Bubbly free and impinging jets: experimental study by means of PIV and PFBI

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Abstract. In the paper, an experimental investigation of the turbulent structure of bubbly free and impinging jets was carried out by means of PIV and PFBI techniques. PIV was applied to measure velocity distributions and turbulent characteristics in the continuous phase, while the PFBI approach was applied to visualize bubbles in the flow and evaluate their sizes. The flow was studied at the Reynolds number of 12,500 and three void fractions \( \beta = 0 \), 1 and 2%. The mean air bubble diameter was estimated to be roughly 0.8 mm for all \( \beta \). It was revealed that, in the free jet, the air bubbles reduce the jet core size by more than 30% at the distance of a half of the nozzle diameter. In the two-phase jet, the radial velocity fluctuations rise faster in the mixing layer in the initial jet region between the nozzle edge and the downstream position of 40% of the nozzle diameter but further downstream they are suppressed about two times by the bubbles. In the impinging jet, the bubbles produce a high peak of the radial component of turbulent fluctuations near the wall at the distance of 70% of the nozzle diameter from the jet axis.

1. Introduction

Two-phase bubbly flows are of a great interest to study because of their wide spreading in nature and intense using in various technical applications. In practice, liquids are often saturated with gas bubbles intentionally to intensify mass transfer between the phases due to a large interfacial area (even at relatively low void fractions) and to increase mixing rate by vortex generation in the bubble wakes. At present, it is generally recognized that continuous and dispersed phases in two-phase media influence each other reciprocally. Depending on the size distribution of bubbles and characteristic scales of turbulence, different effects can be distinguished. For instance, bubble trajectories are affected by the anisotropy of turbulent fluctuations in liquids (turbulent dispersion), while the motion of individual bubbles and their clusters modifies distributions and intensities of turbulent characteristics (turbulence modulation) through a number of physical mechanisms.

Nowadays, mathematical modeling of turbulent flows is substantially complicated, particularly when they are two-phase, as the Navier–Stokes equations governing a liquid flow are nonlinear, which makes it necessary to average them to simplify numerical calculations. Nevertheless, the averaged equations remain unclosed and, therefore, the use of empirical considerations is required to solve the closure problem. The further development and verification of modern closure models are impossible without thorough and detailed information on distributions of various characteristics of both
continuous and dispersed phases measured simultaneously, time dynamics of the dispersed phase associated with the downstream evolution of large-scale vortices, interaction of small-scale turbulence with individual dispersed inclusions and so on that can be initially gathered only in systematic and accurate experimental studies using advanced whole-field measurement techniques with a high spatial and temporal resolution.

Presumably, the most convenient and promising tool to investigate bubbly flows is presently Planar Fluorescence for Bubbles Imaging – PFBI [1, 2] since it allows local visualization of round bubbles in the same section illuminated by a laser light sheet as that employed for PIV measurements. Thus, using a combination of PIV, PFBI and PTV methods, it is possible to estimate simultaneously instantaneous planar distributions of velocities and its fluctuations of continuous and dispersed phases as well as local void fraction within a flow region of interest, including joint correlations of fluctuations of different quantities for the both phases up to the third-order statistical moments. According to [1], the PFBI technique can be hardly applied to study bubbly flows with the volume gas fractions higher than 2%. Nevertheless, this limitation is less rigorous compared to the one for other optical methods for bubbly flow diagnostics (typically about 1%) and does not seem so critical for the present research.

In the paper, bubbly free and impinging round jets are studied experimentally at the Reynolds number Re = 12,500 for several gas volume fractions \( \beta = 0, 1, 2\% \) and the same mean bubble size of roughly \( D_B = 0.8 \text{ mm} \) by means of a combination of high-speed particle image velocimetry and planar fluorescence for bubbles imaging approaches. We report here on a visual analysis of high-speed images registered by a shadow photography technique to determine the mean bubble size, bubble spatial distributions as well as on PIV measurements of spatial distributions of instantaneous flow velocity, with a special emphasis put on the effect of the dispersed phase on the mean flow field and its turbulent fluctuations.

2. Experimental conditions and measurement techniques

The bubbly free and impinging submerged round jets were reproduced in the hydrodynamic rig in Kutateladze Institute of Thermophysics SB RAS. The experimental setup is of closed type and continuous operation. Its test section is made of organic glass with the following dimensions (HxWxL): 425x300x300 mm (see Fig. 1). The operating fluid was distilled water which was driven by a centrifugal pump equipped with a control module to vary the rotor speed. The liquid volume rate was measured by an ultrasonic flowmeter. The water temperature was maintained constant at 30±0.1 °C in the test section by means of a thermostatic regulator filled with tap water as a heat-transfer agent and containing a tubular electrical heater, cooling circuit and aquarium pump to permanently blend the heat carrier. Cooling and heating in the thermostat was implemented by a PID-control system activating an electromagnetic valve to start/stop the coolant supply to the cooling circuit and a switching relay to loop/break the electric line to the heater. The liquid temperature was measured by heat-variable resistors placed in the test section, heat exchanger and settling tank.

