MEASUREMENT OF REYNOLDS STRESS IN BUBBLY FLOW USING ULTRASONIC DOPPLER METHOD

Hideki Murakawa[1] and Hiroshige Kikura[1] and Masanori Aritomi[1]

[1]Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, 2-12-1 Ohokayama, Meguro-ku, Tokyo, 152-8550 Japan, e-mail:murakawa@2phase.nr.titech.ac.jp

Keywords: Bubbly flow, Ultrasonic Doppler Method, Reynolds stress

ABSTRACT

Microscopic structure in bubbly flows is a topic of interest in the study of fluid flows. In the present paper, the Ultrasonic Doppler Method was applied to the measurement of bubbly flows from which Reynolds stress profiles were obtained. Experiments were carried out for an air-water dispersed bubbly flow in a 20mm x 100 mm vertical rectangular channel having a void fraction smaller than 3%. Two ultrasonic transducers were set on the outer surface of the test section with a contact angle of 45° off the vertical, one facing upward and the other facing downward. By applying statistical methods to the two directional velocity profiles, Reynolds stress profiles were calculated. By comparing the Reynolds stress in bubbly flow with that in single-phase flow, it was found that Reynolds stress profiles varied with the amount of bubbles present in the flow. Peak values of the Reynolds stress near the wall increased. This tendency was more pronounced as void fraction increased.

1. INTRODUCTION

Two-phase bubbly flow is one of the most fundamental flow fields appearing in many industrial applications. However, two-phase flow structure has not completely been understood and still needs further investigation in detail. The main reason is the difficulty of measuring without disturbing the given bubbly flow. At the early stage of two-phase measurements, most techniques required intrusion into the flow fields. Examples are the electrical resistivity method, hot-film anemometry, and so on. To avoid disturbing the original flow, non-intrusive measurements have been developed. One of them is the Ultrasonic Doppler Method. The authors have tried to adapt the Ultrasonic Doppler Method to bubbly flow measurements. Advantages of this method include spatial-temporal measurement of the flow, applicability to opaque liquids such as liquid metal and magnetic fluid, line measurement for flow mapping, and adaptability to an existing pipe flow.

Two-phase measurements have been carried out for the last thirty years using several methods. Serizawa et al. (1975) pioneered performance of detailed experiments in bubbly flows using hot-film anemometers. They investigated not only the velocity and void fraction profiles, but also the turbulent intensity profiles and turbulent energy production. Michiyoshi & Serizawa (1986) reported the effects on flow structure of injecting bubbles into liquid flows. Wang et al. (1987) investigated flow quantities in bubbly flow in a vertical pipe and showed that the local void fraction reached a peak value near the pipe wall and the Reynolds stress was increased as a result of bubble injection.

The objective of this study is to clarify the effects of bubble injection on the liquid flow structure using the Ultrasonic Doppler Method. The experiments were performed at Reynolds numbers less than 3200, the transition region in single-phase flow.

2. EXPERIMENTAL APPARATUS

The flow set-up consisted of a vertical rectangular channel made of acrylic, a water circulation system, an air supply system, and the Ultrasonic Doppler Method measurement. The working fluids were air and tap water. The water was seeded with nylon micro tracer particles (Daicel Hüls, WS-200P) at the ratio of 0.1g/l. The specific density of theses particles is 1.02. Their average diameter is 80 μm. The pump circulated water through the lower tank, test channel and upper tank. The water flow rate was controlled and adjusted by operating a valve together with an orifice flow meter. Air was injected through seven needles (i.d. 0.19mm) at the bottom of the test section. The air flow rate was regulated by an air control valve and measured by a float flow meter. Experiments were carried out at atmospheric pressure, water temperature was kept between 19.5 and 20.5ºC using a subcooler. The Ultrasound Doppler Method system included an X-3 PS-I model UVP monitor (Met Flow AG), and a personal computer, which record the water and gas flow rates. For each measuring condition, 30,000 instantaneous velocity profiles were recorded along each measuring lines.

The test section located between the upper tank and air-water mixer. The size of the vertical rectangular channel is 100mm x 20mm x 1700mm. Two ultrasonic transducers were set on the outer surface of the test section with a contact angle of 45º off the vertical one facing upward and the other facing downward. The outer surface of the test channel and the ultrasonic transducers were submerged in the water in order to equalize acoustic impedance.

3. DATA PROCESSING METHOD

3.1 The separation of liquid phase velocity

Since ultrasonic pulses reflected on the bubble's surface and micro particles suspended in liquid phase, the data measured in the bubbly flow using the Ultrasonic Doppler Method included both the liquid phase velocity and bubble's rising velocity. The authors have established a technique for separating the velocity distribution of the gas phase and the liquid phase by using statistical methods (Suzuki et. al. 1999,2002). In this paper, the outline of this technique is described.

