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Gas Volume Fraction and Velocity Profiles

Vertical and Inclined Bubbly Air-Water Flows

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Abstract : Upward inclined gas-liquid flows are frequently encountered in the oil industry and data relating to the local gas volume fraction distribution and the local gas velocity distribution is important, for example, in pressure gradient prediction and in modeling oil well 'blowouts'. In this paper measurements are presented of the local gas volume fraction distribution and the local axial gas velocity distribution which were taken in bubbly air-water flows in an 80 mm diameter pipe which was inclined at angles of 0°, 15° and 30° to the vertical. Qualitative arguments are presented to explain the influence of the liquid superficial velocity on the local gas volume fraction distribution in inclined flow and also to explain the very high axial gas velocities observed towards the upper side of the inclined pipe.

Keywords : Local volume fraction, Local velocity, Inclined gas-liquid flow.

1. Introduction

There are many instances in the oil industry when flow occurs in pipelines that are neither horizontal nor vertical but which are inclined at some angle (other than 90 degrees) to the vertical. In difficult production environments, such as the North Sea, many wells may be drilled from a single production platform to maximize exploitation of a particular reservoir and most of these wells will have long sections which are inclined to the vertical. Overland pipelines in hilly terrain also contain long sections which are inclined at various inclination angles to the vertical. Two phase, gas-liquid flow frequently occurs in both inclined oil wells and in overland pipeline networks. For example, when oil is produced from a reservoir with insufficient formation pressure for the oil to reach the surface, a technique known as 'gas-lift' may be used whereby gas is injected into the well close to its base thus reducing the hydrostatic pressure in the well and allowing the oil to flow to the surface. In such 'gas-lift' wells, gas-liquid flow occurs which may be inclined to the vertical. Inclined gas-liquid flow can also occur in wells in which natural gas is produced along with the oil.

There are several reasons why it is important to know both the local gas volume fraction distribution and the local gas axial velocity distribution in inclined gas-liquid flows. Some of these reasons are given below:

(i) Knowledge of the local gas volume fraction distribution is essential when calculating the pressure gradient in inclined gas-liquid pipelines.

(ii) In oil well drilling operations there is a possibility that the drill bit may encounter a pocket of natural gas which rises rapidly through the drilling mud to the surface causing a 'blowout', which can be highly dangerous to operating personnel and extremely damaging to the environment. The initial entry of gas into the well may be detected by the driller as a so called 'gas kick', and if he is to

take measures to prevent a blowout it is essential that he knows how quickly the gas will reach the surface. Software enabling drillers to take measures to prevent blowouts relies heavily on experimental data for the rise velocity of gas in inclined gas-liquid flows.
(iii) The gas volumetric flow rate Q_g at a given axial location in a gas-liquid flow is given by

$$Q_g = \int_A \alpha_l u_{gl} dA \tag{1}$$

where α_l represents the local gas volume fraction, u_{gl} represents local axial gas velocity and A represents pipe cross sectional area at the axial location of interest.

A new generation of electrical impedance tomographic multiphase flow meters is being produced which enables measurements to be made of both the local gas volume fraction distribution and the local axial gas velocity distribution in gas-liquid flows, thereby enabling Q_g to be determined (Wang et al., 2005). Such a tomographic flow meter, if used in conjunction with an auxiliary device such as a Venturi flow meter, will also enable the liquid volumetric flow rate to be determined. To validate tomographic flow meters, reference measurements of the distributions of both the local volume fraction and the local axial velocity of the gas in inclined gas-liquid flows are required. This paper describes such a reference technique for measuring these distributions and then goes on to present experimental results showing how these distributions are affected by the pipe inclination angle and by the superficial velocities of the flowing phases.

