The effects of bubbles on the structure of upward gas-liquid flow

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Abstract. The paper presents the results of study of the local structure of turbulent gas-liquid flow in vertical pipe. A mathematical model based on the use of Eulerian description for both phases taking into account the action of different forces of interfacial interaction. Special attention is paid to the development of approaches for the simulation of polydispersed bubbly flows taking into account processes of coagulation and fragmentation. Comparison of simulation results with experimental data showed that the developed approach allows to obtain detailed information about the structures of turbulent gas-liquid flows, the distribution of bubbles by size.

1. Intoduction

Two-phase bubbly turbulent flows are extensively used in various fields of industry such as chemical, food, pharmaceutical, nuclear and thermal power engineering [1-3]. Therefore, the simulation of turbulent bubbly flows is of great practical interest and is the subject of many publications. The complexity of modeling such flows involve a large number of phenomena of different nature, since such flows are characterized by strong mutual influence of the carrier and dispersed phase, accompanied by the processes of heat transfer, phase transitions, coagulation, fragmentation, etc. The structure of two-phase gas-liquid flow significantly depends on flow rate parameters of dispersed phase, the magnitude and direction of velocity of the continuous phase, physical properties of materials for the selected system, the geometry of the modern power plants. Knowledge the information about the structure, the averaged and pulsation characteristics of bubble flows is necessary in the design of modern cost-effective manufacturing equipment.

2. Governing equations

System the Reynolds-averaged Navier-Stokes equations to describe the dynamics of a turbulent mixture of liquid and air bubbles with regard to interfacial interaction has the form

$$\frac{\partial(\rho_k \alpha_k)}{\partial t} + \frac{\partial(\alpha_k \rho_k u_j)}{\partial x_j} = 0, \quad \alpha_l + \alpha_g = 1, \quad k = l, g \tag{1}$$

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$$\frac{\partial(\alpha_k\rho_k u_{ki})}{\partial t}+\frac{\partial(\alpha_k\rho_k u_{ki}u_{kj})}{\partial x_j}=-\alpha_k\frac{\partial p}{\partial x_i}+\alpha_k\rho_k g_i+F_{ki}+ \frac{\partial}{\partial x_j}\left[(\mu_k+\mu_{kt})\left(\frac{\partial u_{ki}}{\partial x_j}+\frac{\partial u_{kj}}{\partial x_i}-\frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}\right)\right] \tag{2}$$

Here x_i - cartesian coordinates,, u_i - components of velocity vector, t - time, p - pressure, ρ_l , ρ_g - density of continuous and dispersed phases respectively, α_l - is the volume fraction of liquid phase in mixture, δ_{ij} - is the Kronecker symbol, μ_l ,μ_g - dynamic coefficient of viscosity of water and air, μ_{kt} - is the coefficient of turbulent viscosity, F_{ki} - the strength of interfacial interaction forces. The turbulent viscosity for the carrier liquid phase are determined using a two-parameter turbulence model, modified for two-phase media [4]. In the equations for the transfer of turbulent kinetic energy and its dissipation introduces additional components to the kinetic energy caused by pulsations of the bubbles. The motion of the dispersed phase is determined by the forces of interfacial interaction. The main forces considered have the following components: Archimedes force, resistance force, joined the force, the rotational force of Magnus, the wall friction force [4]. To describe the distribution of bubble sizes in two-phase flow the equation for conservation of number of particles is written, taking into account the processes of coagulation and fragmentation. To solve the equation of conservation for the number of bubbles we use an approach based on the method of fractions [3]. Range of distribution of particle sizes is divided into a number of fractions with fixed boundaries, there can also be exchange of vesicles between different fractions as a result of coagulation and fragmentation. In this method, the distribution of bubble sizes is approximated by a piecewise uniform distribution, thus, the problem of describing the spectrum of droplet size is reduced to the solution of the equations for the volume concentrations of individual fractions.