A bubble's rising velocity is faster than the liquid velocity; so, an instantaneous velocity profile has a typical peak if a bubble crosses the measuring line in the measurement of a bubbly flow. The maximum value of velocity profiles that measured the bubble rising velocity is bigger than those that did not measure it. Figure 9 illustrates the typical data patterns of instantaneous velocity profiles. By adopting an appropriate threshold velocity, the recorded instantaneous velocity profiles were divided into two groups, that is, profiles either including bubbles (GroupA) or not (GroupB). In this study, to clarify the time averaged liquid structure in bubbly flow, GroupA data was calculated.

3.2 The calculation of the Reynolds stress

The Reynolds stress profiles can be calculated from the two directional velocity components (*u* and *v*). Ultrasonic transducers were set at different angles (*α* and *β*) from the flow direction. The mean Reynolds stress profiles were calculated as follows (Durst et al. 1976 and Tropea 1983):

$$\tilde{Q} = \tilde{U}\cos\theta + \tilde{V}\sin\theta \tag{6}$$

$$\tilde{U} = \bar{U} + u, \qquad \tilde{V} = \bar{V} + v \tag{7}$$

$$q_1 = v\cos\alpha + u\sin\alpha, \qquad q_2 = v\cos\beta + u\sin\beta \tag{8}$$

where $\widetilde{U}$ and $\widetilde{V}$ are instantaneous vertical and horizontal velocities and $\widetilde{Q}$ is the instantaneous velocity along the measuring line. $\overline{U}$ and u are the time averaged velocity, and the velocity fluctuation, respectively. The fluctuating velocity components (q_1, q_2) on the two measuring lines can be expressed in Eq.(8). If α equals to β, the Reynolds stress can be expressed as follows from Eq.(6) -(8):

$$-\rho\overline{uv} = \rho\frac{\overline{q_1^2} - \overline{q_1^2}}{2\sin 2\theta} = \rho\frac{q_1^{'2} - q_2^{'2}}{2\sin 2\theta} \qquad (9)$$

where q' is standard deviation of the velocity fluctuation on the measurement line directions.

4. RESULTS AND DISCUSSION

4.1 Velocity profiles in bubbly flow

The graph in Figure 10 illustrates the universal velocity distribution in single-phase flow. In this graph, u^+ and y^+ are defined as follows:

$$u^+ = \frac{\overline{u}}{u_\tau}, \quad y^+ = \frac{yu_\tau}{\nu} \qquad (10)$$

where u is the axial velocity, y is the distance from the wall, and ν is the kinematic viscosity of the water. The value of y is corrected for the error considered to arise from the part of the measurement line overlapping with the wall surface and reported by Taishi et al. (2002). The value for u_τ is the friction velocity in single-phase flow, which is given by the follow equations (Durst et al. 1996):

$$C_f = 2\left(\frac{u_\tau}{u_m}\right)^2 = 0.073\,\mathrm{Re}_m^{-1/4}, \quad \mathrm{Re}_m = \frac{u_m \cdot 2D}{\nu} \qquad (11)$$

where $2D$(=20mm) is the width of the channel and u_m is the mean velocity.

Generally, it is well known that the velocity distribution in a turbulent flow region near the wall can be written as

$$u^+ = 5.75\log y^+ + 5.5 \qquad (12)$$

In single-phase flow, the velocity profiles approach the form defined by Eq.(12) with increasing Reynolds number. This tendency agrees well with the findings reported by Durst et al. (1996). From these results, it is proven that single-phase flow was in the turbulent transition region under this condition.

Figure 11(a),(b) show the mean velocity profiles in bubbly flow for different gas flow rates. These figures are calculated only used for liquid velocity (Group A). These results indicate that bubbles influence liquid structure at the vicinity of the wall. This tendency is more pronounced at low Reynolds number. Under conditions that place the flow in the transition region, were the flow single-phase (i.e. Figure 11(b)), the mean velocity increased with in the vicinity of the wall increasing gas flow rate. On the contrary, the mean liquid velocity in the logarithmic region decreases with increasing gas flow rate. Thus it can be seen that in the channel flow, bubbles accelerate the liquid and promote the liquid structure to the turbulent flow regime because of the bubbles' buoyancy. However, Figure 11(a) shows a slightly different phenomenon from other conditions. As gas flow rate increase, the velocity distributions increase at most of channel positions. This tendency is seems to be related to the liquid phase being laminar flow.

