pattern. Three kinds of inclination angles (θ =80°, 85°, 90°) were studied for D=30 mm. An additional test was performed for θ = 90°with tube of 47 mm in i.d.

For simplicity, meanings of all symbols used in this paper are listed as follows: C_1, C_2 are coefficients, D tube diameter, Fr Froude number, $Fr_s = V_s/(gD)^{1/2}$, $Fr_T = V_T/(gD)^{1/2}$, g gravitational acceleration, N total number of small bubbles in liquid slug, N_d number of small bubbles with diameter

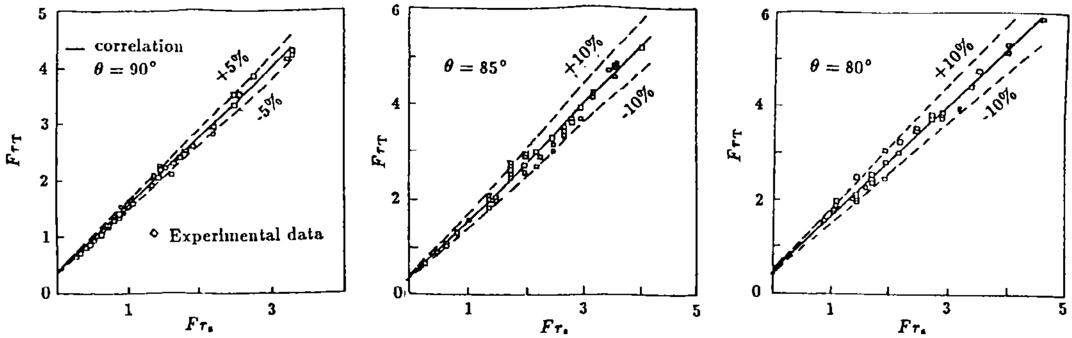
$d \pm 0.5$ mm, r_0 radial position of bubble nose, V_f liquid film velocity, V_G superficial gas velocity, V_L superficial liquid velocity, V_s mixture velocity, V_T Taylor bubble velocity, x axial distance, y distance from gas-liquid interface to tube wall, θ inclination angle, δ liquid film thickness, ζ nondimensional axial distance, η nondimensional liquid film thickness.

3.1 The velocity of Taylor bubble

For vertical tube with a diameter of 25.9 mm, Nicklin *et al* [8] found that for Reynolds numbers of $(8\sim50)\times10^3$ bubble velocity is very well correlated by

$$V_T = C_1 V_s + C_2\sqrt{gD} \quad (2)$$

The measured nondimensional velocities of Taylor bubble for three kinds of inclination angles are presented in Figs.2~4. These are accurate averages over five bubbles at the same flow rate. The velocity of Taylor bubble is well correlated by Eq.[2]. The relative error is 0.05 for vertical tube, and 0.10 for the other two kinds of inclination angles. The least square fit values of C_1 and C_2 are shown as follows: C_1=1.219, C_2=0.350 for $\theta = 90°$; C_1=1.198, C_2=0.372 for $\theta = 85°$; C_1=1.193, C_2=0.454 for $\theta = 80°$.



Figs.2~4 Bubble Froude number $Fr_T = V_T/(gD)^{1/2}$ vs liquid Froude number $Fr_s = V_s/(gD)^{1/2}$ in vertical tube with D=30 mm, θ = 90°(2), 85°(3) and 80°(4)

The coefficient C_1 decreases as the angle of inclination declines from the vertical position. The existing investigations show that the value of C_1 is affected by the liquid velocity ahead of the Taylor bubble nose. For vertical upward flow, the nose tip of Taylor bubble lies in the tube centerline where the liquid velocity is maximum (equal to 1.22 V_s for turbulent flow). For inclined tube, however, the nose tip usually has the shift in radial position which leads to the coefficient C_1 decreasing.

In contrast, the non-dimensional drift velocity C_2 increases as the angle of inclination declines from the vertical position. This result is consistent with that of Bonnecaze *et al.*[6] who gave a qualitative explanation for this behavior, arguing that the gravitational potential makes the liquid velocity along the curved surface at the bubble nose first increase and then decrease as the angle of inclination changes from the vertical position toward the horizontal one. Bendiksen[5] assumed as a preliminary approximation, that levels and buoyancy effects act independently, and proposed

$$C_2 = C_2^h \cos\theta + C_2^v \sin\theta \quad (3)$$

where

$$C_2^v = 0.35 \quad (4)$$

$$C_2^h = 0.542 \quad (5)$$

Comparisons between the proposed values of C_1, C_2 and those of Nicklin *et al* [8] for vertical tubes and Bendiksen for inclined tubes are shown in Table 1. It can be seen that C_1 of the present paper is slightly larger than that of Nicklin *et al* for the vertical tube. For the other two kinds of inclination angles, the recommended C_1 is close to the upper limit and C_2 slightly different from Bendiksen's results.