The bubbly upward jets were formed by a round converging nozzle of 110 mm height with an inner diameter at its outlet edge \( D_N = 15 \text{ mm} \). The ratio of the inlet cross-section area of the nozzle to the outlet one was 16. In case of the impinging jet, the distance between the nozzle outlet and the impingement surface was \( H = 3D_N \). The Reynolds number based on the superficial liquid velocity \( V_0 = 4 \cdot Q_w/(\pi \cdot D_N^3) = 0.663 \text{ m/s} \), where \( Q_w \) is the water volume rate (measurement error is 2%), and \( D_N \) equaled to Re = 12,500. In order to saturate the flow with bubbles, an air-water mixer of a special design was used to provide a quasi-monodisperse size distribution of air bubbles. The air was supplied to the mixer by a compressor through a couple of filters of rough (5 µm) and fine (0.01 µm) cleaning. The air overpressure at the mixer inlet was specified by a high-precision reducer in the range of 9.8–19.6 kPa depending on the air volume rate \( Q_A \). The air temperature, pressure and volume rate were measured together by a thermal mass flowmeter (TSI model 4140) with the measurement uncertainties 0.1 °C, 0.1 kPa and 2%, respectively. The length of a stainless steel pipe with 20 mm inner diameter between the nozzle and mixer was 0.56 m. Different values of the ratio of air volume rate to the full...
flow rate $\beta = Q_a/(Q_a+Q_b)$ in the jet flows were achieved by changing $Q_a$ using a needle valve. In experiments, $\beta$ possessed three values: 0, 1 and 2%. The mean diameter of the air bubbles $D_B$ was approximately 0.8 mm for all $\beta$.

Figure 1. A photograph of the test section of the hydrodynamic rig in IT SB RAS. The nozzle in configuration of the impinging jet is visible inside the test section. The flow is illuminated by the laser light.

In order to implement the shadow photography technique, a 100 W white LED-lamp with a diffusive screen for uniform illumination placed at the distance of 330 mm to the measurement section was utilized as a continuous backlight source. The bubble patterns were recorded by a Photron FASTCAM SA5 CMOS-camera (digit capacity 12 bits, resolution 1,024x1,024 pix., acquisition rate 7 kHz) equipped with a Nikon AF Micro-Nikkor 60 mm f/2.8D lens. For planar fluorescence imaging (PFBI approach), the water was merged with Rhodamine 6G as a fluorescent dye, the concentration of which was very low (about 20 µg/l). So, the water properties, especially its viscosity and surface tension, can be considered unchanged. In order to illuminate and register the bubbles suspended in the flow, a PIV system with a high temporal resolution consisting of a pulsed Nd:YAG Photonics Industries DM-532-50 laser (wavelength 532 nm, repetition rate 15 kHz, pulse duration 10 ns, pulse energy 15 mJ), Photron FASTCAM SA5 camera with the same lens as in the SP method and a low-pass optical filter (transmission edge at 570 nm) and Berkeley Nucleonics Corporation pulse/delay generator (model 575) for external synchronization was employed. The distance between the camera and the measurement section that passed through the jet axis was roughly 360 mm. The thickness of a laser light sheet was about 0.8 mm. The plane dimension of the measurement region was approximately 63.5x63.5 mm. In the experiment, the recording rate was 2 kHz. As bubbles illuminated by a laser light produce bright glares in images and, thereby, contaminate raw PIV data, a laser-induced fluorescence (LIF) approach was applied to avoid their undesirable effect on the measurements. For this, fluorescent seeding particles made of polymethyl methacrylate filled with Rhodamine B of MicroParticles GmbH production (hydrophobic, size distribution 1–20 µm, wavelength range 550–700 nm) were added into the operating liquid for PIV measurements.

The raw data (a series of 10,000 PFBI snapshots for each regime) gathered continuously during 5 seconds were processed using a PC with “ActualFlow” software [3]. At first, two procedures, namely subtraction of the mean two-frame intensity field averaged over the whole sample range and masking, were successively applied to enhance the quality of the registered images and to remove the areas corresponding to the nozzle and shadows from the subsequent calculations. Velocity fields were calculated using the iterative cross-correlation algorithm with a continuous window shift and deformation and 75% overlap between the interrogation windows. In addition, at this step of processing the local particle concentration was accounted for. In order to have a relatively large dynamic range, the initial size of the interrogation window was chosen to be 64x64 pixels but it was subsequently reduced so that the final interrogation window was 8x8 pixels, which provided a high enough spatial resolution. The obtained instantaneous velocity vector fields were then validated with the following procedures: peak validation with the threshold of 2.0, adaptive median 7x7 filter and cluster validation with the coefficient of 50 (the details of PIV data processing can be found in [4]).
3. Results and discussion

In this section, some selected results of the experimental study of submerged round free and impinging bubbly jets are presented. We give a brief discussion of instantaneous images from the high-speed visualization by the PFBI approach in comparison with those for shadow photography (SP) technique followed by downstream evolutions of the mean velocity and turbulent fluctuations for the continuous phase extracted from the PIV measurements.

