Individual bubbles moving in an inclined flat channel

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Abstract. The results of an experimental study of single bubble movement in an upward bubble flow in an inclined flat channel are presented. The measurements were carried out for a liquid Reynolds numbers $2000 \div 22700$ and for channel inclination angles $0 \div 90$. It is shown that in a gas-liquid flow the channel inclination angle has a significant effect on the flow characteristics. The data obtained in the experiments show that bubble rise velocity is lower than that in a large volume of a quiescent liquid and is affected channel inclination angle. With an increase in the Reynolds number, the influence of the channel inclination angle on the two-phase flow decreases.

1. Introduction

Gas-liquid flows are often encountered in chemical and microbiological industries, in power engineering and other fields. The complexity of the flow structure, the geometry diversity and a large number of operating parameters often require the use of empirical data for modeling and theoretical description of gas-liquid flows behavior. For this reason, an experimental study of two-phase flows is important till now.

Experimental studies of the upward gas-liquid flow in vertical pipes and channels are widely and in detail presented in the literature. Most experimental studies of bubble flows are devoted to flows in vertical pipes. In this case, the gas phase distribution is formed by the action of lateral forces on floating bubbles in the presence of a velocity gradient [1]. Much less attention was paid to bubbly gas-liquid flows in horizontal and inclined channels, although in this case the orientation of the channel may be very important.

In paper [2] the hydrodynamics of a bubble gas-liquid flow in an inclined rectangular channel was studied. It was shown that the orientation of the channel substantially affects the hydrodynamics of the flow. The strong influence of the angle of inclination on the heat transfer from the wall in a bubble flow in an inclined flat channel was shown in [3]. A sharp increase in the heat transfer coefficient was observed even at very low void fraction values lower 0.01. In a flat inclined channel at an inclination angle $\theta=45^\circ$, for small gas additions to the liquid ($\sim 1.5\%$), it is possible to obtain an increase in heat transfer from the upper wall of the channel to 35\% (for the Reynolds number $Re = 7700$) and an increase in the tangential stress to 37\% (for the Reynolds number $Re = 8660$). These results show that the study of flows in inclined channels is of interest.

This paper presents an experimental study of the air bubbles dynamics in a gas-liquid flow in a flat inclined channel with different channel inclination angles in the absence of interphase heat exchange. The experimental study was carried out using the shadow photography method with the following regime parameters of the flow: the channel inclination angle $\theta=0 \div 90^\circ$, the Reynolds number
Re=2000÷22700, the distance from the point of gas introduction into the fluid flow to the place of the shooting L=900 mm.

Figure 1. Experimental setup.
1 – main tank,  
2 – centrifugal pump,  
3, 4 – flow meters,  
5 – valves,  
6 – pre-chamber with confuser,  
7–9 – setup sections,  
10 – compressor,  
11 – flow controller,  
12 – valve,  
13 – upper tank,  
14–17 – temperature control system.

2. Experimental setup and technique
A slightly modified experimental setup from [3] was used. The experimental setup (Fig. 1) was a two-phase circulation loop closed in liquid. The test liquid from the tank 1, using a centrifugal pump 2, through the flow meters 3 and 4 was fed into the test section. The test section is a rectangular plexiglass channel with a cross section of 10x100 mm and a length of 1.7 m. Rotameters were used as liquid flow meters. The flow rate was regulated adjusting valves 5. At the inlet of the test section, a pre-chamber 6 with confuser and a grid was installed to flatten the flow across the channel cross-section. The test section consisted of several sections 7÷9 connected by flanges. After the test section, the liquid was supplied to the upper tank 13, where it was separated from the gas and again supplied into the main tank 1. Gas (air) was supplied from the compressor 10. Gas flow rate was determined using an FMA5518 flow controller (OMEGA Engineering, Inc.) 11. Additional adjustment of the gas flow rate could be made by valve 12. Gas was introduced into the fluid flow through single capillary (hypodermic needle) with a 0.3, 0.4 and 0.6 mm o.d. The capillaries were glued into the Plexiglas section, placed on the lower channel wall. Gas bubbles were formed at the separation of gas from the ends of the capillaries. The gas-liquid flow, obtained by mixing gas and liquid, entered the measuring section. Measurements of the bubble diameters were made in section that is 900 mm from the gas injection point. The temperature of the test liquid was kept constant at 25°C with the help of an automatic temperature control system 14÷17. The channel inclination angle $\theta$ was counted from the vertical, so the position $\theta=0^\circ$ corresponded to the vertical position of the channel, and $\theta=90^\circ$ – horizontal.

