Liquid mean velocity and turbulence in a horizontal air-water bubbly flow

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Abstract The liquid phase turbulent structure of an air-water bubbly horizontal flow in a circular pipe has been investigated experimentally. Three-dimensional measurements were implemented with two "X" type probes oriented in different planes, and local liquid-phase velocities and turbulent stresses were simultaneously obtained. Systematic measurements were conducted covering a range of local void fraction from 0 to 11.7%. The important experiment results and parametric trends are summarized and discussed.

Keywords Air-water bubbly flow, Hot-film anemometry, Liquid velocity, Turbulence

CLC number TK121

1 Introduction

Turbulent air-water bubbly flow occurs in many engineering fields. Accurate prediction of bubbly flow requires thorough understanding of the local instantaneous interaction between scattered and continuous phases. However, it is only in recent years that much progress has been made in understanding the local structure of these flows.

Progress has been made to use the hot-film anemometry technique in measurements of turbulence structure and liquid phase distributions in vertical bubbly flows,[1-5] however only limited reports were found to use the technique to examine the two-phase characteristics in horizontal flow channels. In recent measurements of horizontal bubbly flow with HFA,[6] local axial liquid mean and turbulent fluctuating velocities were determined, and the one-dimensionally oriented measurement was carried out only through a vertical tube diameter.

Compared to vertical flows, horizontal bubbly flow is more complicated due to its asymmetry resulting from buoyancy effect, and accordingly the flow will demonstrate a 3-D flow behavior. The HFA measurement in horizontal bubbly flows represents a real challenge to the investigators in the fields who want to conduct more detailed and multi-dimensional measurements with HFA in horizontal gas-liquid flows.

It was for these reasons that the present experimental work was undertaken. Data were taken with hot-film anemometers in systematic fashion over the range J_g: 0~0.44 m/s, and J_f: 3.0~4.0 m/s. In the experimental conditions, the local liquid velocity, and Reynolds stress were measured in full-developed air-water bubbly horizontal flow in a Pyrex glass pipe. It is hoped that this data set will serve as a standard against which models can be tested, at least over the range of conditions employed herein.

2 Experimental facility

The experimental facility is shown schematically in Fig.1. A centrifugal pump provides the water flow. Measurements of the liquid flow rate were made with an orifice flowmeter in conjunction with a 1151 pressure transducer. The orifice was calibrated using a time-volume method, and based on the standard deviation of the calibration, it has an estimated uncertainty of ±3.9 percent of full scale. Air is supplied to the facility via a 0.5m^3 compressed air tank back to an air compressor. Air flow rates were measured with a rotameter in conjunction with a pressure gate. The rotameter was calibrated by the producer, and based on

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the standard deviation of the calibration, the rotameter is accurated to within ±2.7% of full scale. The air and water streams enter a mixing chamber where a two-phase mixture is produced.

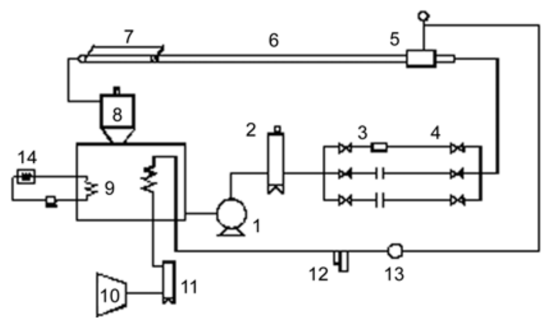

Fig.1 Schematic of testing loop.

1. Centrifugal pump, 2. Water tank, 3. Water flowmeters, 4. Control valves, 5. Air-water mixer, 6. Test section, 7. Quick-closing valve, 8. Air-water separator, 9. Water storage tank, 10. Air compressor, 11. Air tank, 12. Air filter, 13. Air flowmeter, 14. Heat cool system.

A special mounting section was constructed to hold the traversing mechanism for the hot-film probe. The section had a length of 200 mm and the same inside diameter (35 mm I.D.) as the test tube, and was connected to the loop at L/D = 172 downstream of the mixing chamber through the flanges at both ends of the section. The probe was mounted on a Plexiglas block, and a vernier scale with a resolution of 0.01 mm and a digital display was used to traverse the probe in the direction perpendicular to the tube axis. The entire mounting section could be rotated around the tube axis by adjusting the flange mounting angles, so that measurements through vertical, horizontal and inclined tube diameters could be implemented respectively. A total of 11 or 15 probe locations were selected through each pipe diameter (see Fig.2).

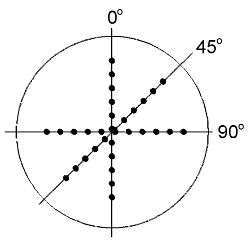

Fig.2 Probe positions across test section.