3.1. Bubbly free jet

Figure 2 shows jointly examples of the PFBI and SP visualization of the bubbly free jet for the same flow regime to facilitate a comparison between the methods. The bubble patterns in the SP images are highly overlapped even when the volume gas concentration is relatively low ($\beta = 1\%$, not shown). In case of $\beta = 2\%$ (Fig. 2-a), it becomes extremely difficult to correctly distinguish individual bubbles in some flow regions. This occurs because, in SP approach, all bubbles situated in the flow region of interest and coming into the view of the camera (i.e. located along its line of sight) are registered. An application of the PFBI method allows overcoming of this problem. In PFBI images (Fig. 2-b), the bubble patterns are also overlapped but they look indeed differently. The bubbles intersecting the measurement section produce bright rings with sharp borders (in-focus), while the intensity of those patterns formed by the bubbles somewhat shifted from the measurement section is noticeably reduced and their edges become blurred (out-of-focus) (see Fig. 2-b). Taking this into consideration, one can recognize in-focus overlapping bubbles by applying sophisticated algorithmic approaches for their identification, e.g. the correlation procedure [1].

Figure 2. Instantaneous photos of the initial region of the free bubbly jet captured by the (a) shadow photography and (b) PFBI techniques for the volume gas fraction $\beta = 2\%$. The nozzle outlet is at the bottom of images. The flow direction is upward. Small bright spots in the PFBI image are fluorescent tracer particles employed for the PIV measurements.

The measured mean velocity distributions of the carrier phase are presented in Fig. 3 at four cross-sections $z/D_N = 0.5, 1.5, 2.5 \text{ and } 3.5$. The jet core was found to break up at approximately $z/D_N = 3$. In the single-phase flow, the mean liquid velocity profile, being flat at the nozzle outlet, gradually slopes and expands laterally downstream (Fig. 3a), so that initially stagnant water becomes disturbed at the distance of $r/D_N = 1$ from the jet axis in the cross-section $z/D_N = 3.5$. The mean velocity $V_z/V_0$ along the jet axis diminishes slowly downstream and equals to 1.05 at $z/D_N = 0.5$ and 1.03 at $z/D_N = 3.5$. In case of the two-phase flow, the mean velocity profiles are similar to the ones for $\beta = 0\%$ but, in the initial flow region, the jet core is substantially reduced: its width does not exceed $0.6D_N$ at $z/D_N = 0.5$, while it is equal to $0.9D_N$ in the single-phase jet at the same cross-section (see Fig. 3a). The mean velocity on the contrary increases in the jet core with the void fraction by 4% and 6% for $\beta = 1\%$ and 2%, respectively. The discrepancy in the $V_z$ profiles decreases downstream and, at $z/D_N = 2.5$, the distributions become quite similar for all $\beta$ so that the velocities differ less than by 1%. However, further downstream the maximum velocity drops faster in the bubbly flow rather than in the single-phase one. When $\beta = 2\%$, the maximum of $V_z/V_0$ at $z/D_N = 3.5$ is below by 5% as compared to that for $\beta = 0\%$ (Fig. 3a).
In the single-phase case, the crosswise turbulent fluctuations at the nozzle edge \((z/D_N \approx 0)\) are sufficiently suppressed \(\langle \nu_r^2 \rangle / V_0^2 \sim 0.001\), Fig. 3b) whereas the amplitude of the streamwise ones is relatively high \(\langle \nu_z^2 \rangle / V_0^2 \approx 0.055\) (Fig. 3c). This is because the longitudinal velocity fluctuations develop inside the supply duct but the transverse ones are conversely reduced when the flow is contracted by the nozzle. Downstream, \(\langle \nu_r^2 \rangle\) begins to grow rapidly in the jet mixing layer starting from \(z/D_N \approx 0.25\) and reaches its maximum of 0.035\(V_0^2\) at \(z/D_N \approx 0.8\) but, further downstream, it decays down to 0.015\(V_0^2\) at \(z/D_N \approx 3\) (where the jet core breaks up) and then remains constant (Fig. 3b). \(\langle \nu_z^2 \rangle\) oppositely declines gradually with an increase of \(z/D_N\) until it takes the constant value of 0.035\(V_0^2\) at \(z/D_N \approx 3\) (Fig. 3c).

