JOURNAL OF APPLIED ELECTROCHEMISTRY **24** (1994) 607–611

Investigation of the wall region of gas–liquid flow using an electrodiffusional technique

O. N. KASHINSKY

Institute of Thermophysics, 630090 Novosibirsk, Russia

Received 10 May 1993; revised 16 November 1993

Measurements of the hydrodynamic characteristics of upward gas–liquid flow in an inclined channel were performed. Experiments were made by an electrodiffusional method using microprobes for wall shear stress and liquid velocity measurements. Special attention was paid to the study of two-phase flow structure in the vicinity of the wall. A strong effect of the channel orientation on the characteristics of the flow was demonstrated. The results show that maximum wall shear stress values correspond to an intermediate channel inclination. High values of near-wall void fraction result in the reduction of liquid velocity fluctuations in horizontal and near-horizontal channel positions.

Nomenclature

f	frequency of fluctuations, Hz
S_τ	spectral density of wall shear stress fluctuations
u	liquid velocity ($\mathrm{m\,s^{-1}}$)
u'	intensity of liquid velocity fluctuations ($\mathrm{m\,s^{-1}}$)
u_τ	friction velocity, $(\tau_w/\rho)^{1/2}$ ($\mathrm{m\,s^{-1}}$)
V_l, V_g	superficial liquid and gas velocities ($\mathrm{m\,s^{-1}}$)
y	distance from the wall (mm)

Greek symbols

α	local void fraction
β	gas flow rate ratio
ν	liquid viscosity ($\mathrm{m^2\,s^{-1}}$)
ρ	liquid density ($\mathrm{kg\,m^{-3}}$)
θ	angle of channel inclination (degree)
τ_w	wall shear stress ($\mathrm{N\,m^{-2}}$)
τ'	intensity of wall shear stress fluctuations ($\mathrm{N\,m^{-2}}$)

1. Introduction

Gas–liquid two-phase flows in various flow conditions have recently been the subject of extensive studies. Much attention has been paid to upward flow in vertical pipes [1, 2]. It was clearly demonstrated that an important parameter affecting mean and turbulent flow structures was the distribution of the gas concentration across the pipe. In the case of a vertical pipe both wall-peaked and centre-peaked void profiles are observed. It was shown in [2] that the most significant deformation of the flow takes place in the case of a high void concentration near the wall. In upward flow gas bubbles travel towards the pipe wall due to lateral forces acting on the bubble moving in the liquid with a velocity gradient. Unfortunately, in this case the shape of the void profiles cannot be changed by varying the flow conditions. To study the effect of void distribution on the flow structure different flow configurations must be considered. Bubbly flow in an inclined flat channel is a very convenient case because the void distribution can be easily altered by changing the channel orientation.

2. Experimental details

Experiments were performed on the setup described in detail in [3]. The test section was a rectangular channel made of Plexiglas. The inner cross section of the channel was 10 mm × 100 mm. Liquid was pumped into the channel from a centrifugal pump, the flow rate was measured by rotameters. Air from a pressure line was supplied into the channel through 12 holes of diameter 0.25 mm drilled in the channel wall 140 mm downstream from the channel inlet. The airflow rate was measured by an orifice meter. The channel was mounted on a rotating support which permitted change in the channel orientation. The test section is schematically shown in Fig. 1. The angle of inclination, θ, was recorded from the vertical line. For positive θ the wall with holes for air injection was the upper one. In order to measure hydrodynamic parameters of the two-phase flow an electrodiffusional method was used [4, 5]. A wall shear stress probe was embedded in the channel wall 920 mm downstream from the inlet. The probe was mounted in the same wall from which bubbles were injected into the liquid (Fig. 1). A 'blunt-nose' velocity probe [2, 5] was used for local void fraction and liquid velocity measurements. The size of the wall shear stress probe was 0.03 mm × 0.3 mm, the diameter of the velocity probe was about 0.06 mm. The velocity

---

This paper was presented at the International Workshop on Electrodiffusion Diagnostics of Flows held in Dourdan, France, May 1993.

0021-891X

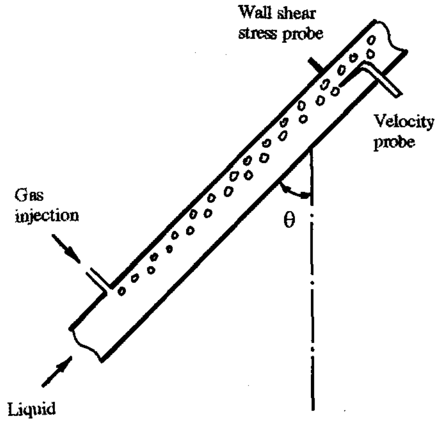

Fig. 1. Experimental setup.

probe was mounted on a traversing mechanism and could approach the upper channel wall at the point where the wall shear stress probe was installed. The test liquid was a solution of 0.01 M potassium ferri and ferrocyanide and 0.2 M sodium bicarbonate in distilled water. The temperature of the test liquid was maintained at 25° C.