2. The Dual-Sensor Probe

Measurements of the distributions of the local volume fraction and axial velocity of the gas in vertical and inclined air-water flows were made using a dual-sensor probe, already described in detail (Lucas et al., 2004). The probe was manufactured using two stainless steel needles of 0.3 mm diameter mounted inside a stainless steel tube with an outer diameter of 4 mm (Fig. 1). Each needle was coated with waterproof paint and insulating varnish but this was removed from the tips of the needles using fine emery paper.

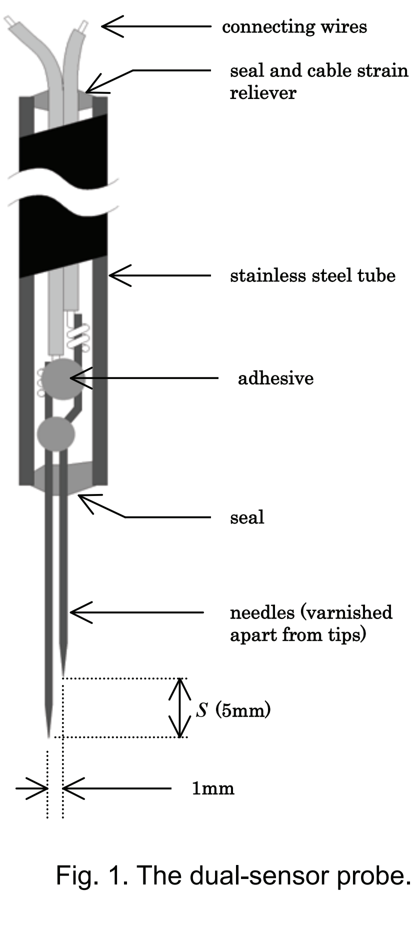

Fig. 1. The dual-sensor probe.

Thus, the front and rear sensors of the probe were located at the very tips of the needles. The conductance of the medium surrounding the tip of each needle was measured using simple dc circuits. The principle of operation of the dual-sensor probe can be explained as follows. Consider the situation where the probe is mounted parallel to the pipe axis in an inclined, bubbly, air-water pipe flow, the two sensors of the probe being separated by an axial distance *s.* Let us further suppose that the velocity of the gas bubbles is purely axial. If the surface of a bubble makes first contact with the front sensor at time t_{1f} the measured conductance at the front sensor will fall sharply at this time as the sensor is immersed in air instead of water. If the front sensor makes last contact with the surface of the bubble at time t_{2f} the measured conductance at the front sensor rises sharply at this time as the sensor is again surrounded by water. The times at which the rear sensor makes first and last contact with the surface of the bubble are t_{1r} and t_{2r} respectively. Suppose N bubbles hit both the front and rear sensors during a sampling period T. For the i^{th} bubble two time intervals $\delta t_{1,i}$ and $\delta t_{2,i}$ may be defined as follows:

$\delta t_{1,i} = t_{1r,i} - t_{1f,i}$ and $\delta t_{2,i} = t_{2r,i} - t_{2f,i}$. The mean local axial bubble velocity u_{gl} at the position of the probe is then given by

$$u_{gl} = \frac{2s}{N}\sum_{i=1}^{N}\frac{1}{(\delta t_{1,i} + \delta t_{2,i})} \quad (2)$$

If the air bubbles have a plane of symmetry normal to their direction of motion then use of Eq. (2) minimizes the errors in the calculated value of u_{gl} due to the effects of curvature of bubbles that hit the probe 'off centre' (Steinemann and Buchholz, 1984).

The mean local volume fraction α_l of the bubbles at the position of the probe can be estimated from the conductance signal from either the front or the rear sensor (Serizawa et al., 1975). For the front sensor α_l is given by

$$\alpha_l = \frac{1}{T}\sum_{i=1}^{N}(t_{2f,i} - t_{1f,i}) \quad (3)$$

In real, as opposed to ideal, vertical and inclined air-water flows the velocities of the air bubbles are not purely axial but have small lateral components as well. It has been shown (Wu et al., 2001) that these lateral velocity components can cause the surface of a bubble to strike both the front and rear sensors nearly simultaneously, giving rise to very small values of $\delta t_{1,i}$ and $\delta t_{2,i}$. To minimize the effects of this problem the axial separation s of the sensors should be designed to be in the range $0.5d \le s \le 2d$ (where d is the mean bubble diameter) as recommended by Wu et al. In the present study d was in the range 5 to 8 mm and so the sensor separation s was set equal to 5 mm.

