Flow structure and heat transfer in a turbulent vertical bubbly flow downstream of a sudden duct expansion

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The flow structure and heat transfer in bubbly flows in a sudden duct expansion were studied. The data was obtained both in a pipe and a flat channel with a sudden expansion. Measurements are performed using shadow photography and PIV/LIF system. For modelling two-phase bubbly flow the set of RANS equations is used. Reynolds stress transport model is used to predict the turbulence of the liquid phase. The influence of sudden channel expansion on the distribution of bubbles and its velocity is shown. It is shown, that in the pipe with sudden expansion there are not a strong influence of bubbles on the hydrodynamical structure and heat transfer in the flow recirculation zone. In a contrast, in the vertical channel with back facing step the strong increasement of void fraction were found in similar region. It can result in increasement of heat transfer.

1. Introduction

Two-phase bubbly flows are common in different practical applications. Most of studies in this field are dedicated to investigations in vertical pipes. It was found in literature that recirculation flow determines the turbulent flux structure and the intensity of the transfer for momentum, mass, and heat. It can be used in different types of exchangers. But just some works can be found in literature on the topic of two-phase bubbly recirculation flows [1-4]. Experimental investigations of flow structure in ducts with sudden expansion were performed in [1, 2]. The numerical model for predictions of the flow structure in pipe sudden expansion were presented in [3]. In [4] the experimental study of heat transfer in bubbly flow downstream of a pipe sudden expansion and validation of numerical model [3] was performed.

The purpose of this paper is to present a data about flow structure of bubbly flow in a pipe and a flat channel with a sudden expansion. The data about hydrodynamical structure and heat transfer performance behind the pipe’s sudden expansion is presented. The distribution of bubbles over a duct cross section is very important parameter. The distributions of individual velocities of bubbles and void fraction distribution is presented in the last part of the paper. It can be used to obtain another hydrodynamical parameters of two-phase flow for safe operation and for the prediction of various emergency scenarios in heat generators.
2. Experimental setup and measurement methods
The experimental setup consists of a closed circuit in a liquid and an open circuit in the gas phase. The test liquid (distilled water) was pumped from the main tank to the test section. The pipe with sudden expansion (pipe diameters before and after the expansion $D_1=15$ mm, $D_2=42$ mm, step height $h=13.5$ mm) and the flat channel with the height before the expansion $H_1=8$ mm and the step height $H=12$ mm were used as test sections (Fig. 1a, b). In both cases bubbles were generated by feeding air into the liquid flow through capillaries with inner diameter of 0.7 mm. The capillaries are uniformly distributed across the duct cross-section.

The gas flow rate is determined using a gas flow controller, the liquid flow rate is measured by ultrasonic flow rate meter. The measurement error of the liquid and gas flow rates is $\pm 2\%$ of the measured value.

Direct heating and the thermography using infrared camera were used to measure heat transfer characteristics. In order to perform the measurements of liquid phase velocity distributions a Particle Image Velocimetry (PIV) "Polis-PIV" system was used. In order to obtain velocities and positions of bubbles in a flat channel a high-speed shadow method of imaging was used.

3. Numerical model
For the modeling of dispersed phase (gas bubbles) Eulerian two-fluid approach was used. The Eulerian approach is based on kinetic equations for a one-point PDF of bubbles coordinates, velocity, and temperature in the turbulent Gaussian fluid flow fields. The bubbles’ behavior in turbulent liquid and their back action on the flow is determined by drag, gravity lift, virtual mass, wall lubrication forces, turbulent transport, and turbulent diffusion [3].

The carrier liquid (water) flow is treated as a steady-state, incompressible and axisymmetrical. Mass conservation continuity, two-momentum and energy equations with taking into account the effect of bubbles presence were used. Axisymmetric approach was applied for the system of RANS equations, the turbulence model and the equations for the dispersed phase (gas bubbles) [3]. The turbulence of the liquid phase is predicted using the model of Reynolds stress transport (second moment closure-SMC) [5]. The SMC model predicts the turbulent Reynolds stresses directly from partial differential equations and allows us to compute the anisotropic flow. The low-Reynolds number elliptic blending second-moment closure of [5] is utilized in the present study. It is modified for the presence of bubbles by the model [6].

In the present study the effect of break-up and coalescence of bubbles is not considered as well as the effects of pressure drop of the liquid and heat up of the gas phase on the bubble size.