Calibrations of wall shear stress and velocity probes were made in the same channel with a single-phase flow immediately before and after each experimental run. The difference in the probe current between successive calibrations did not exceed 1% for the same liquid flow rate.

3. Results

3.1. *Local void fraction*

Experiments in an inclined channel were performed with the same values of liquid and gas flow rates. The superficial liquid velocity V_l was 0.48 m s^{-1}, the superficial gas velocity V_g (taken at the atmospheric pressure) was 0.086 m s^{-1}. The only varying parameter was the angle of channel inclination, θ. The value $\theta = 0$ corresponded to a vertical channel position, $\theta = 90°$ corresponded to a horizontal channel. The coordinate of the velocity probe y was measured from the upper (for positive θ) wall, the probe was traversed from the wall up to the distance $y = 5.5$ mm (0.5 mm more than the halfwidth of the channel).

Results of local void fraction, α, measurements are shown in Fig. 2. The shape of the void profile changes significantly with channel orientation. In a vertical and near-vertical channel the shape of the void profile is similar to that in a vertical pipe [1, 2]. There is a peak of α approximately 2 mm from the wall; the values in the central part of the flow are approximately constant. In this case the profile of α seems to be mainly affected by the lateral force acting on the rising bubble. Significant profile asymmetry starts at $\theta = 20°$. From this angle there is a strong decrease of α in the centre of the channel. This trend becomes more pronounced at higher values of θ. The position of the void maximum shifts closer to the wall, the value of α at this point becomes higher. The highest void fraction values observed were about 0.6 for a horizontal channel. It is clear that for positive θ gas bubbles move to the upper wall due to buoyant forces which seem to be much higher than the lateral hydrodynamic force. When θ increases bubbles migrate from the downward half of the channel to the upward half, so the mean void fraction in the upper half of the channel increases. It can be seen from Fig. 2 that if θ is more than 50°, almost all the bubbles are in the upper half of the channel (because the value of α at $y = 5$ mm is close to zero).

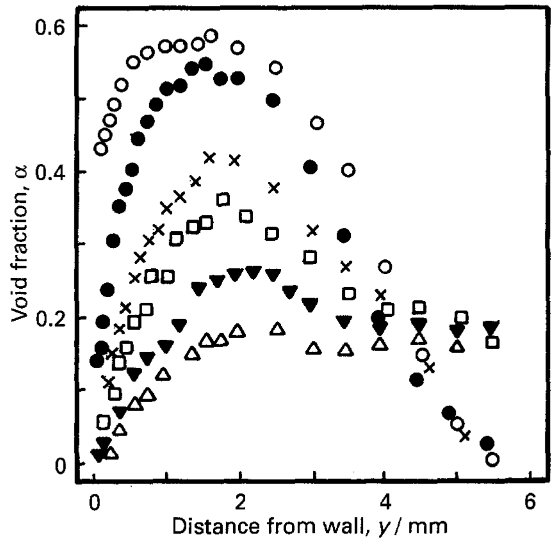

Fig. 2. Local void fraction in an inclined channel θ: (△) −10°, (▼) 0°, (□) 10°, (×) 20°, (○) 50° and (●) 90°.

The behaviour of the α profile in a horizontal channel ($\theta = 90°$) near the wall is different from the profiles for smaller θ. The values of α in this case do not go to zero at $y \to 0$; α appears to approach a finite value at the wall. However, the records of the wall shear stress probe in this regime remain continuous; there are no reductions in the signal, as for the case of the velocity probe. High values of α near the wall are caused by a strong deformation of bubbles 'pushed' to the wall by buoyant forces. Nevertheless, the wall remains wet; no dry spots are detected by the wall probe.