3. Results

Verification of this model was carried out by comparing the calculation results with the experimental gas-liquid flow data. We chose the experimental data presented in [5], which has been studied for a polydisperse flow in pipe (pipe diameter D=50.8 mm, height H=3060 mm). Experiments were carried out with the water-air mixture at atmospheric pressure and at a constant temperature. The superficial velocity of liquid at the inlet was $< J_l >$ = 0.49 - 2.01 m/c, which corresponds to a Reynolds number $\mathrm{Re}=\rho_l < J_l > D/\mu_l=(0.5-7)\cdot 10^4$. The diameter of the bubbles of dispersed phase ranged d = 0-12 mm, and volumetric gas content expendables in range α_g = 0 - 25%. The superficial velocity of the bubbles $< J_g >$ at the inlet varies from $< J_g >$= 0.02 - 0.5 m/c. Distributions of parameters in all figures are shown in cross-section, which is located at a distance $x_3/D=53$ from the entrance.

On figures 1,2 shows the average axial velocity profiles of the carrier and dispersed phases selected for the following two flow modes: 1- $< J_l >$ = 0.49 m/c, $< J_g >$= 0.19 m/c, α_g = 25.3%; 2 - $< J_l >$= 2.01 m/c, $< J_g >$= 0.47 m/c, α_g = 21.3%. From these figures it is seen that the two-phase flow velocity profiles become more filled with adding high concentration of bubbles in the central part of the tube. The value of the maximum speed is reduced in comparison with single-phase flow. It should be noted that the greatest deformation velocity profiles observed at a small distance from the wall, which is consistent with experimental data [5]. The flat velocity profile in the central part of the tube show a high degree of turbulence of the gas-liquid bubble flow.

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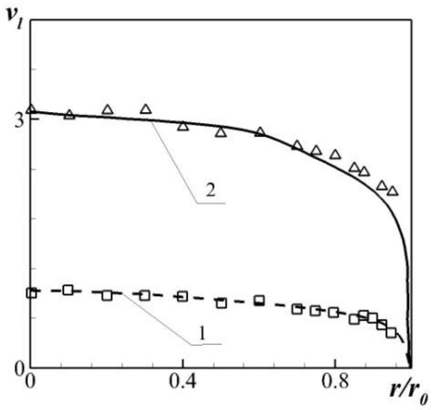

Figure 1. The distribution of the velocity profile of the carrier phase in the cross section of the pipe for different flow regimes:: 1- $< J_l >$ =0.49 m/c; 2-2.01 m/c

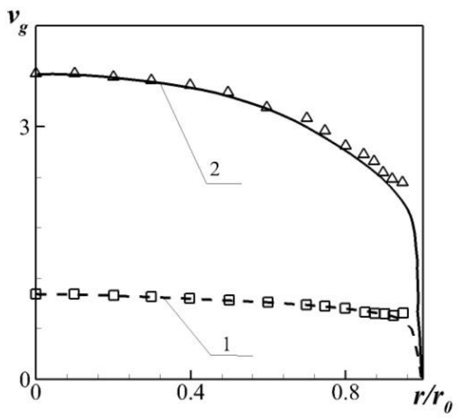

Figure 2. The distribution of the velocity profile of the disperse phase for different flow regimes: $< J_l >$ =0.49 m/c; 2-2.01 m/c

