Numerical analysis of flow patterns and heat transfer in bubbly polydispersed downflow in a vertical pipe

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Abstract. The numerical results of the flow structure in a vertical bubbly polydispersed downward flow in a pipe are presented. The mathematical model is based on the Eulerian approach, which considered the back effects of bubbles on the mean characteristics and turbulence of the carrier fluid phase. The set of axisymmetrical RANS equations is used for modeling two-phase bubbly flows. Turbulence of the carrier fluid phase is predicted using the Reynolds stress transport model. The interfacial transfer of mass, momentum, and energy requires averaging over the computational control volume. The effect of break-up and coalescence of bubbles is taken into account. The effect of variation in the gas volumetric flow rate ratio, inlet mean fluid temperature, and its velocity on the flow structure and heat transfer in the two-phase flow is analyzed. The addition of air bubbles results in a significant increase in the heat transfer rate (up to three times). This effect augments by increasing the gas volumetric flow rate ratio.

1. Introduction

Two-phase bubbly flows are frequently used in chemical technologies, power engineering, and many other practical applications [1]. Typically, such flows are turbulent with interfacial coupling between the fluid carrier phase (water) and gas bubbles (air). The upward or downward flows without heat transfer between the pipe surface and two-phase gas-liquid system have been investigated in detail in the last few decades. The bubbly flows with heat transfer were examined insufficiently. The correct simulation of bubble distributions over a channel or pipe section is of great importance for safe operation and prediction of various emergency scenarios in heat generators connected to various energy elements.

The flow structure and heat transfer in two-phase bubbly flow have many features in comparison with the single-phase one. These features include the process of bubble interaction with turbulent eddies, effect of bubbles on heat transfer modification, bubbles nucleation and their growth on the wall surface, change of bubble volume due to the pressure and temperature gradients, bubble break up and coalescence [2]. A common practice in studying the complex phenomena in turbulent multiphase flows is their separate investigation [2]. The effect of bubbles on the flow structure, fluid phase turbulence and heat transfer modification in a sudden pipe expansion is numerically studied. The nucleation process and bubble break up and coalescence are ignored. We have obtained all numerical results for monodispersed bubble diameter. This is a threshold for simulation of heat transfer in a turbulent bubbly flow downstream of a sudden pipe expansion.
In the present paper, we performed the numerical study of the flow and heat transfer in bubbly polydisperse turbulent flows using the Eulerian two-fluid model in downward pipe flow. This study may be interesting for scientists and engineers dealing with heat transfer enhancements in power equipment. The aim of the present paper is numerical study of the effect of dispersed phase on the flow structure and heat transfer in the turbulent vertical bubbly flow in a pipe.

2. Mathematical model

2.1. Governing equations

The numerical model is based on the Eulerian approach. The fluid phase is treated as a continuum while the gas phase (bubbles) is considered as the dispersed phase. In the two-fluid approach, both phases are considered as interacting continua. This technique involves the solution of a second set of Navier–Stokes-like equations in addition to those of the carrier (fluid) phase. In order to account for the interaction between the phases, that is, momentum transfer and heat and mass transfer, the conservation equations have to be extended by appropriate source/sink terms. 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 [3–5]. Properties such as the mass of particles per unit volume are considered as a continuous property and the particle velocity is the averaged velocity over an average control volume.

The two-fluid model [6,7] consists of the set of equations for each phase, including: equation for continuity, two equations for momentum conservation and energy equation. A set of axisymmetric RANS equations is used for the fluid phase. The low-Reynolds-number elliptic blending Reynolds stress model (RSM) by [8] is used in the work. The RSM predicts the turbulent Reynolds stresses directly from partial differential equations and allows us to compute the anisotropic flow. It is modified for the presence of bubbles by the model [9].

To describe mass and momentum transfer between gaseous and carrier phases, the interfacial transfer terms appear in each equation to couple the different phasic effects [6,7]. It is assumed that there is no a phase change (vapor formation) on the wall surface.

The bubble-size distribution is the crucial point for simulation of bubbly polydisperse flows. The vapor formation due to the phase changes, pressure or density changes and bubbles coalescence and breakup have the strong effect on the bubble-size distributions. In this paper, only coalescence and breakup processes have been taken. They are the main mechanisms that lead to polydisperse bubble-size distributions. It is assumed that the bubbles hold the spherical shape. The basic mechanism of coalescence is associated with bubble collisions due to their entrainment into the turbulent motion of fluid, as illustrated in [10]. It is assumed that only two bubbles collide, which occurs most often in reality. Coalescence consists of three processes: (1) collision of bubbles; (2) formation of a thin liquid film between two colliding bubbles, which traps and drains gradually and (3) process, when liquid film between two bubbles reaches a critical thickness, ruptures and forms one large bubble.

Bubble break-up occurs due to their interaction with turbulent eddies, as shown in [10]. The rate of bubble break-up is determined by the interphase forces, which result in deformation and break-up of the bubble. The well-known model of [11] is employed in the paper for modeling the bubble-eddy collision rate. Bubble size distributions are predicted by modeling the coalescence and break-up processes using the population balance model of [11]. The bubble diameter in the flow changes both along the pipe length and over the cross-section.