3.2. *Wall shear stress*

Results of wall shear stress measurements are presented in Fig. 3. τ_w is the time-averaged wall shear stress, τ' is the r.m.s. value of wall shear stress fluctuations. A strong effect of the channel orientation on the wall shear stress is observed. It is important that there is a strong τ_w variation in a near-vertical channel. The highest τ_w values correspond to an intermediate flow inclination, $\theta = 30 - 50°$. When the channel approaches the horizontal position, the wall shear stress again becomes lower. A similar effect of flow orientation on the mass transfer from the wall to the flow was reported in [3]. Single-phase values for the same V_l are $\tau_w = 0.92$ N m^{-2}, $\tau' = 0.36$ N m^{-2}. In all cases the values of τ_w in the gas–liquid flow are much higher than in single-phase flow. The same effects

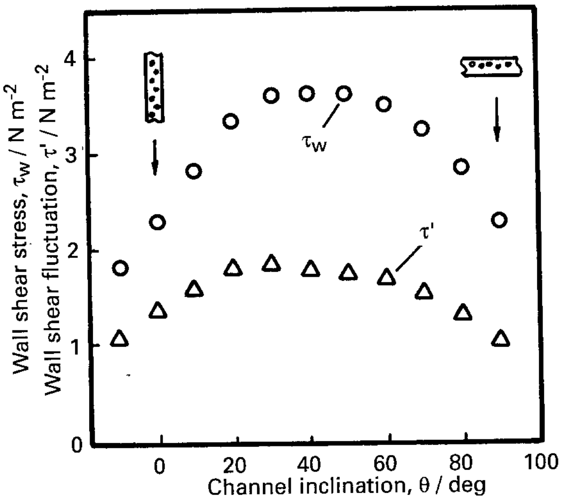

Fig. 3. Mean and fluctuating wall shear stress. Single phase: (○) and (△).

were observed in a vertical bubbly flow with near-wall bubble peaking [2, 5]. The main parameters which may affect the wall shear stress are: the bubble concentration near the wall, the distance of the void maximum to the wall and the relative bubble velocity with respect to the liquid (slip velocity). The position of the void maximum, Fig. 2, does not change significantly with channel orientation. So the main parameter which produces a strong increase of τ_w at small θ, is the increasing bubble concentration near the wall due to bubble migration from the downward part of the channel. The reason for the decrease of τ_w when θ approaches 90° is the lower slip velocity compared to a vertical or inclined channel.

The intensity of wall shear stress fluctuations depends on the channel orientation in a similar manner. Again, its value is much higher than in the single-phase flow. The ratio τ'/τ_w in two-phase flow varies from 0.6 at $\theta = 0°$ to 0.47 at $\theta = 90°$ compared to 0.38 in a single-phase flow. The main reason for the increase in intensity of wall shear stress fluctuations is again the relative velocity of the bubbles.

3.3. *Velocity profiles*

Liquid velocity profiles measured in two-phase flow are qualitatively similar to those measured in a bubbly flow in a vertical pipe. Away from the wall the liquid velocity remains constant, independent of y. A strong gradient of liquid velocity exists near the wall. Typical liquid velocity profiles in the near-wall region are shown in Fig. 4. Here the measured liquid velocity u is compared to the velocity gradients computed from measured wall shear stress values (solid lines marked by corresponding symbols enclosed into circles). It is seen that there is some moderate agreement between measured velocity and velocity gradient at the wall only for several points closest to the wall. Further, there is a strong deviation from the linear velocity profile. The viscous sublayer in the gas–liquid flow is too thin to be measured by the velocity probe. Fig. 5 shows the dimensionless presentation of the liquid velocity in 'universal' semilog coordinates. The 'friction velocity' $u_\tau = (\tau_w/\rho)^{1/2}$ was based on measured two-phase wall shear stress values; ρ is the liquid density. The solid lines represent the single-phase 'universal' velocity profile in the viscous sublayer and the turbulent region [6]. A good agreement is observed between the predicted and measured velocity profiles in single-phase flow. All the profiles measured in gas-liquid flow deviate significantly from the 'universal' law. It is interesting to see that this deviation is strongest for $\theta = 50°$.

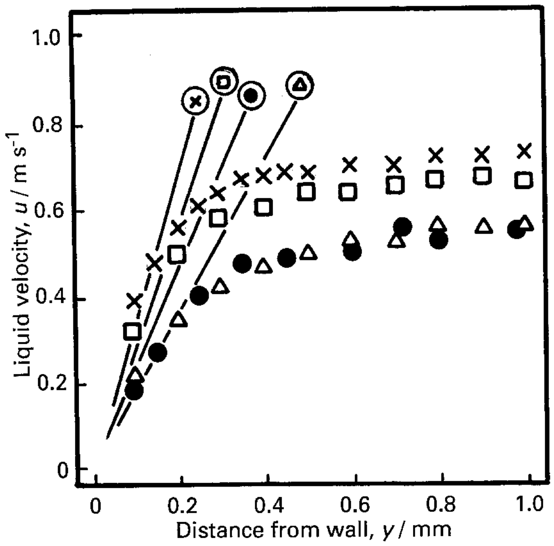

Fig. 4. Liquid velocity. Solid lines: velocity gradients obtained from wall shear stress measurements. θ: (△) −10°, (□) 10°, (×) 20° and (●) 90°.