3. The Inclinable Multiphase Flow Loop

Measurements of the local axial bubble velocity distribution and the local gas volume fraction distribution in vertical and inclined, bubbly, air-water flows were made using the dual-sensor probe in a multiphase flow loop with a 2.5 m long, 80 mm internal diameter, inclinable working section. Tap water was pumped into the base of the working section via a turbine meter which enabled the water superficial velocity u_{ws} in the working section to be calculated. Air was pumped into the working section via a series of 1 mm diameter holes equispaced around the circumference of the base of the working section. The mass flow rate of the air was measured before it entered the working section using a thermal mass flow meter. Measurements of the pressure and temperature in the working section enabled the mean air superficial velocity u_{gs} to be calculated. A reference measurement $\overline{\alpha}_{ref}$ of the mean air volume fraction in the working section at a given flow condition was obtained using a differential pressure measurement, compensated for the effects of frictional pressure loss. This technique is widely described in the literature (Lucas and Jin, 2001) and so no further description will be given here.

The dual-sensor probe described in section 2 was mounted in a fully automated, two-axis traversing mechanism which enabled the probe to be moved to any spatial location in a plane at an axial distance of 2m from the inlet to the working section. For the experiments described in this paper, the probe was traversed across 8 equispaced diameters in the flow cross section. Data was obtained at 11 equispaced locations on each diameter (at the pipe centre and at distances from the pipe centre of ±7.6 mm, ±15.2 mm, ±22.8 mm, ±30.4 mm and ±38 mm) giving a total of 81 distinct measurement locations. At each measurement location, and for each flow condition, data was acquired from the dual-sensor probe for a period of 30 seconds.

4. Local Gas Volume Fraction Profiles

Local gas volume fraction profiles were obtained for values of water superficial velocity u_{ws} in the range 0.64 ms^{-1} to 1.14 ms^{-1}, values of air superficial velocity u_{gs} in the range 0.033 ms^{-1} to 0.166 ms^{-1} and for pipe inclination angles θ away from the vertical of 0°, 15° and 30°. The profiles are shown in Figs. 2 and 3 where the colour red represents the maximum value of the local gas volume fraction α_l at a particular flow condition and the colour blue represents the minimum value of α_l at this flow condition. For the results shown in Figs. 2 and 3 α_l was typically calculated from between 600 and 1500 bubbles, where α_l was a maximum, and between 300 and 800 bubbles, where α_l was half the maximum value. For each flow condition the area-weighted mean gas volume fraction in the flow cross section $\overline{\alpha}$ was calculated from the measured values of α_l and was found (on average for all of the flow conditions investigated) to be within 5 % of $\overline{\alpha}_{ref}$. This gave good confidence in the accuracy of the measured values of α_l.