4.2 Reynolds stress profiles in bubbly flow

Reynolds stress profiles measured in single-phase flow appear in Figure 12(a). Reynolds stress increases as Re_m increases. The Reynolds stress profiles normalized by u_τ^2 used in Eq.(11), are shown in Figure 12(b) also. The maximum values of the normalized Reynolds stress are different in each profile. These maximum values are inversely proportional to Re_m. These results are good agreement with Wei et al. (1989).

From Figure 13, it is found that Reynolds stress profiles are affected by bubble injection such that the values of the Reynolds stress increased with increasing bubble injector. The differences between the value of the Reynolds stress in single-phase flow and the one in bubbly flow decrease as liquid flow rate increases. Further more, Reynolds stress is strongly affected near the wall (y/D<0.4). These results show that bubble injection takes a strongly role in promoting turbulence transition, particularly in the near-wall region, and this effect decreases with decreasing liquid flow rate. Michiyoshi et al. (1985) and Wang et al. (1986) measured Reynolds stress profiles in bubbly flow in a vertical pipe. They reported that the Reynolds stress normally increased with increasing gas flow rate. But for some flow rates, the Reynolds stress is less than it is at higher gas flow rates. In the present study's results, similar tendency appeared. The results showed that some gas injection tended to reduce the turbulence in the liquid. However those conditions depend on gas, and liquid flow rates, bubble size, and channel geometry.

5. CONCLUSIONS

Measurements of liquid structure in bubbly flow were performed using the Ultrasonic Doppler Method. As a result, the following phenomena occurring in a vertical rectangular channel are clarified:

- Bubbles accelerate the liquid velocity in the vicinity of the wall, and this tendency is enhanced as liquid flow rate is reduced.
- Reynolds stress profiles are affected by bubble injection, and these effects become stronger at low liquid flow rates.
- The Reynolds number as increases, the value of the Reynolds stress is increased in the near-wall region (y/D<0.4).

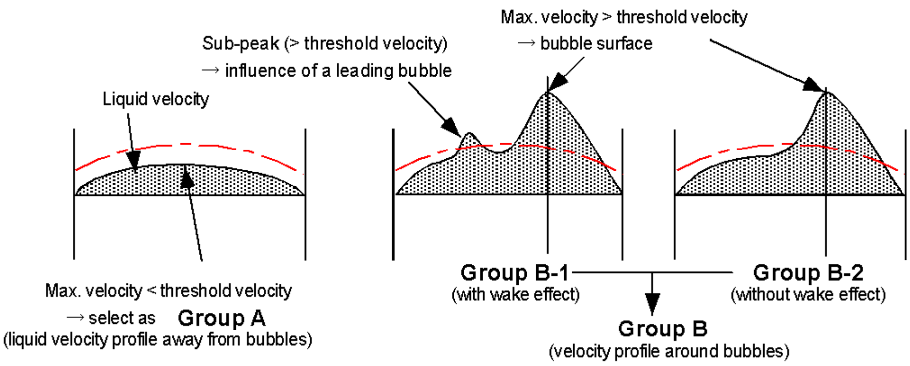


Figure 9 Typical data pattern and their classification

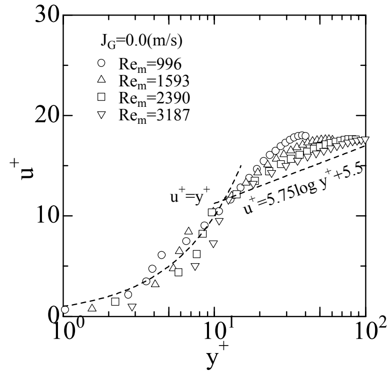
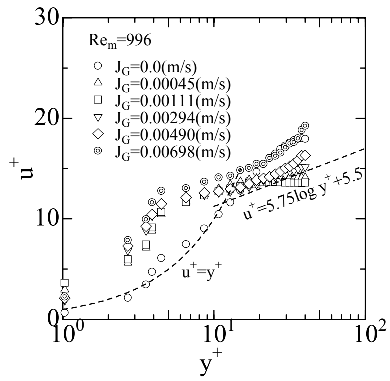
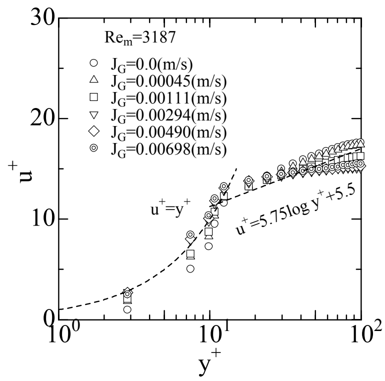