Two-phase flow results presented in Fig. 5 are typical for bubbly flows with a high bubble concentration near the wall. The liquid velocity profiles measured in an upward bubbly flow in vertical pipes [2, 5] show the same behaviour.

3.4. *Velocity fluctuations*

Measured values of r.m.s. liquid velocity fluctuations, u', are shown in Fig. 6. The behaviour of u' is different in single-phase and two-phase flows. Very close to the wall the values of u' in two-phase flow are usually higher than in single-phase flow. This correlates well with the increase of τ' in two-phase flow (Fig. 3).

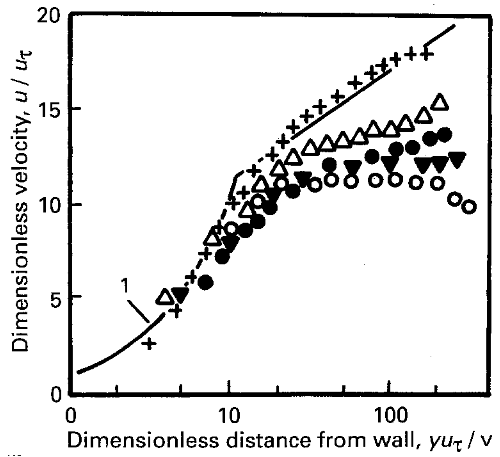

Fig. 5. Dimensionless liquid velocity. (+) Single phase. θ: (△) −10°, (▼) 0°, (○) 50° and (●) 90°.

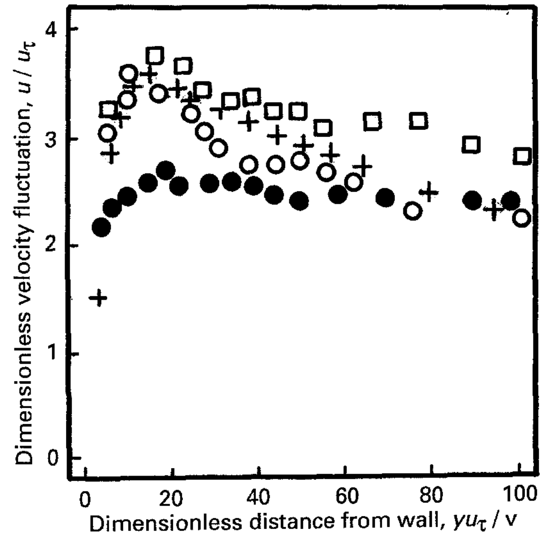

Fig. 6. Intensity of liquid velocity fluctuations. (+) Single phase. θ: (□) 10°, (○) 50° and (●) 90°.

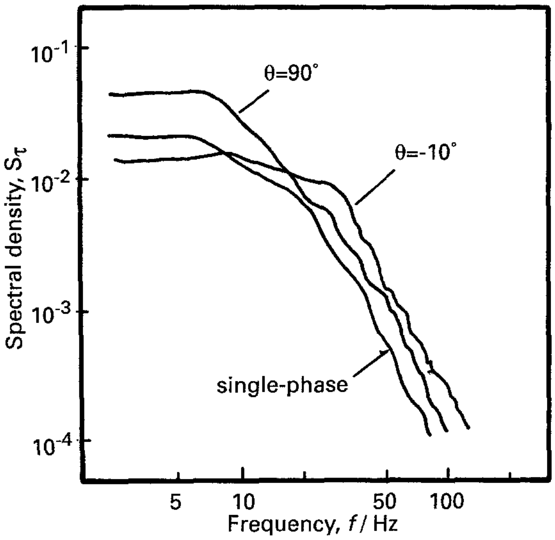

Fig. 7. Spectral density of wall shear stress fluctuations in single-phase and two-phase flow.

For a near-vertical channel, $\theta = 10°$, the values of u'/u_τ are higher than in single-phase flow for all values of yu_τ/ν. As the angle θ increases, a decrease in liquid velocity fluctuations is observed at some distance from the wall. This effect is most pronounced for a horizontal channel, $\theta = 90°$. The intensity of liquid velocity fluctuations is distinctly lower than in single-phase flow for almost all distances from the wall.

