Heat transfer in bubbly downward flow at low gas flow rates

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Abstract. The effect of small gas phase additions on heat transfer in downward bubbly flow was shown. Data on the size of bubbles detaching from the edges of an array of capillaries in a liquid flow are given. The influence of the disperse phase dimensions on the heat transfer is discussed. The preliminary data of PIV investigation of liquid velocity distribution is also presented. It is shown that change in the size of the dispersed phase can lead to both intensification and deterioration of heat transfer as compared with a single-phase flow at constant flow rates of liquid and gas at the channel inlet. The mechanism of heat transfer intensification was described early. The cause of the heat transfer deterioration is turbulence suppression in the near-wall region.

1. Introduction

The problem of turbulent transfer in bubbly two-phase flows is relevant for nuclear power engineering, chemical industry, medicine, and combined production of oil and gas. Modern methods of prediction of such flows, such as Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES), take considerable time even on supercomputers. To develop and test the models that are less demanding in terms of computer system resources, it is necessary to know the averaged and fluctuation flow characteristics. The structure of a two-phase gas-liquid flow essentially depends on the orientation of the channel and the flow direction. In particular, in a two-phase flow in a vertical pipe, characteristics of upward and downward flows differ significantly [1-3]. In an upward flow, the buoyancy force direction coincides with the liquid flow direction, whereas in a downward flow the buoyancy force acting on a bubble and the flow velocity are oppositely directed. Thus, with identical gas flow rates, the true gas content in an upward flow is lower than that in a downward one. An upward flow with low flow rates of liquid and gas exhibits a saddle-like distribution of the void fraction. In a downward flow, the void fraction distribution maximum is usually in the central part of the channel, and there is a single-phase liquid layer observed near the pipe walls.

A downward flow, as a rule, is axially symmetric and therefore more convenient for verification of new theoretical models. In the literature, there are a number of papers devoted to experimental and theoretical research of a downward flow [1-9]. But the quantity of works which deal with investigation of heat transfer is still limited.

The goal of this work is to study the influence of dispersed phase sizes at constant gas and liquid flow rates on heat transfer from the heated wall to bubbly flow. In this paper, the downward bubble flow regime was considered. During the experiments, the mean bubble detachment diameter <d>
from the capillary array was controlled. The change in the size and number of bubbles affects the local hydrodynamics of the flow and, accordingly, heat transfer.

2. Experimental setup
The experiments were carried out in a vertical tube with inner diameter of 20 mm. To determine the size of bubbles, the shadow images of the flow were used. The effect of bubbles on heat transfer was determined using a high-speed thermal camera and miniature resistive temperature sensors with a nominal resistance of 1000 ohms at 0°C. To measure heat transfer, a thin-walled section of a pipe with a length of 520 mm and a wall thickness of 0.2 mm was heated. Heating was carried out using a source of direct electric current. The basis for heat transfer measurements is presented in [10-11]. Wall shear stress measurements were performed using electrochemical method. The review of the experimental setup can be found in [9]. PIV system "Polis" was used for measuring the velocity distribution of the liquid phase. The liquid from tank was divided into two flow lines and supplied into the gas-liquid mixer with the help of a centrifugal pump. The liquid flow rate was regulated by valves and controlled with the help of volumetric flow meters. The gas was delivered into mixer through the capillaries. A gas-liquid flow was formed in the upward flow, then, it was delivered through a U-shaped section to the downward segment. Then a gas-liquid flow passed into optical test section, where PIV was used. From the optical section the gas-liquid flow was delivered into a heat transfer measuring unit, where a high-speed thermal camera and miniature resistive temperature meter were used. From the outlet section the gas-liquid mixture returned back to the tank.

3. Experimental results
In order to perform experimental investigations with a controlled dispersity of the gas phase in the flow, the preliminary experiments were carried out. The gas was continually injected to the liquid flow via some amount of capillaries - N. The amount of capillaries was varied from 3 to 24 with a step 3. At a constant gas flow rate, the capillary groups were switched off alternately, which changed the gas flow rate in each of the remaining capillaries. The average liquid velocity during the experiments was constant, \( V_L = 0.25 \text{ m/s (Re = 5000) } \). During the experiments, the flow rate of the gas fed was constant, \( Q_g = 50 \text{ ml/min (} \beta = 0.01) \). The flow rate per capillary \( Q_{\text{cap}} = Q_g/N \) was varied from 2.1 to 16.7 ml/min.