The gas injection modifies this behavior of the turbulent characteristics noticeably. In the two-phase jet with both \(\beta = 1\) and 2\%, \(\langle \nu_r^2 \rangle\) rises quickly downstream from the very nozzle edge up to 0.015\(V_0^2\) for \(\beta = 1\%)\) and 0.012\(V_0^2\) for \(\beta = 2\%)\) at \(z/D_N \approx 0.55\) because the bubbles force the flow turbulization in their wakes. However, further downstream they conversely suppress the turbulence so the amplitude of the transverse fluctuations does not change. The longitudinal fluctuations are also affected by the bubbles in a similar way: they are higher at the nozzle edge in the bubbly jet \((\langle \nu_z^2 \rangle / V_0^2 \approx 0.085)\) than the ones for the single-phase flow but drop very fast downstream to \(\langle \nu_z^2 \rangle / V_0^2 \approx 0.025\) at \(z/D_N \approx 0.45\) (Fig. 3c).

Figure 3. Downstream evolution of velocity characteristics of the continuous phase in the free bubbly jet at different void fractions: (a) the streamwise component of the mean velocity at four cross-sections and time-averaged squares of velocity fluctuations in the (b) transverse and (c) longitudinal directions along the jet mixing layer \((r/D_N = 0.5)\). \(z\) and \(r\) are axial and radial coordinates, respectively. The reference point \((z/D_N = 0, r/D_N = 0)\) is at the centre of the nozzle outlet.

3.2. Bubbly impinging jet
The mean liquid velocity decreases rapidly along the jet axis \((r/D_N = 0)\) when the flow approaches the stagnant point at the wall (e.g., at \(z/D_N = 2.9\), it equals only to 0.2\(V_0\), see Fig. 4a). The gas injection does not almost affect it in this longitudinal section though the buoyancy force acts on the bubbles and, thereby, the bubbles might accelerate the carrier phase (but this is not the case). Along the impingement surface \((z/D_N = 2.9)\), the mean velocity magnitude \(V\) initially increases progressively with \(r/D_N\) up to 0.78\(V_0\) at \(r/D_N = 0.85\) as a result of the flow deflection due to the wall influence but then declines monotonously (by the law of 1/\(r\)) because of the flow expansion. The bubbles in general diminish \(V\). This effect is not notably pronounced for \(\beta = 1\%)\) but clearly seen for \(\beta = 2\%)\) (Fig. 4a) so that the maximum of \(V = 0.61V_0\). The radial component of turbulent fluctuations gradually grows with
in the single-phase jet. It becomes by an order of magnitude greater (\langle v_r^2 \rangle/V_0^2 = 0.03) at \( r/D_N = 2 \) as compared to \( \langle v_r^2 \rangle/V_0^2 = 0.003 \) at \( r/D_N = 0 \). The dispersed phase does not substantially change the intensity of the radial fluctuations at the jet axis (they reach only \( \langle v_r^2 \rangle/V_0^2 \approx 0.005 \) for both \( \beta = 1\% \) and 2\%, Fig. 4b) but increases the amplitude of the axial ones (not shown) from \( \langle v_z^2 \rangle/V_0^2 = 0.004 (\beta = 0\%) \) to 0.008 (\( \beta = 2\% \)). The main difference between the single- and two-phase impinging jets is that the bubbles cause the appearance of a maximum in the radial velocity fluctuations at \( r/D_N = 0.7 \) (\( \langle v_r^2 \rangle/V_0^2 = 0.035 \) and 0.05 for \( \beta = 1\% \) and 2\%, Fig. 4b). Downstream, the fluctuations decay so that behind \( r/D_N = 1.2 \) no considerable discrepancy between the one- and two-phase jets can be observed.

Figure 4. Downstream evolution of velocity characteristics of the continuous phase in the impinging bubbly jet close and parallel to the wall (\( z/D_N = 2.9 \)) at different void fractions: (a) the modulus of the mean velocity and (b) time-averaged square of velocity fluctuations in the radial direction. The coordinate system is the same as in Fig. 3.

4. Summary
The bubbly free and impinging jets with void fractions up to \( \beta = 2\% \) and the mean bubble size of 0.8 mm were studied by the PIV and PFBI methods at the Reynolds number \( Re = 12,500 \). Under such conditions, in case of the free jet, the air bubbles were found to reduce substantially the transverse dimension of the jet core (more than by 30\% at \( z/D_N = 0.5 \)) and cause a faster growth of the radial component of turbulent fluctuations in the mixing layer from the nozzle edge up to the distance of \( z/D_N \approx 0.55 \) but suppress them about two times further downstream as compared to the single-phase flow. In the impinging jet flow, the bubbles produce a maximum of the radial liquid velocity fluctuations near the wall at \( r/D_N = 0.7 \) which is absent in the single-phase jet.

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