To compare the results of this work with the results of [3], the same test liquid was used – a solution of potassium ferri- (0.16%) and ferrocyanide (0.21%) and sodium carbonate (2.55%) in distilled water.

The study of the gas bubble diameters was carried out using the shadow photography method (Fig. 2). Bubbles were shot on the Nikon J4 2 camera through the optical section. The shooting speed was 100 fps at a resolution of 1280x720 pix. To ensure a uniform light field, the illumination of the flow was produced by an LED matrix 150x150 mm 1.

The resulting images were processed by software. We used the method of image processing and the selection of bubbles, similar to the method described in [4]. The diameter of the gas bubbles was
calculated from the area of the bubble in the image as the equivalent diameter using the formula $D = \sqrt{(4S/\pi)}$. The accuracy of determining the bubble boundary was ± 1 point. For photos taken by a Nikon J4 camera on calibration frames, 1 mm = 48 points. Thus, with the size of bubbles in the diameter range of 0.3÷7 mm, the relative error in determining the diameter was 0.005÷0.05. The distance from the point of gas injection into the liquid flow in the experiments was 900 mm.

![Figure 2. Unit for gas bubble diameter studies. 1 – LED matrix, 2 – camera.](image)

3. Results and discussion

To test the measurement technique and measuring system, bubble rise velocity measurements were carried out in a vertical channel with quiescent liquid. Measuring values were compared with calculated bubble rise velocity for the same bubble diameters. When liquid flowing around a rigid sphere drag coefficient is equal [5]:

$$
\begin{align*}
C_d &= 24 / Re_b, \quad \text{at } Re_b < 2 \\
C_d &= 18.5 / (Re_b)^{0.6}, \quad \text{at } 2 \leq Re_b < 500 \\
C_d &= 0.44, \quad \text{at } 500 \leq Re_b
\end{align*}
$$

Comparisons have shown that the measuring values coincide well with the calculated ones for a large volume of a quiescent liquid (fig. 3). The difference does not exceed 10%.

Measurements of gas bubble velocities in inclined channel demonstrated that gas speed is affected channel inclination angle and bubble diameter. Small bubbles in vertical and near vertical channel orientation ($\theta=0, 10^\circ$) move as rigid spheres in a quiescent liquid (fig. 4). At the pictures $U_\text{m} = Q/S$ is the superficial liquid velocity. And $U_r$ is local liquid velocity at the distance equal to the bubble radius from the wall (coordinate corresponding bubble centre position) for single phase turbulent flow calculated according Reichardt formula [6]:

$$
U^+ = \frac{1}{k} \ln(1 + ky^+) + \left( A - \frac{\ln(k)}{k} \right) \left( 1 - e^{-\frac{y^+}{11}} - \frac{y^+}{11} e^{-0.33y^+} \right).
$$

While channel inclination angle increases bubble velocity decreases. Bubbles move with the speed equal to liquid velocity at the position of bubble centre i.e. bubbles don’t move relative to liquid. In some cases bubble speed is lower that liquid velocity that means liquid flow around the bubbles from the back end. This fact was experimentally demonstrated in [7]. At some liquid Reynolds numbers $Re_l$ bubble speed is higher than liquid velocity that means bubble move away the wall to the channel core. Effect of bubble speed decrease was denoted in work [8] for bubbles moving in quiescent liquid along an inclined surface.
Bubbles with larger diameter have lower speed ever in vertical flow starting from some liquid Reynolds number depending bubble diameter (fig. 5 and 6). At low liquid velocity lateral lift force (Saffman force [9]) is small due to low velocity gradient over bubble diameter. As liquid velocity increases velocity gradient and so Saffman force increases and bubbles are stronger forced toward the wall. For large Reynolds numbers effect of channel inclination angle on bubble velocity is negligible.

**Figure 3.** Bubble rise velocity.

**Figure 4.** Gas velocity for $d_b=0.7$ mm.

**Figure 5.** Gas velocity for $d_b=1.4$ mm.

**Figure 6.** Gas velocity for $d_b=1.7$ mm.
Conclusions
The data obtained in the experiments show that bubble rise velocity is lower than that in a large volume of a quiescent liquid and is affected channel inclination angle. With an increase in the Reynolds number, the influence of the channel inclination angle on the two-phase flow decreases.

The results show that the size of the bubble significantly affects its movement in the channel. Under some conditions, small bubbles (d<1 mm) can be pulsed out of the wall region and move in the core of the flow. Larger bubbles move in the wall neighborhood.

It is shown that in a gas-liquid flow the channel inclination angle has a significant effect on the flow characteristics. The data obtained in the experiments show that with an increase in the Reynolds number the influence of the channel inclination angle on the two-phase flow decreases.

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