To minimize the temperature drift of the hot-film probes, a heat cool system was used to supply water to keep the water temperature constant, around (28±0.1) ^{o}C.

During the test the overheat ratio of the probe was set to 1.08, a bit higher than the ratio suggested by the manufacturer, 1.05. It was found that the sensor with a higher overheat ratio is more sensitive to velocity change, and less sensitive to temperature change.

For a better resolution of the turbulent fluctuation and a higher accuracy in phase discrimination, a 20 kHz sampling rate with 1s sampling time was selected.

3 Measuring methodology

In the present study 3-D measurements were implemented with two "X" type probes in horizontal air-water bubbly flows: a standard 90° "X" type probe, 1246~60W, was utilized to measure U,V, u', v' and $\overline{u'v'}$ in axial and radial directions, and another standard "X" type probe, 1240~20W to measure U,W, u', w' , $\overline{u'w'}$ in axial and circumferential directions. The cylindrical coordinate system of current measurements is shown in Fig.3.

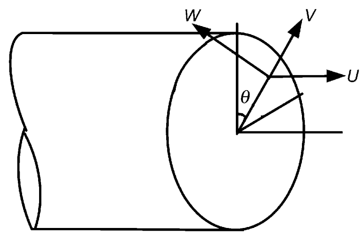

Fig.3 The cylindrical coordinate system.

Like any probe method used in the measurement of gas-liquid two-phase flow, the bridge output of the hot-film anemometer also shows a sharp difference between signals of the continuous liquid phase and the scattered gas phase. To evaluate parameters of the continuous liquid phase, it is first necessary to detect signal of the scattered phase and have it eliminated to leave only the continuous phase signal.

Fig.4(a) is a typical hot-film anemometer response, measured with a sampling rate of 20 kHz. As would be expected for turbulent flow, the voltage is seen to fluctuate around some average value, and the voltage depressions and spikes are due to the bubbles hitting and passing the probe, respectively.

To remove the voltage depressions and spikes, the first important task is to identify the phases. We adopted the phase discrimination methods of Liu and

Bankoff.[5]

The result shows that the methods work well. A bubble-filtered signal is shown in Fig.4(b). After the bubbles have been removed from the signal, the voltages are ready to be converted to velocities using the calibration curve and the relative turbulence terms can be calculated afterwards.

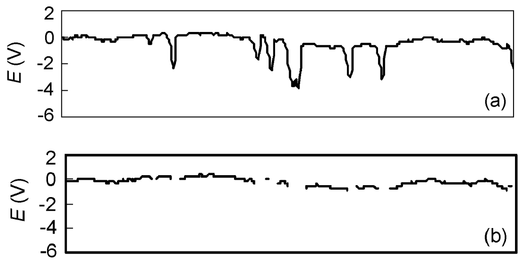

Fig.4 Raw and filtered hot-film signal. (a) Raw signal; (b) Filtered signal.

4 Results and discussion

Variation of mean axial liquid velocity measured along a vertical diameter is described in Fig.5(a). Here the abscissa position $r/R = -1$ refers to the bottom of the tube, whereas $r/R = 1$ to the top. The mean axial velocity demonstrates asymmetric profiles with the largest velocities located in the bottom part of the tube. The degree of asymmetry increases with increasing airflow rate. The liquid-phase velocity distribution in the bottom part of the tube resembles a fully developed single-phase turbulent flow characteristic, implying that there is a liquid layer exiting there. However, at the upper part of the tube where the population of bubbles is high, the value of the liquid-phase velocity distribution goes even below the single-phase profile.

Symmetric profiles of the mean liquid velocities are found along horizontal diameter. As shown in Fig.5(b) the velocity curves moves upwards when airflow rate is increased.

The profiles of turbulent intensities, defined as $\sqrt{\overline{u'^2}}/U$, $\sqrt{\overline{v'^2}}/U$ and $\sqrt{\overline{w'^2}}/U$, are presented in Fig.6(a), (b), (c), respectively. In the bottom part of the tube, the value of turbulence intensity of air-water two-phase flow is equal to or slightly greater than the relative single-phase value. However, in the upper part of tube two-phase value increases substantially apparently due to the introduction of the bubbles. Generally speaking, the larger the airflow rate, the higher the turbulence intensity. The profile goes up with r/R

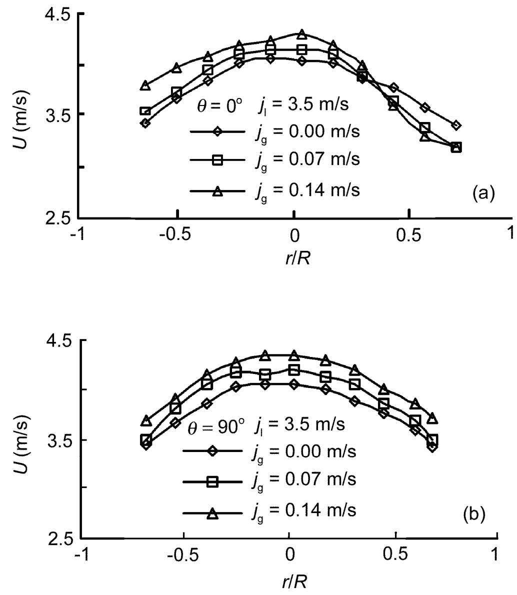

Fig.5 Liquid-phase velocity distribution.

