Modeling bubble distribution and heat transfer in polydispersed gas-liquid flow in a backward-facing step

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Abstract. The numerical results on the flow, bubble distributions and heat transfer in a bubbly polydisperse flow in a horizontal duct with a backward-facing step are presented. The numerical model uses the Eulerian approach taking into account the back effects of bubbles on the mean and turbulent characteristics of the carrier fluid phase. The model takes into account the interphase momentum transfer, bubble break-up and coalescence processes. The set of 2D RANS equations is used for modeling two-phase bubbly flows. Turbulence of the carrier fluid phase is predicted using the second moment closure. The method of δ-function approximation is employed for simulation of gas bubble break-up and coalescence. The effect of the gas volumetric flow rate ratios on the flow structure and heat transfer in the two-phase flow is numerically studied. An increase in the gas volumetric flow rate ratios leads to a significant increase in the wall friction coefficient (almost 1.5 times in comparison with the single-phase flow regime). The addition of air bubbles results in a significant increase in the heat transfer rate (up to 50%).

1. Introduction
Turbulent two-phase bubbly flows in vertical or horizontal ducts are often used in chemical, nuclear, power and other practical applications. Usually, such flows are turbulent with a strong interface interaction. They may be complicated by flow separation at sharp edges, its recirculation, polydispersity of gas bubbles, break-up, coalescence of bubbles and heat transfer [1,2]. To our knowledge, the first experimental studies of two-phase bubbly flows in a duct with a backward-facing step were [3,4]. Gas-liquid bubbly flow has been experimentally investigated in a horizontal duct with a backward-facing step. The complexity of the numerical modeling of such flows is associated with the need to take into account a number of multiscale factors of various physical nature: turbulence of the carrier medium, gas bubble-turbulence interaction, break-up and coalescence processes. Bubble diameter \(d\) and gas volumetric flow rate ratio \(\beta\) mainly determine the void fraction distribution and heat transfer rate [5,6]. Therefore, the accurate modeling of gas bubble distribution (void fraction) across the duct or pipe cross-section in separated turbulent bubbly flows is one of the crucial points in understanding the physical mechanisms in such flows.

The aim of the paper is the numerical study of the effect of gas flow rate ratios \(\beta\) on the mean and fluctuational patterns of the carrier fluid flow and heat transfer enhancement in the two-phase bubbly flow in a horizontal duct with a backward-facing step. The work employs the approach of [6] describing the dynamics of the flow and heat transfer of the bubbly flow, with considering bubble break-up and coalescence processes.
2. Numerical model

The bubbly flow is modeled using the Eulerian two-fluid approach that treats the dispersed phase as a continuous medium with properties analogous to those of liquid [7]. This technique involves the solution of a second set of Navier–Stokes-like equations in addition to those of the carrier (liquid) phase [7]. The motion and heat transfer of the carrier fluid turbulent flow is modeled by the 2D steady-state, incompressible RANS equations [6]. It includes continuity, two-momentum and energy equations with taking into account the effect of bubble presence. The back effect of bubbles on the mean and fluctuational characteristics of turbulent carrier fluid flow is determined by drag, gravity lift, virtual mass, wall lubrication forces, turbulent transport, and turbulent diffusion. The carrier phase turbulence is predicted using the Second Moment Closure – SMC model of [9]. The effect of gas bubbles on carrier phase turbulence is modeled by the model of [10].

The Eulerian approach is based on kinetic equations for a one-point probability density function of particle coordinates, velocity, and temperature in the turbulent Gaussian fluid flow fields [8]. The dispersed phase (air bubbles) is treated as a compressible continuum. The set of non-steady-state compressible Navier–Stokes-like equations is used. The polydispersity of the two-phase bubbly flow is described by the method of δ-approximation [5]. The break-up and coalescence processes are predicted according to the model of [11].

The mean transport equations for both gas and dispersed phases and the SMC model are solved using a control volumes method on a staggered grid. The QUICK scheme is used to approximate the convective terms, and the second-order accurate central difference scheme is employed for the approximation of diffusion terms. The SIMPLEC algorithm couples flow velocity and pressure and it is used for the velocity correction. The basic grid with 256x100 control volumes along the longitudinal and transverse directions is used for all numerical simulations. Grid convergence is verified for three grid sizes: 128×50, and 400×150 control volumes. A more refined grid is applied in the recirculation region and in the zones of flow detachment and reattachment.