Figure 3 shows the profiles of void fraction along the pipe section for the selected mode. In either mode, the gas is dispersed with significant void fraction α_g , where there are processes of coagulation and fragmentation bubbles in turbulent flow (α_g = 0.23; 0.18). Averaged profiles of experimental data from [5] are shown as symbols (1-□, 2-Δ). For small flow rates the bubble mixture (curve 1) observed peak concentration of bubbles in the boundary region and a shallow uniform concentration distribution of bubbles in the central part of the channel. Figure 4 illustrated the distribution profiles across the pipe the volume-surface average particles diameter d_{32} corresponding to the chosen regime parameters. It can be seen that at low liquid flow rates (curve 1) there observed a uniform distribution of the average bubble diameter in the channel cross section. This indicates that for a given values of gas-liquid flow rate of coagulation resulting in a slight increase the average bubble radius (up to 4mm). However, the speed of the processes of coagulation and fragmentation are small and there is some equilibrium state. The difference of the degree of influence of interfacial forces on bubbles of different sizes leads to the fact that the bubbles in diameter smaller then original size are shifted to the near-wall region. Note that the considered flow regime can be characterized as a flow in which the bulk of the bubbles moves near the wall. Increasing the flow rate to $< J_l >$ = 2.01 m/c significantly changes the structure of the gas-liquid flow stream. The volumetric gas concentration in the central part of the tube reaches a maximum value, which decreases monotonically as it approaches to the channel walls. The growth rate of the liquid leads to the fact that the intensity of collisions of bubbles increases. It grows because of the greater concentration of bubbles per unit volume, leading to smaller distances between the bubbles, comparable to their diameters. Increased involvement of bubbles in the turbulent fluctuations leads to an increase in the intensity of coagulation, as indicated by the large value of the average bubble size in the central part of the channel. However, the decrease in the mean diameter near the walls shows that at this speed the processes of involvement of bubbles in turbulent eddies is sufficient for mass fragmentation of bubbles. The movement of gas-liquid flow at a rate of $< J_l >$ = 2.01 m/c is characterized by the intensification of the processes of coagulation and fragmentation, and the action of the transverse interfacial forces leads to a redistribution of bubbles of various sizes over the cross section of the channel. Due to the action of the interfacial forces is displaced of smaller bubbles to the wall region, while aggregated bubbles accumulate in the center of the channel. The structure of the flow at low flow rates, is characterized by the accumulation of bubbles near the walls, replaced the opposite. At higher speeds, the gas-liquid flow of main mass of bubbles moves in a central region, and near the walls the concentration is negligible.

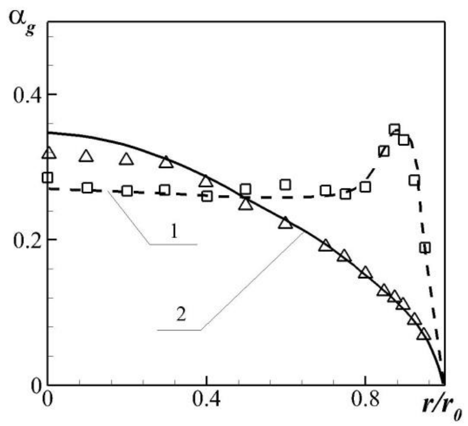

Figure 3. Distribution of the concentration of bubbles in the cross section of the pipe at different flow regimes: 1- $< J_l >$ =0.49 m/c; 2-2.01 m/c

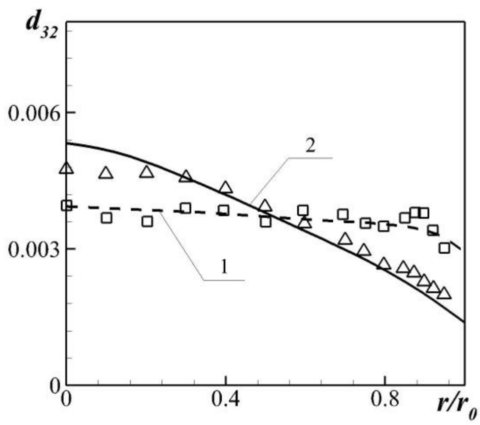

Figure 4. The change in the average diameter of bubbles d_{32} in the cross section of the pipe for different flow regimes: 1- $< J_l >$ =0.49 m/c; 2-2.01 m/c

4. Conlusions

The numerical model to describe the flow of gas bubbles in a turbulent flow is presented. Model satisfactorily describes the structure of the gas-liquid flow, and the local distribution of bubbles over the cross section in the tube. Presented the calculations of different modes of bubble flows show the complexity and mutual influence between the transfer of bubbles of variable sizes, the effects of coagulation, fragmentation and the effect of interfacial forces. Interfacial forces play a decisive role in the distribution of the main parameters (the concentration of bubbles, the speed of the carrier and dispersed phase, the specific interfacial surface area) in the cross section of the tube. Good agreement of simulation results with experimental data proves the correctness of the choice of these models.

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