Figure 10 Mean velocity profiles in single phase flow

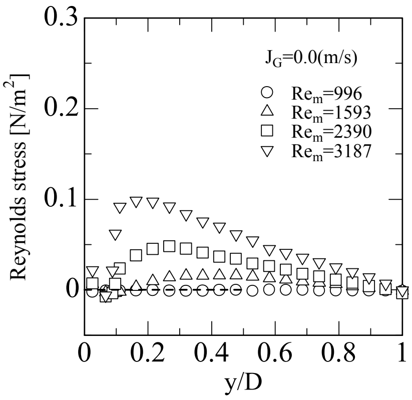


(a) Re_m=996

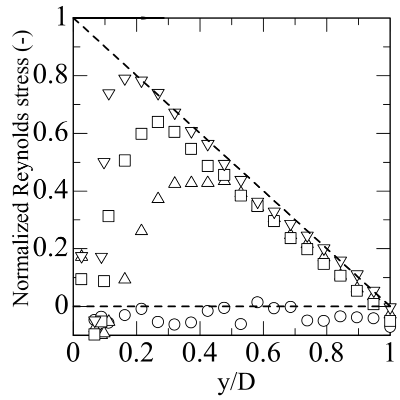


(d) Re_m=3187

Figure 11 Mean velocity profiles for different gas flow rate

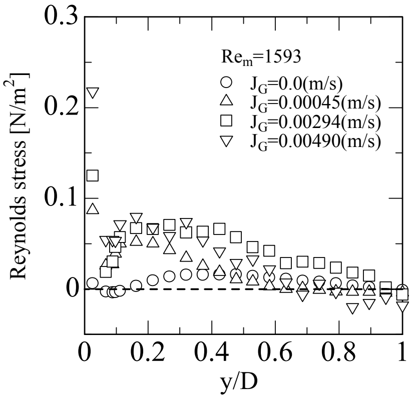


(a) Reynolds stress profiles

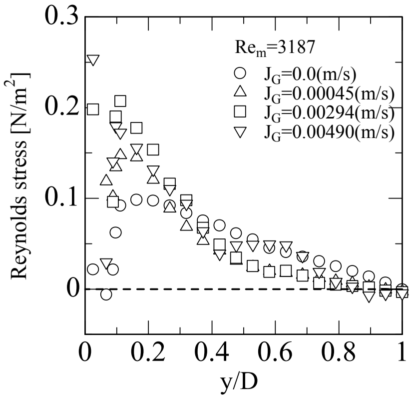


(b) Normalized Reynolds stress profiles

Figure 12 Reynolds stress profiles for different Reynolds numbers in single phase flow



(b) Re_m=1593



(d) Re_m=3187

Figure 13 Reynolds stress profiles for different gas flow rate in bubbly flow

REFERENCES

Serizawa, A., Kataoka, I., Michiyoshi, I. (1975). *Turbulence structure of air-water bubbly flow-II. Local properties*, Int. J. Multiphase Flow 2: 235-246

Michiyoshi, I., Serizawa, A. (1986). *Turbulence in two-phase bubbly flow.* Nuclear Engineering and Design 95: 253-267

Wang, S.K., Lee, S.J., Jones Jr, O.C., Lahey Jr, R.T. (1987). *3-D turbulence structure and phase distribution measurements in bubbly two-phase flows*. Int. J. Multiphase Flow 13: 327-343

Suzuki, Y., Aritomi, M., Takeda, Y., Mori, M. (1999). *Effect of bubble motion on liquid flow structure surrounding bubbles in bubbly flows.* In Proc. 7th Int. Conf. Nucl. Eng.(ICONE7), ICONE-7163

Suzuki, Y., Nakagawa, M., Aritomi, M., Murakawa, H., Kikura, H., Mori, M. (2002). *Microstructure of the flow field around a bubble in counter-current bubbly flow,* Experimental Thermal and Fluid Science, in print

Durst, F., Melling, A., Whitelaw, JH. (1981). *Principle and practice of laser Doppler anemometry.* London: Academic Press 407-425

Tropea, C. (1983). *A note concerning the use of a one-component LDA to Measure shear stress terms.* Experiments in Fluids Vol. 1 Technical notes: 209-210

Durst, F., Kikura, H., Lekakis, I., Jovanovic, J., Ye, Q. (1996). *Wall sheare stress determination from near-wall mean velocity data in turbulent pipe and channel flows.* Experiments in Fluids 20: 417□428

Taishi, T., Kikura, H., Aritomi, M. (2002). *Effect of the measurement volume in turbulent pipe flow measurement by the ultrasonic velocity profile method.* Experiments in Fluids 32: 188□196

Wei, T., Willmarth, W.W., (1987). *Reynolds-number effects on the structure of a turbulent channel flow.* J. Fluid Mech 204: 57-95