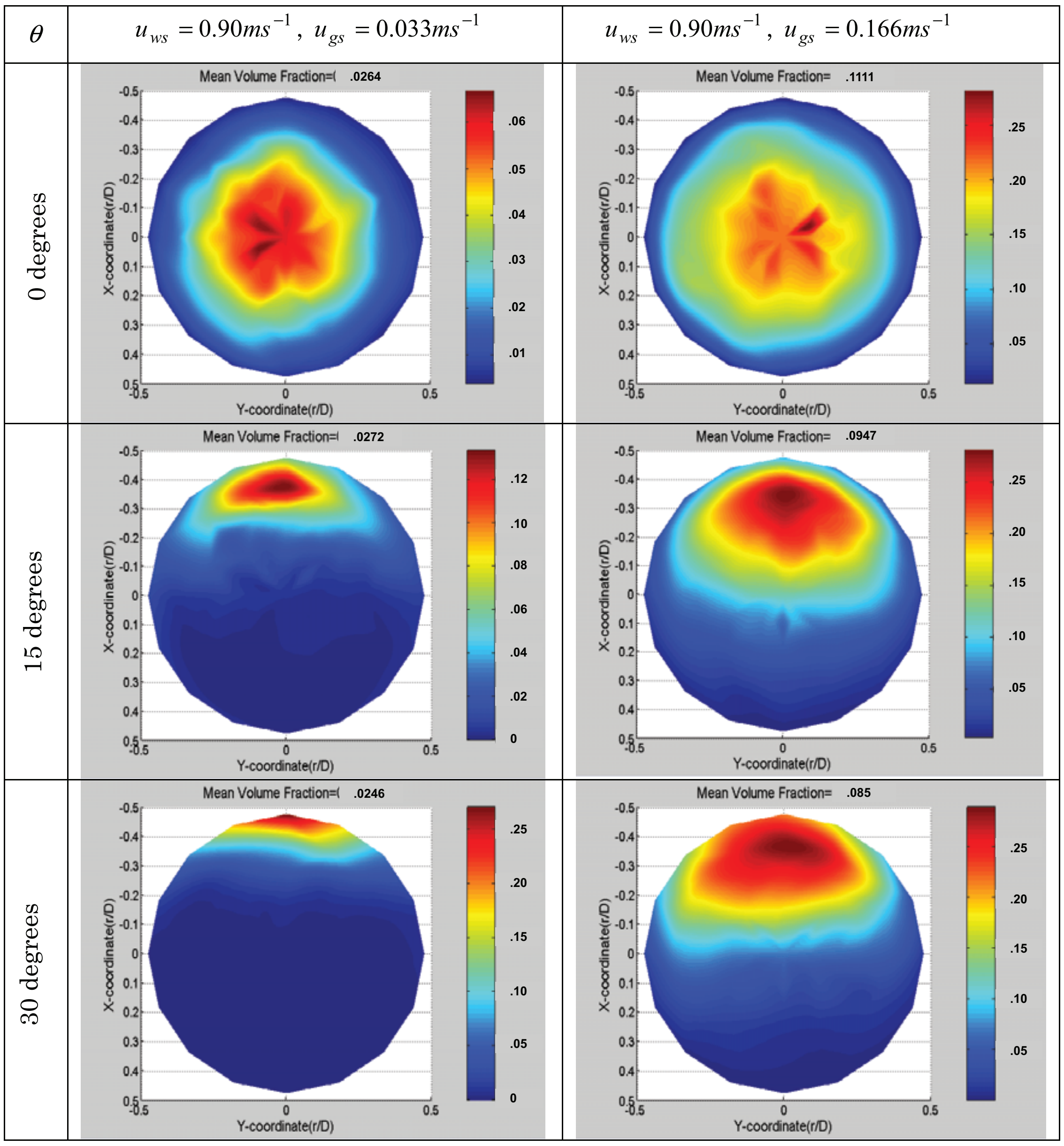

Fig. 2. Local gas volume fraction distributions at constant water superficial velocity (case I left and case II right), r represents radial position, D is pipe diameter.

It should be noted that the range of values of α_l is different for each of the graphs shown in Figs. 2 and 3, as indicated by the colour scale to the right of each graph. Also shown at the top of each graph is the reference value $\overline{\alpha}_{ref}$ of the mean gas volume fraction at that flow condition.