Table 1 Comparisons of C_1, C_2 with Nicklin's and Bendiksen's

	$\theta = 80°$		$\theta = 85°$		$\theta = 90°$	
C_1	Present result	Bendiksen's	Present result	Bendiksen's	Present result	Nicklin's
	1.193	1.0~1.2	1.198	1.0~1.2	1.219	1.2
C_2	Present result	Eq.(3)	Present result	Eq.(3)	Present result	Nicklin's
	0.445	0.439	0.372	0.396	0.35	0.35

It should be pointed out that the results presented by Nicklin *et al* and Bendiksen *et al* were correlated by the data of a single bubble in flowing liquid which does not consider the influence of the small bubbles in the liquid slug ahead of the Taylor bubble. In gas-liquid slug flow, there are a large number of small bubbles in liquid slugs, which move at a velocity less than the Taylor bubble velocity. Therefore, the Taylor bubble will catch up and coalesce with some small bubbles, which increases the translational velocity of the Taylor bubble.

3.2 Position of Taylor bubble nose

We also observed the stable bubble shape by means of the present apparatus. Fig.5 demonstrates the shapes of bubbles for three kinds of inclination angles at the same gas-liquid flow rate. For a vertical tube, the Taylor bubble is symmatrical in axis. For the inclined tube, however, the bubble nose usually drifts off the centerline and its position is the function of the mixture velocity as well as inclination angle. The lower the liquid velocity is, the farther the nose of bubble drifts off the tube centerline. It gradually approaches to the centerline as liquid velocity increases (Figs.6,7). Comparison is shown in Fig.8. For a low liquid velocity, the nose of the bubble will be close to the upper wall as the inclination angle declines from the vertical position. When the mixture velocity exceeds the certain limit, the bubble nose will locate in the centerline, and its position will be independent of the mixture velocity. Increasing the mixture velocity further, the shape of bubble will become irregular due to the turbulent force. There are a great deal of small bubbles in liquid ahead of the bubble and the accurate shape can nearly be distinguished.

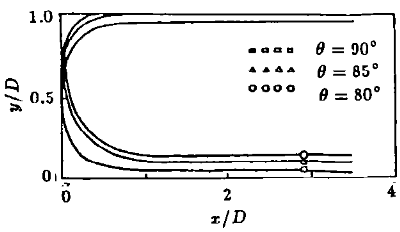
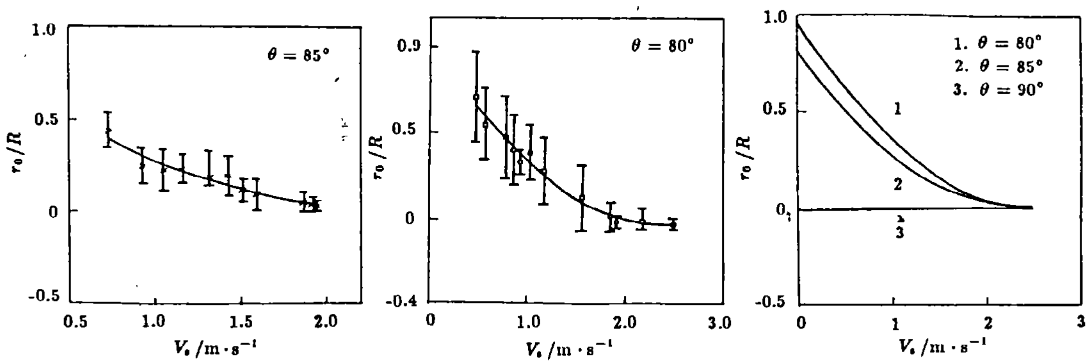


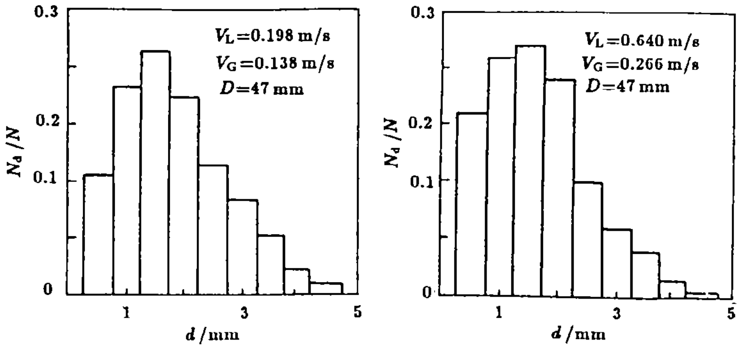
Fig.5 The shape of the Taylor bubble



Figs.6~8 Position of the Taylor bubble nose r_0/R vs the mixture velocity V_s in inclined tube with different inclination angles