2.2. Numerical implementation

The mean transport equations for both gas and dispersed phases and SMC model are solved using the 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 adopted for the diffusion terms. The velocity correction is used to satisfy continuity through the SIMPLEC algorithm, which couples velocity and pressure.
The results of preliminary calculations for the single-phase flow in a pipe with a length of 150R are used for the gas-phase velocity and turbulence on the pipe edge. These conditions are sufficient to achieve fully developed turbulent gas flow. The symmetry conditions are set on the pipe axis for gas and dispersed phases. No-slip conditions are set on the wall surface for the carrier phase. At the outlet edge, the computational domain condition ∂ϕ/∂r = 0 is set for all variables.

The first cell is located at distance y = yU*/ν = 0.3–0.5 from the wall, where U* is the friction velocity obtained for the single-phase flow in the inlet pipe and ν is the kinematic viscosity. At least 10 control volumes have been generated to be able to resolve the mean velocity field and turbulence quantities in the viscosity-affected near-wall region (y* < 10). Grid sensitivity studies are carried out to determine the optimum grid resolution that gives the mesh-independent solution. For all numerical investigations performed in the study, a basic grid with 256×100 control volumes along the axial and radial directions is used. 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 computations are carried out at the atmospheric pressure. The wall temperature varies within tw = 25–40°C, initial water temperature is tw = 20°C. Pipe diameter is 2R = 20 mm, and volumetric gas flow rate ratios are β = 0–0.1. The inlet distribution of gas bubbles is set in the form of a uniform profile of parameters over the pipe cross-section. The predictions are carried out in the absence of phase transitions on the pipe walls. All simulations are performed for five bubble fractions (N = 5) at the inlet cross-section: d1 = 1, 2, 3, 4 and >5 mm. It is assumed that the first three fractions of bubbles have the same velocities and temperature, while the velocity of other two fractions differs from the first three: U_{b,k=1} = U_{b,k=2} = U_{b,k=3} ≠ U_{b,k=4} ≠ U_{b,k=5} and T_{b,k=1} = T_{b,k=2} = T_{b,k=3} ≠ T_{b,k=4} ≠ T_{b,k=5}.

Figure 1a shows the profiles of the mean axial fluid phase velocity in universal coordinates for various volumetric gas flow rate ratios, where U* = U/U* and y* = yU*/ν. It is observed that the gas bubbles affect distributions of the fluid phase axial velocity. The value of fluid phase velocity in the bubbly flow is larger than that in the single-phase fluid flow. This trend becomes more pronounced with an increase in β and it can be explained by the entrainment of the carrier fluid phase by bubbles and decrease in the pipe cross-section occupied by the fluid phase.

Distributions of normalized temperature Θ = (T_w - T) / (T_w - T_0) over the pipe cross-section are shown in Figure 1b. Here, T_w is the wall temperature and T_0 is the fluid temperature on the pipe axis.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** The axial fluid flow velocity profiles in semi-logarithmical coordinates (a) and temperature profiles (b) in bubbly flow for various volumetric gas flow rate ratios. 1 – β = 0 (single-phase fluid flow), 2 – 0.01, 3 – 0.05, 4 – 0.1.
The increase in $\beta$ leads to an increase in the filling of temperature profiles in the near-wall region. It causes the heat transfer enhancement in two-phase bubbly flow in comparison with the single-phase fluid flow. In the flow core the values of temperature in the two-phase bubbly flow are qualitatively similar to those for the single-phase fluid flow.

Figure 2 shows the effect of volumetric gas flow rate ratios on heat transfer enhancement ratio. $1 - \text{Re} = 5 \times 10^4$, $2 - 10^5$, $3 - 2 \times 10^4$, $4 - 4 \times 10^3$.

The measurements of [12] for the upward flow regime were used in the case of heated bubbly flow for comparison. Measurements were taken for an ascending flow of the mixture of water and air bubbles under the atmospheric pressure. The tube diameter was $2R = 16.9$ mm, the average flow discharge velocity was $J_i = 0.93$ m/s for fluid and $J_b = 0.32$ m/s for gas, the bubble diameter was $d = 4.2$ mm, and heat flux density supplied to the wall of the tube was $q_w = 117.5$ kW/m². The length of the region of formation of the fluid flow with air bubbles without heat transfer was 0.77 m and length of the heated zone was 0.97 m. The temperature of the fluid phase was measured at distance $x/(2R) = 100$ from the cross-section, where the gas phase was introduced. The bubbles were injected through a capillary with the diameter of 2 mm and located on the tube axis.

Figure 3 illustrates comparative analysis of the results obtained using the developed model and experimental data [12]. The data on the temperature profiles for the one-phase flow of fluid (dashed curve) and bubble flow (solid curve) are represented. At the flow core, the temperature of fluid varies...
insignificantly, and changes are mainly observed in a thin near-wall region. This is typical of experimental data [10] as well as of the results of our numerical calculations. It can be concluded that the agreement with the results of measurements of fluid temperature distribution over the tube radius is satisfactory.

5. Conclusion
The mathematical model is based on the use of Eulerian approach, considering the back effect of bubbles on the mean characteristics and turbulence of the carrier phase. Turbulence of the carrier fluid phase is predicted using the model of Reynolds stress transport. Bubble dynamics is described taking into account the changes in the average volume of bubbles due to the expansion at a change in their density, break-up and coalescence processes. The study is carried out at the change of initial diameter of air bubbles in the range of $d_m = 1–3$ mm and their volumetric gas flow rate ratio of $\beta = 0–10\%$. The turbulent flow structure and heat transfer for a bubbly polydispersed downflow is numerically investigated. It is shown that the addition of air bubbles causes a significant increase in the heat transfer rate (up to three times), and these effects increase with increasing gas volumetric flow rate ratios.

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