The observation of liquid velocity fluctuations suggests that there exist different mechanisms of interaction between bubbles and liquid. Liquid agitation is produced by bubbles moving at a definite slip velocity with respect to the liquid. This mechanism should increase the intensity of liquid fluctuations. Data obtained in a vertical upward bubbly flow demonstrate the increase of wall shear stress fluctuations in two-phase flow (Fig. 3, $\theta = 0$). An increase of velocity fluctuations for the nearly vertical positions is significant away from the wall, because in this case void fraction is high in the centre of the channel. In the horizontal channel the relative velocity of bubbles is small, and no liquid agitation is introduced by bubbles. A possible explanation of the reduction of fluctuations near the wall in horizontal flow is the high local void fraction. In this case the volume occupied by liquid is small, and the development of high-intensity fluctuations is impossible. This effect is very similar to the effect of microbubble drag reduction [7], although the decrease of wall shear stress was not indicated in the present set of experiments in the channel.

Spectral densities of wall shear stress fluctuations measured in a single-phase and two-phase flows are shown in Fig. 7. Spectra are presented in dimensional form, the spectral density S_τ is plotted in arbitrary units, f is the fluctuation frequency. All the curves shown in the Figure correspond to approximately the same value of mean wall shear stress. For this reason the single-phase spectrum was taken at higher liquid velocity $V_l = 0.83\,\mathrm{m\,s^{-1}}$. It can be seen that the spectra differ both in the low-frequency and the high-frequency regions. In the high-frequency region ($f > 20\,\mathrm{Hz}$) the values of S_τ are higher in two-phase flow compared to single-phase flow. It is interesting to note that the values of spectral density are higher for the near-vertical channel ($\theta = -10°$) than for the horizontal channel ($\theta = 90°$). Similar behaviour of wall shear stress spectral densities were observed in an upward bubbly flow in a vertical pipe [5]. These results show that the main reason for the spectrum broadening in a high-frequency region is the relative speed of bubbles moving near the wall. In the case of a horizontal channel the slip velocity of bubbles becomes low and the corresponding spectrum is closer to a single-phase flow than the spectrum in a vertical or inclined channel.

4. Conclusions

Measurements of the hydrodynamic characteristics of gas–liquid flow in an inclined rectangular channel demonstrate the strong effect of the channel orientation on the flow parameters. The distribution of local void fraction is basically affected by buoyant forces pressing bubbles to the upper wall. This results in a significant increase of mean wall shear stress and r.m.s. values of wall shear stress fluctuations. The maximum wall shear stress value is achieved for channel inclinations of 30 to 50° with respect to the horizontal.

Liquid velocity profiles are strongly deformed compared to single-phase channel flow. There is a significant deviation of the velocity profiles from a single-phase 'universal' distribution.

The level of liquid velocity fluctuations depends on the channel orientation. In a vertical and inclined channel velocity fluctuations are higher than in a single-phase flow. In a horizontal and near-horizontal channel the values of liquid fluctuations are reduced compared to a single-phase flow. The deviation of the wall shear stress fluctuation spectral density from a single-phase value is highest for intermediate channel inclinations.

Results obtained show that the most important parameters affecting the flow structure near the wall are the relative velocity of bubbles (slip velocity) and the local bubble concentration near the wall. The former parameter results in an additional flow agitation, the latter leads to reduction of liquid fluctuations.

Application of the results may be found in the prediction of wall shear stress and wall-to-liquid mass transfer in curved channels of complex geometry.

References

[1] A. Serizawa, I. Kataoka and I. Michiyoshi, *Int. J. Multiphase Flow* **2** (1975) 235.

[2] V. E. Nakoryakov, O. N. Kashinsky, A. P. Burdukov and V. P. Odnoral, *Int. J. Multiphase Flow* **7** (1981) 63.

[3] O. N. Kashinsky, A. V. Chinak, M. S. Uspensky and B. N. Smirnov, *J. Eng. Phys.* **64** (1993) 523.

[4] T. J. Hanratty and J. A. Campbell, *in* 'Fluid Mechanics Measurements' (edited by R. J. Goldstein), Springer, Berlin (1983) p. 559.

[5] V. E. Nakoryakov, A. P. Burdukov, O. N. Kashinsky and P. I. Geshev, 'Electrodiffusional Method for Studying Local Structure of Turbulent Flows', Novosibirsk Institute of Thermophysics (1986).

[6] H. Schlichting, 'Boundary Layer Theory', McGraw-Hill, New York (1960).

[7] N. K. Madavan, S. Deutsch and C. L. Merkle, *Phys. Fluids* **27** (1984) 356.