3.3 Size of dispersed bubbles in the liquid slugs

Additional experiment was performed for $\theta = 90°$ with tube of 47 mm in i.d., and statistical distribution of the dispersed bubble size in the slugs was obtained. The experimental observation demonstrates that the size of the bubble near the tube wall is usually small due to the highest shear there. The diameters of most bubbles are within 1~2 mm. The maximum diameter of dispersed bubbles in air-water slugs is less than 5 mm. Figs.9 and 10 show two examples of the bubble size distribution histograms in the slugs. As can be seen, the fraction of the bubbles with much smaller size increases and that with much larger size decreases with the increase in the mixture velocity. This is because the turbulent force increases with increase in the mixture velocity, which causes larger bubbles to split.



Figs.9,10 Statistical distribution of the dispersed bubble size in liquid slugs (two examples)

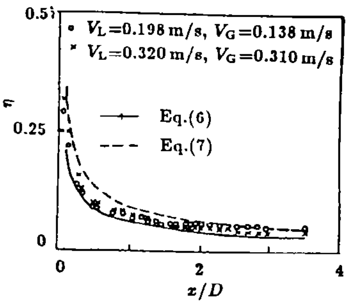


Fig.11 Nondimensional liquid film thickness (η) vs nondimensional axial distance (x/D) in vertical tube

3.4 Falling liquid film

The falling liquid film is a main part of gas-liquid slug flow. In some heat transfer problems involving slug flow, the local film thickness is an important governing parameter. By assuming potential flow conditions at the bubble nose and in the film, and by assuming that the nose of the bubble was a portion of a spherical surface, Davies and Taylor[9] presented the following expression for the local film thickness around Taylor bubble:

$$\eta_{\rm p} - \eta_{\rm p}^2 = 0.0583\zeta^{-0.5} \tag{6}$$

where $\eta_{\rm p} = \delta_{\rm p}/D$ is nondimensional potential film thickness, and $\zeta = x/D$ is nondimensional axial distance. Considering viscous effects, Ozgu[10] proposed the following approximate equation:

$$\frac{\eta_{\rm p}}{\eta} = 0.667 \tag{7}$$

where $\eta = \delta/D$ is nondimensional film thickness. Fig.11 shows the experimental data and the calculated results of Eqs.(6,7). Eq.(6) agrees well with the experimental data in the region of the bubble nose. As ζ increases, however, Eq.(7) is much better than Eq.(6) as compared with the experimental result. This is because the predictions of Eq.(6) neglect the viscous boundary layer effects in the film and can be expected to apply only at small values of ζ.

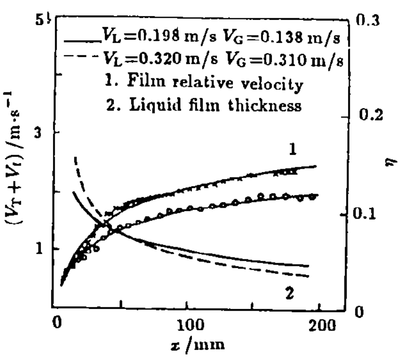


Fig.12 The nondimensional thickness (η) and the relative velocity ($V_{\rm T} + V_{\rm f}$) of liquid film vs the axial distance in vertical tube (D=47 mm)

By measuring dispersed bubbles in the liquid film, we have obtained the information on the velocity of the falling liquid film. As the velocity of the liquid film was determined according to the small bubble motion, it can only be detected for the region in present of the bubbles. Fig.12 shows the velocities of the liquid film and the corresponding liquid film thickness in two kinds of flow conditions. The velocity of the liquid film tends to be constant at the rear of the Taylor bubble.

4 Conclusion

The detailed information on the motion of the Taylor bubble in vertical and inclined upward slug flow has been obtained. For inclined tubes, the experimental data of Taylor bubble velocity are well represented by Eq.(2). The values of C_1 are smaller than that for vertical tube because the nose tip of Taylor bubble usually has the shift in radial position. The non-dimensional drift velocity C_2 increases as the angle of inclination declines from the vertical position in the range of the flow rate in the present experiment.

The present paper has also studied the characteristics of the dispersed bubble in liquid slug and the falling liquid film by making use of the flow visualization technique. The fraction of the dispersed bubbles with smaller size in liquid slug increases as the mixture velocity increases. The maximum diameter of dispersed bubbles in air water slugs is less than 5 mm. Both the velocity and the thickness of liquid film around Taylor bubble tend to be constant at the rear of bubble.

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