3. Numerical results and their discussion

All predictions are performed for a mixture of water and polydispersed air bubbles at atmospheric pressure for a bubbly polydisperse horizontal flow in a duct with a backward-facing step (see Fig. 1). The Reynolds number of the flow $\text{Re} = U_m 2H/\nu = 2 \times 10^4$, and its mass average velocity before the separation cross-section $U_m = 1 \text{ m/s}$. The height of the channel before separation $h = 10 \text{ mm}$, the step height $H = 10 \text{ mm}$, the degree of expansion $\text{ER} = (h + H) / h = 2$, the wall temperature $T_w = \text{const} = 313 \text{ K}$, and the initial temperatures of liquid and gas bubbles $T_i = T_{b1} = 293 \text{ K}$. Note that only the upper wall of the flat duct is heated. The inlet distribution of the gas phase is set in the form of a uniform parameter profile over the pipe cross-section. In the input section, the averaged phase velocities have the same value. The simulations are carried out under the condition that there are no phase changes (steam formation) on the duct walls. The gas volumetric flow rate ratios vary in the range $\beta = 0–10\%$ and the initial diameter of air bubbles $d_1 = 0.5–2 \text{ mm}$. The predictions are performed for four $\delta$–functions in the inlet cross-section.

![Figure 1. Diagram of a gas-liquid polydisperse horizontal flow in a flat duct with a backward-facing step.](image)

$I$ – bubbly two-phase flow.
Figure 2a shows the distribution of the mean longitudinal velocity of a carrier liquid in a two-phase flow along the length of the duct with variation in the concentration of gas bubbles. A sharp decrease in the fluid velocity due to the sudden expansion of the flat duct is observed after the cross-section of the flow detachment. The fluid velocity in a two-phase bubbly flow is higher than the corresponding value for a single-phase fluid flow due to the presence of air bubbles.

The effect of changes in the volumetric gas flow rate ratios on the distribution of local void fraction over the duct cross-section \( \alpha \) are shown in Fig. 2b. It should be noted, that bubbles enter the computational region in the lower part of the duct and there is uniform distribution of gas bubbles in the inlet cross-section. Further, they move both along the length and height of the duct due to the forces acting on the gas bubble. In polydisperse vertical non- and isothermal bubbly flows in pipes or ducts, the dispersed phase redistributes over the cross-section under the action of radial forces (Saffman forces, turbophoresis, turbulent dispersion and wall force): large bubbles are located mainly in the core of the flow, and small ones are accumulated in the wall zone [5,6,12]. Obviously, one of the main factors affecting the motion and dispersion of the gas bubbles in horizontal flows toward the upper wall is the Archimedes force. The movement of bubbles toward the upper part of the duct is observed and redistribution appears immediately after the cross-section of flow sudden expansion. Moreover, in the lower part of the duct, the number of bubbles decreases significantly and the zone almost free from gas bubbles appears. In almost all sections (except the first at \( x/H = 2 \)), the maximal value of void fraction is located in the near-wall region of the duct. A more pronounced accumulation of bubbles near the duct wall is revealed after the two-phase bubbly flow reattachment in comparison with the separation region. The similar features are obtained for isothermal upward gas-liquid flows in pipes or ducts without sudden expansion [5]. The profiles of void fraction are characterized by an almost zero value in the immediate vicinity of the duct upper wall. This is explained by the fact that under the influence of wall lubrication force the bubbles cannot approach the wall.

![Figure 2](image_url)

**Figure 2.** Profiles of mean longitudinal velocity of the fluid (a) and void fraction (b) for various gas volumetric flow rate ratios along the duct length. (a): 1 – \( \beta = 0 \) (single-phase fluid flow), 2 – \( \beta = 2\% \), 3 – 5\%, 4 – 10\%. (b): 1 – \( \beta = 2\% \), 2 – 5\%, 3 – 10\%.

The distribution of the wall friction coefficient between the upper wall and two-phase flow \( C_f = 2 \tau_w / (\rho U_m^2) \) along the length of the duct is shown in Fig. 3 by varying the concentration of gas bubbles at the inlet. Line 1 is the result of predictions of the coefficient of wall friction for a single-phase fluid flow. An increase in the gas volumetric flow rate ratios leads to a significant increase in the absolute value of the wall friction coefficient (almost 1.5 times in comparison with the single-phase flow regime). We note that the minimum value of the friction on the wall located in the
recirculation region shifts upstream with an increase in the diameter of bubbles and gas volumetric flow rate ratios $\beta$.