Figure 1a displays the probability distribution function (PDF) of bubble sizes at different \( Q_{\text{cap}} \). With \( Q_{\text{cap}} < 4 \text{ ml/min, the bubble detachment mode is realized, sensitive to the balance of forces at the edges of the capillaries. In this mode, the bubble detachment diameter depends weakly on the gas flow. The average bubble detachment diameter } <d_b> \text{ is 0.45–0.5 mm. The PDF of bubble diameter distribution has a sharp peak. With } Q_{\text{cap}} \text{ growing, the events of bubble coalescence near the edge of the capillaries grow. The shape of PDF is changed in a comparison with a previous one. When } Q_{\text{cap}} \text{ reaches the maximum value, }<d_b> \text{ rises to 1.8 mm.} \)

Figure 2 shows the distribution of the heated wall temperature in single- and two-phase flows. The liquid temperature at the inlet of the test section was constant for all cases. The experiments were performed using a high speed IR camera at a constant heat flux, Reynolds number Re = 7000 and gas flow rate ratio \( \beta = 0.015 \), only the dimensions of the bubbles were changed (see photo). The scale is presented at the right side of the figure. The mean bubble diameter was varied in the range of 0.3-2 mm. One can see that the addition of gas bubbles to the stream can lead both to intensification of heat transfer (a reduction of the wall temperature) and to its deterioration (rise of the wall temperature in comparison with a single-phase case), depending on the dispersed composition of the gas phase. Our estimation showed that the relation of heat transfer coefficient in the two-phase flow to heat transfer coefficient in the single phase flow changes from 0.6 to 1.4 with a rise of bubble diameters. This regime (Re = 7000, \( \beta = 0.015 \)) was selected because the highest heat transfer deterioration was found for the smallest bubbles in the whole range of Re investigated (5000<Re<11000). But for another liquid and gas flow rates the heat transfer deterioration can be found also.
The mechanism of growth of wall shear stress, as well as of the heat transfer coefficient, in a downward bubbly flow was described earlier [2, 3]. When bubbles are added to a flow, the fluid velocity profile alters with subsequent increase in the liquid velocity gradient in the wall region and thus in wall shear stress and heat transfer coefficient.

This conclusion is well correlated with our data which were obtained using particle image velocimetry (figure 3). These figures show the flow development in the flux which is containing bubbles with different sizes and, for comparison, for single phase flow. This data is in a good
agreement with the literature. It is clearly seen that the maximums of the liquid velocity for large bubble diameters are situated in the near-wall region of the flow. Possibly this observation is connected with movement of bubbles in a central region of the flow and changing of the liquid streamlines.

It was shown early [9] that the reason of heat transfer deterioration is the turbulence suppression in the near wall region of the flow. Unfortunately, it is impossible to carry out experiments using PIV for the smallest bubbles because the flow is not transparent in this case.

4. Conclusions
The data on the size of bubbles detaching from the edges of an array of capillaries in a liquid flow are presented. An investigation of heat transfer of the downward bubbly flow was carried out for different

Figure 3. Liquid velocity distribution for Re = 7500. a - single phase flow; b - \( \beta = 0.015, <d_b> = 1 \) mm; c - \( \beta = 0.015, <d_b> = 3 \) mm.
bubble sizes. It was previously shown [3, 9] that the introduction of small gas bubbles into the flow can cause the turbulence suppression in the near-wall region. For the tested flow regimes, this causes deterioration of heat transfer as compared to a single-phase flow by up to 40%. Large bubbles lead to a higher degree of turbulence in the near-wall region, an increase in the average friction, and intensification of heat transfer. It should be noted that similar results can be obtained with extremely small amounts of gas ($\beta \sim 0.01$) introduced into the flow.

PIV data on liquid velocity distribution are presented. The data obtained are in a good agreement with previously observed behavior of bubbly downflow.

Similar results have not been presented in the literature before, but there are data confirming the possibility of suppressing the turbulence of the downward bubbly flows in the region near the walls of pipes and channels [1, 3, 7].

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