For θ = 0°, the local gas volume fraction profiles shown in Figs. 2 and 3 are essentially axisymmetric and can be described by a 'power law' expression of the form $\alpha_l = 0.5\overline{\alpha}(1 - r/R)^q (q+1)(q+2)$ where $\overline{\alpha}$ is the area-weighted mean value of the gas volume fraction obtained from the dual-sensor probe, R is the pipe radius and r represents radial position. [The fact that the vertical flow graphs shown in Figs. 2 and 3 are not entirely axisymmetric suggests that data could have been acquired for longer than the 30s sampling period that was actually used]. For the range of flow conditions investigated, it was found that the term q is related to $\overline{\alpha}$ by the correlation $q = 0.9014e^{-4.823\overline{\alpha}}$ with values of q in the range 0.6 to 0.8 (Lucas et al., 2004). In vertical bubbly gas-liquid flows the shape of the local gas volume fraction distribution can be dependent upon the mean gas bubble size (Hibiki and Ishii, 1999). For gas bubbles of about 5 mm diameter and above such as those used in the present investigation 'power law profiles', with the maximum value of α_l occurring at the pipe centre, are commonly reported in the literature.

For the case where u_{ws} = 0.90 $\mathrm{ms^{-1}}$ and u_{gs} = 0.033 $\mathrm{ms^{-1}}$ (case I) it can be seen from Fig. 2 that as θ is increased to 15° most of the gas becomes located towards the upper side of the inclined pipe, however the peak value of α_l occurs a short distance away from the upper side of the pipe. For the same values of u_{ws} and u_{gs}, when θ is increased to 30° the gas moves even closer to the upper side of the inclined pipe and it is apparent from Fig. 2 that α_l tends to remain constant in 'bands' normal to the diameter joining the upper side of the pipe to the lower side.

For the case where u_{ws} = 0.90 $\mathrm{ms^{-1}}$ and u_{gs} = 0.166 $\mathrm{ms^{-1}}$ (case II) it is again clear that for θ = 15° and θ = 30° the peak value of α_l occurs a short distance away from the upper side of the pipe. For case II and for θ = 30° it is again apparent that, away from the pipe wall, α_l is relatively constant in bands normal to the diameter joining the upper side of the inclined pipe to the lower side. However for θ = 30° there is a much greater tendency in case II, close to the pipe wall, for the contours of α_l to follow the curvature of the pipe wall, than was the situation for case I.

In Fig. 3 results are presented for the cases where u_{gs} = 0.123 $\mathrm{ms^{-1}}$ and where u_{ws} takes values of 0.64 $\mathrm{ms^{-1}}$ (case III) and 1.14 $\mathrm{ms^{-1}}$ (case IV). It is interesting to note that for θ = 15° the gas bubbles are confined to a much smaller region of the flow cross section when u_{ws} = 1.14 $\mathrm{ms^{-1}}$ than when u_{ws} = 0.64 $\mathrm{ms^{-1}}$ even though the mean gas volume fraction is not vastly different. The same phenomenon is even more apparent for θ = 30°. It has been proposed (Beyerlein et al., 1985) that when there is axial shear in the liquid phase, a gas bubble will experience a lateral force in the radial direction, causing it to move away from the faster moving liquid towards the slower moving regions. This lateral force is proportional to $-du_w/dr$ where u_w is the local axial liquid velocity and r represents the direction of increasing pipe radius. In Fig. 4 it is shown that large axial velocity gradients exist in inclined air-water flows. Although measurements were not obtained for the liquid velocity profile, previous research (Lucas, 1995) suggests that the local axial liquid velocity will attain a maximum value close to the upper side of the inclined pipe and then decay rapidly to zero at the pipe wall. For a given value of θ, close to the pipe wall at the upper side of the inclined pipe the magnitude of du_w/dr will be greater for u_{ws} = 1.14 $\mathrm{ms^{-1}}$ than for u_{ws} = 0.64 $\mathrm{ms^{-1}}$, and so each gas bubble will experience a greater force towards the upper side of the inclined pipe for u_{ws} = 1.14 $\mathrm{ms^{-1}}$. This causes the bubbles to be more tightly confined into a smaller region of the flow cross section as observed in Fig. 3.