The addition of gas bubbles into the turbulent fluid flow has a significant effect on heat transfer from the wall to the two-phase flow to the upper wall of the duct. This can be seen from the data shown in Fig. 4. The local Nusselt number at a constant wall temperature was determined by the difference between the wall temperature $T_W$ and the mean-mass temperature of the carrier fluid (liquid) in this section $T_m$:

$$\text{Nu} = -\frac{\partial T}{\partial y} \frac{H}{(T_W - T_m)}$$

where $y$ is the transverse coordinate normal to the wall, $H$ is the step height. Dashed line 1 is heat transfer prediction for the single-phase separated flow of carrier fluid (liquid) under other identical conditions. With an increase in the volumetric gas flow rate ratios $\beta$, there is a noticeable increase in the heat transfer (up to 50%) in comparison with the single-phase flow (see Fig. 5a). This is explained by an increase in the gradients of mean velocity, temperature, and additional turbulization of the fluid phase caused by the bubbles in the near-wall region of the duct. The position of the heat transfer maximum shifts upstream at $\beta = 10\%$ is $x_{\text{Nu, max}}/H = 4.9$, and the position of flow reattachment approximately coincides with it, $x_R/H = 5$ at $\beta = 10\%$. The locus of the maximal value in heat transfer is close to the position of the point of flow reattachment, as shown in [13].

An increase in the initial mean bubbles size has a more complex effect on heat transfer (see Fig. 4b). Initially, as the diameter of the bubble increases, heat transfer from the upper wall to the two-phase flow augments (curves 1 and 2). It causes additional turbulization in the near-wall region due to the carrier fluid flow when the gas bubbles are added. This effect becomes less noticeable for the largest bubbles studied in the paper (line 4). This can be explained by the fact that, for a fixed gas volumetric flow rate ratio, the total number of large bubbles is much smaller than in the case of small bubbles. They cannot come close to the wall, and heat transfer enhancement ratio becomes lesser.

**Figure 3.** Wall friction in bubbly separated flow for various gas volumetric flow rate ratios (a): $1 - \beta = 0$ (single-phase fluid flow), $2 - 2\%, 3 - 5\%, 4 - 10\%$. 
Figure 4. The effect of gas volumetric flow rate ratios (a) and initial mean bubbles diameter (b) on heat transfer in bubbly flow along the duct length. (a): $d = 1$ mm; $1 - \beta = 0$ (single-phase fluid flow), 2 – 2, 3 – 5, 4 – 10%. (b): $\beta = 5\%$; 1 – $d = 0$ (single-phase fluid flow), 2 – 0.5, 3 – 1, 4 – 2 mm.

Conclusion

The results of numerical simulation of the flow structure of polydispersed turbulent bubbly flow and heat transfer in a duct with a backward-facing step are presented. The mathematical model is based on the use of the Eulerian approach, considering the back effect of bubbles on the mean characteristics and turbulence of the carrier phase. The turbulence of the carrier liquid phase is predicted using the model of second moment closure. Bubble dynamics is described taking into account changes in the average volume of bubbles due to the expansion at the change in their density, break-up and coalescence. The study is carried out at the change of initial diameter of air bubbles in the range of $d_1 = 0.5–2$ mm and their volumetric gas flow rate ratio $\beta = 0–10\%$.

The fluid velocity in a two-phase bubbly flow is higher than the corresponding value for a single-phase fluid flow due to the presence of air bubbles. An increase in the gas volumetric flow rate ratios leads to a significant increase in the absolute value of the wall friction coefficient (almost 1.5 times in comparison with the single-phase flow regime). The position of the heat transfer maximum shifts upstream. The position of flow reattachment approximately coincides with it. With an increase in the volumetric gas flow rate ratios $\beta$, there is a noticeable increase in heat transfer (up to 50%) in comparison with the single-phase flow. The locus of the maximal value in heat transfer is close to the position of the point of reattachment of the flow. An increase in the initial mean bubbles size has a more complex effect on heat transfer. Initially, as the diameter of bubble increases, heat transfer from the upper wall to the two-phase flow augments. This effect becomes less noticeable for the largest bubbles studied in the paper. This can be explained by the fact that, for a fixed gas volumetric flow rate ratio, the total number of large bubbles is much smaller than in the case of small bubbles.

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