4. Results and discussion
Radial distributions of the mean axial velocity of the liquid behind the sudden expansion of the pipe in the single-phase ($I$) and two-phase bubbly ($2$) flows are shown in Fig. 2. In the recirculation region negative velocities can be found both for single and two-phase flows ($x/h = 4$). The maximal difference between the measured and predicted results for both single-phase and carrier fluid in the two-phase bubbly flow is up to 10%.

![Fig. 1. Schemes of test sections: a - pipe with sudden expansion; b - channel with back facing step.](image-url)
Fig. 2. Profiles of mean axial velocities of liquid phase downstream of the sudden pipe expansion at $x/h = 4$ (a) and $16$ (b). Points are measurements, lines are simulations. 1 – single-phase flow at $\beta = 0\%$, 2 – liquid in two-phase flow at $\beta = 5\%$.

Distributions of the parameter for heat transfer enhancement $ER_{\text{max}} = \frac{Nu_{\text{max}}}{Nu_{0,\text{max}}}$ in bubbly flow with various gas volumetric flow rate ratios $\beta$ are shown on the Figure 3. The figure shows the results for two stations downstream of the sudden pipe expansion at $x/h = 20$ and $28$. Here $Nu_{\text{max}}$ and $Nu_{0,\text{max}}$ are the maximal value of the Nusselt number for the bubbly flow and single-phase flow under other identical conditions. Points and lines are the results of measurements and numerical simulations performed by the authors.

A significant increase in the heat transfer rate occurs upon adding air bubbles into the liquid. According to the measurements and simulations, the increase in heat transfer reaches almost three times for the case of $Re_H = 1.02 \times 10^4$ and $\beta = 10.1\%$. The increased heat transfer coefficient is caused by significant deformation in the velocity profiles of the two-phase flow compared to the single-phase flow and by the increase in the liquid velocity gradient near the pipe wall. The heat transfer enhancement was found mainly in the flow relaxation zone. Actually, these conclusions are in agreement with the measured one. Only a few bubbles penetrate into the flow recirculation region and they are available only in the flow core and shear layer. We obtain a small effect of the gas bubbles on the measured and predicted heat transfer in the flow recirculation region and around reattachment point due to the relatively large bubble size ($d > 1.7$ mm). A recent numerical work [3] showed that small bubbles ($d < 1.5$ mm) caused heat transfer intensification over the entire length of the recirculation zone, while the larger ones caused intensification mostly in the flow relaxation region. The bubbles migrate towards the wall after the reattachment point of the flow and accumulate there due to the action of the lift force; it leads to an increase in fluid phase turbulence and heat transfer in this region.

Fig. 3. The distributions of heat transfer enhancement ratios for various gas volumetric flow rate ratios $\beta$ at $Re_H = 1.02 \times 10^4$. Points and lines are authors’ measurements and computations respectively. 1 – $x/h = 20$, 2 – $28$. 
Figure 4a shows data on the velocity distribution of individual bubbles along the length and width of the sudden expansion of a flat vertical channel. Here L is a line along the channel width (L=0 m is a channel wall position L=0.1 m is the channel centerline). A decrease in the velocity of the bubbles, as well as the carrier liquid was found behind the sudden expansion. It can be pointed that in the recirculation zone of the flow bubbles move along more curved trajectories than before, which is apparently caused by a high degree of flow perturbation.

The local void fraction distribution behind the step is shown in Figure 4b. There is a tendency to increase the local void fraction at some distance from the step. As shown by the visualization of the streamlines in a single-phase flow, the location of areas of highest gas content approximately corresponds to the end of the recirculation area (x/H = 7-8).

Conclusions
The results of experimental and numerical simulations of the flow structure and heat transfer in bubbly flows in a sudden duct expansion are presented. Measurements of bubble sizes, velocities and void fraction distribution are performed using shadow photography, liquid phase velocities are measured by PIV/LIF system. For modelling two-phase bubbly flow the set of RANS equations is used. Reynolds stress transport model is used to predict the turbulence of the liquid phase. The influence of sudden duct expansion on the distribution of bubbles and its velocity, liquid phase velocities and heat transfer is shown. It is pointed, that in the pipe with sudden expansion there are not a strong influence of bubbles on the hydrodynamical structure and heat transfer in the flow recirculation zone. In a contrast, in the vertical channel with back facing step the strong increasement of void fraction were found in similar region. It can result in increasement of heat transfer. This topic will be the purpose of the further studies.

Acknowledgements
The study was performed by partially financial support of the Russian Foundation for Basic Research (Project No. 18-08-00477), heat transfer measurements were performed under the state contract with IT SB RAS (AAAA-A18-118051690120-2).

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