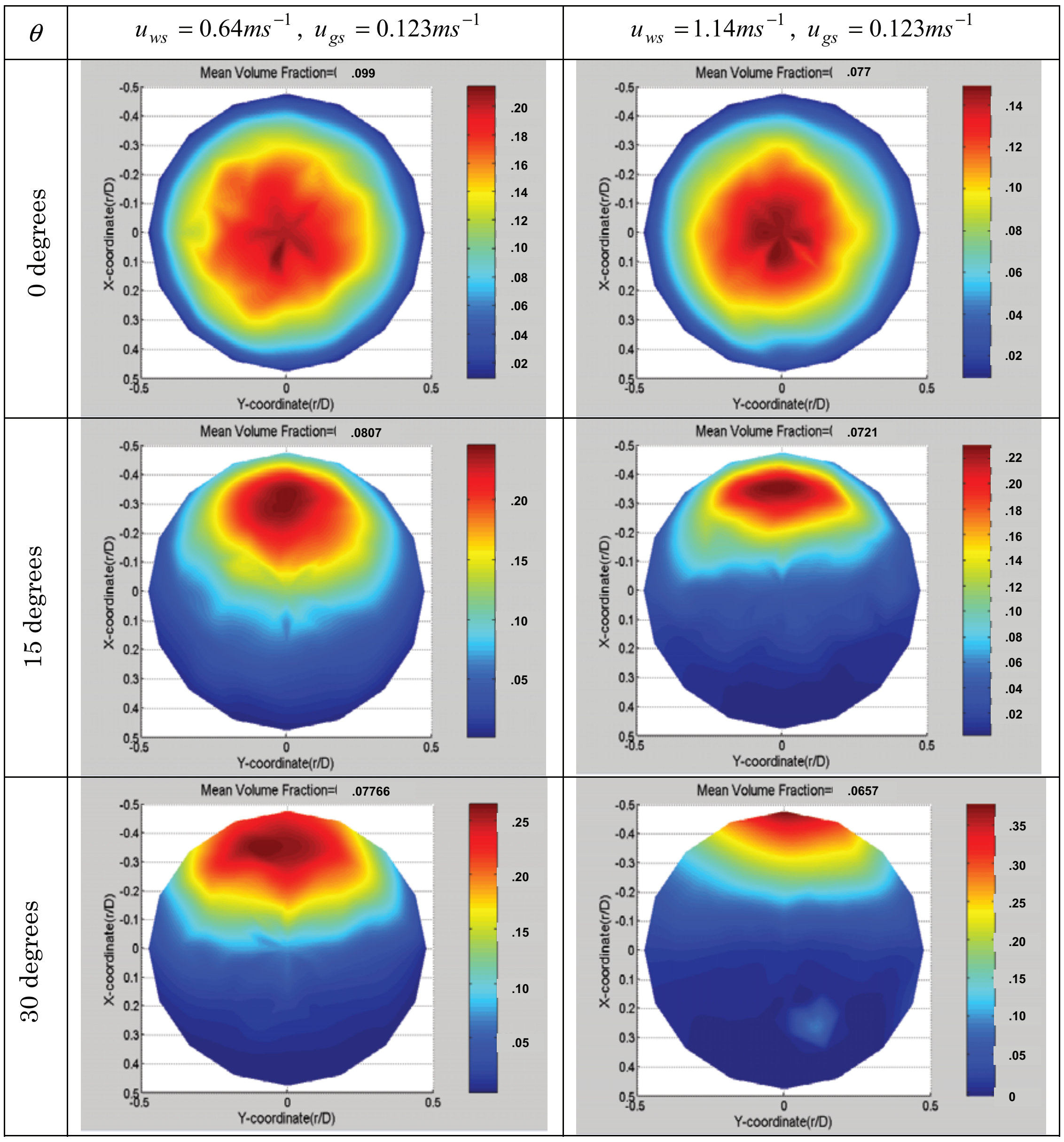

Fig. 3. Local gas volume fraction distributions at constant gas superficial velocity (case III left and case IV right), *r* represents radial position, *D* is pipe diameter.