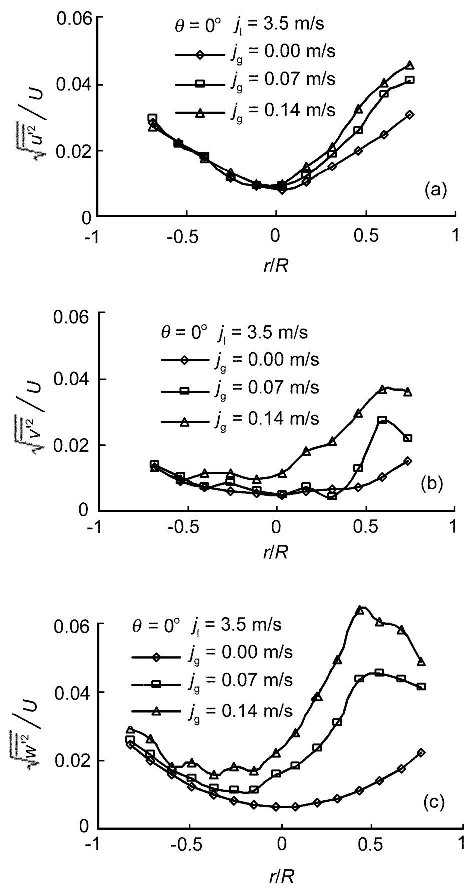

Fig.6 Liquid-phase turbulent intensity.

until it is peaked, and then drops down abruptly. The peak of axial turbulence intensity appears at radial positions greater than r/R = 0.8, and radial and circumferential turbulence intensities reach their maximum value at about r/R = 0.7 and 0.3, respectively. Among the three orthogonal directions, the radial turbulence intensity assumes the smallest values.

The profile of cross-correlation $-\overline{u'v'}$ and $-\overline{u'w'}$ are indicated in Fig.7(a),(b), which are proportional to the shear stress acting on the local circumferential surface everywhere in the tube, except near the wall where a laminar viscous shear stress layer exits. It should be noted that the profiles show the same tendency as the turbulence intensities on effect of increasing air flow rates and variation with radial position.

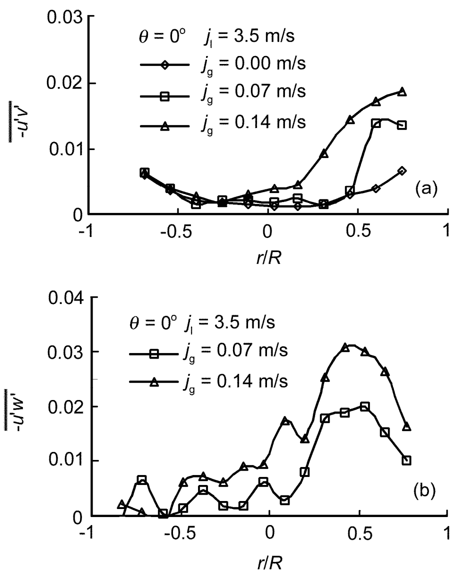

Fig.7 Liquid-phase turbulent stress.

5 Summary

In this paper, hot-film probes were used to measure the velocity and turbulence of continuous liquid phase of horizontal air-water bubbly flows in a 35 mm I.D. tube. Three-dimensional measurements were implemented with two "X" type probes, 1246~60W and 1240~20W. Local liquid-phase velocities and turbulent stresses were simultaneously obtained.

The measurements indicate that the axial mean liquid velocity demonstrates asymmetric profiles along a vertical tube diameter. In the bottom part of the tube, the velocity resembles a fully developed single-phase turbulent flow characteristic**,** however its distribution goes even below the single-phase profile in the upper part of the tube. Symmetric profiles of the mean liquid velocities are found along horizontal tube diameter. The introduction of air bubbles greatly enhance the turbulent level in terms of the turbulence intensities in axial, radial and circumferential directions at the upper part of the tube. In the bottom part of the tube, the value of turbulence intensity of air-water two-phase flow is equal to or slightly greater than the relative single-phase value. The profiles of cross-correlation $-\overline{u'v'}$ and $-\overline{u'w'}$ show the same tendency as the turbulence intensities on effect of increasing air flow rates and variation with radial position.

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