5. Local Gas Velocity Profiles

In Fig. 4 local axial gas velocity profiles are shown for the cases where u_{ws} = 0.90 ms^{-1} and u_{gs} = 0.033 ms^{-1} (case I) and for u_{ws} = 1.14 ms^{-1} and u_{gs} = 0.123 ms^{-1} (case IV). In Fig. 4 the colour red represents the maximum value of the local axial gas velocity u_{gl} at a given flow condition, whilst the colour blue represents the minimum value of u_{gl}. Again, the range of values of u_{gl} is different for each flow condition shown in Fig. 4 as indicated by the scale to the right of each graph. For each flow condition a volume-fraction-weighted mean gas velocity $\overline{u}_g$ was calculated from the measured values of u_{gl} and α_l. $\overline{u}_g$ was always found to be within 10 % of the reference mean gas velocity given by $\overline{u}_{g,ref} = u_{gs} / \overline{\alpha}_{ref}$. This gave good confidence in the accuracy of the measured values of u_{gl}.

It is clear from Fig. 4 that for θ = 0° the profile of u_{gl} is essentially axisymmetric however, as θ is increased it is clear that the axial velocity of the gas bubbles becomes significantly greater at the upper side of the inclined pipe than at the lower side.

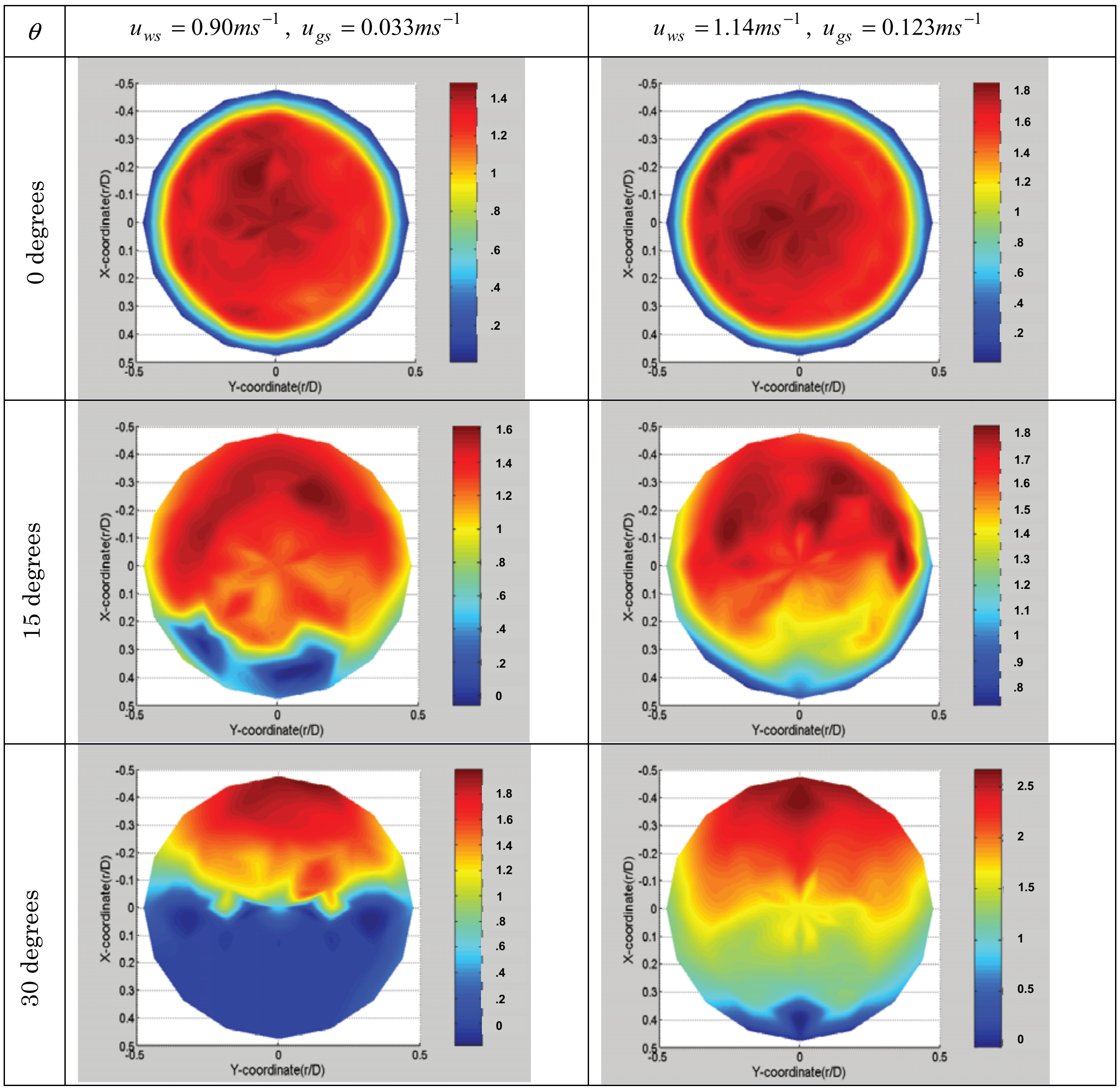

Fig. 4. Local gas velocity profiles (case I left and case IV right), *r* represents radial position, *D* is pipe diameter (velocity is in ms^{-1}).

For example, for case IV and for θ = 30° the axial gas velocity u_{gl} at the upper side of the pipe is greater than $2.5\,\mathrm{ms}^{-1}$ whilst at a distance of approximately $0.2\,R$ from the lower side of the inclined pipe u_{gl} is approximately equal to $0.75\,\mathrm{ms}^{-1}$. This variation in the value of u_{gl} for inclined gas-liquid flows can be qualitatively explained as follows. In a steady state flow, at a given point in the flow cross section, there is a balance between the applied pressure gradient, which acts in the positive axial direction (i.e. the direction of flow) and gravitational and viscous forces which both act in the negative axial direction. With reference to an existing model of inclined multiphase flow (Lucas, 1995) the local gravitational force is related to the mean local density of the multiphase mixture whilst the local viscous forces are related to the local axial velocity gradient of the multiphase mixture. In an inclined gas-liquid flow, the local density of the multiphase mixture is relatively small at the upper side of the inclined pipe due to the relatively high local gas volume fraction. As a consequence the local gravitational force acting on the fluid in the negative axial direction is much smaller at the upper side of the inclined pipe than at the lower side. This means that in a steady state flow, the local viscous forces acting on the fluid in the negative axial direction must be relatively high at the upper side of the inclined pipe and this, in turn, is manifested by the large local axial velocity gradients observed at the upper side of the pipe. This has many practical implications including (with reference to section 1) the fact that in oil well drilling operations, when a gas kick occurs, the gas can reach the surface much more quickly in an inclined well than in a vertical well of the same overall length.

6. Conclusions

For the vertical bubbly gas-liquid flows investigated, the local gas volume fraction and axial velocity distributions were axisymmetric. As the inclination angle of the flow was increased, the gas bubbles tended to migrate towards the upper side of the inclined pipe. However hydrodynamic forces on the bubbles, arising from shear in the liquid phase, caused the gas bubbles to become confined into a smaller region of the flow cross section at the upper side of the pipe as the liquid superficial velocity was increased (as described in section 4). The lower density of the gas-liquid mixture at the upper side of the inclined pipe gave rise to relatively high axial velocities in this part of the flow cross section. The effect of pipe inclination on the maximum axial gas velocity must be taken into consideration, for example, when modeling oil well 'blowouts'.

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