Bubbles Effect on Turbulence in Free and Confined Jet Flows

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Abstract The present work is devoted to the deterministic experimental study of gas-saturated free and impinging turbulent jets by PIV and PTV techniques and by a novel Planar LIF imaging approach for diagnostics of gas-liquid flows with round bubbles. The combined application allowed to obtain spatial distributions of instantaneous liquid and gas velocity, and local void fraction for two-phase bubble flows. Spatial distributions of statistical characteristics were obtained including third-order moments. The influence of the gas phase parameters on the hydrodynamic structure of the studied flows is demonstrated. Opposite effects of bubbles on turbulence were found in the impinging jet flow: in the mixing layer of the jet, turbulent fluctuations become suppressed with increase of the volumetric gas content, while in the near wall regions significant increase of the fluctuations was observed.

1. Introduction
Two-phase bubble flows are frequently encountered in nature and many industrial applications: absorption devices, evaporators, scrubbers, air lifting pumps. In cavitation, aeration, flotation processes dispersed gas phase plays a key role. The mutual effect of continuous and dispersed phase is now widely acknowledged: the bubbles (particles) trajectories are influenced by the local non-equilibrium turbulence of the fluid phase (turbulent dispersion) and the motion of bubbles and their agglomerates has an impact on the fluid phase turbulence (turbulence modulation) due to a number of physical mechanisms. During modeling of multiphase flows, temporal, spatial and ensemble averaging are the most used averaging techniques. In general, averaged equations remain non-closed that makes necessary the use of closure models. Development and verification of modern approaches for simulation of sufficiently anisotropic turbulent multi-phase flows, such as Reynolds-Stress Models, requires comprehensive experimental information to be retrieved. The mixed correlations of liquid velocity-void fraction (including the third-order moments) are of a special interest in this case. However, for estimation of such data, simultaneous measurements of the liquid phase velocity and dispersed phase distributions are required that represent very complex experimental task.

Starting from the works by Serizava et al. (1975) and later, Lance and Bataille (1991), there are a lot of experiments presented in literature on the studying of reduction or enhancement of turbulence by bubble dispersed phase. Most of them, however, consider pipe flows or bubble columns and are restricted by estimation of distributions of mean and RMS velocities, dispersed phase fraction and sizes. Mutual interaction of the gas phase and large-scale eddies can significantly affect turbulent structure of the free-shear flow such as jets. At the moment there is a lack of comprehensive experimental data on turbulent structure of gas-saturated shear layers (including jet flows), which occur in a number of practical applications. One of the latest works that could be mentioned is a paper by Rightley and Lasheras (2000) where the planar free shear layer saturated with bubbles was investigated experimentally. The emphasis was done on the role of large scale vortex structures in the bubble dispersion and the energy redistribution within the carrier phase.

At the moment, there is a number of non-intrusive optical techniques for two-phase flows planar diagnostics. PIV/LIF technique exploiting fluorescent tracers combined with Shadow technique
(ST) is utilized extensively for measurements in bubble flows (e.g. Tokuhiro et al. 1998, Lindken and Merzkirch 2002). ST provides shapes and locations of bubbles for flows with relatively low gas content. One of the main problems faced in ST is bubbles overlapping. Also, planar Global Phase Doppler and Interferometric Particle Imaging techniques should be mentioned which are based on out-of-focus imaging and work well for relatively low concentrations and sizes of bubbles/droplets (Damaschke et al. 2002).

The present work is devoted to the deterministic experimental study of the gas phase effect on the structure of the free and impinging turbulent jets saturated with quasi-monodisperse round bubbles. The measurements were performed by the combined application of PIV, PTV and a developed PLIF imaging technique.

2. Experimental setup and measurement system

Measurements were performed in a plexiglass working section (400 mm height, 200 mm width, 200 mm length) which was the part of a closed hydrodynamic loop. The loop was equipped with a pump which rotation speed was controlled by an inverter and a flowmeter. 10%-ethanol solution in distilled water was used as a working liquid and a thermostat was utilized to maintain fluid temperature constant of 30±0.5 °C. Free and impinging jet flows were organized by a contraction nozzle with the outlet diameter \( d = 15 \) mm. In the latter case, an impinging surface was mounted at the distance \( H = 3d \) from the nozzle exit. Schemes of the jet flows are presented in Figure 1b and c. The flow Reynolds number defined on the basis of a mean flow rate velocity \( U_0 = 0.93 \) m/s, the nozzle diameter \( d \), and kinematic viscosity \( \nu \) was equal to 12,000. To introduce air phase into the flow, a compressor was used to provide supply of the air, whose parameters were controlled by a thermometer, a manometer and by a mass-flowmeter. A special design of bubble generator provided close-to-monodisperse distribution of bubbles by size. The jet flows were studied with three values of gas content: \( \beta = 1.2\%, 2.4\% \) and \( 4.2\% \), and three mean bubble diameters: \( D_b = 0.6, 0.85 \) and \( 1.1 \) mm. An example of bubbles distribution obtained by means of a shadow technique for \( \beta = 2.4\% \), \( D_b = 0.85 \) mm case is presented in Figure 3a.

A “PIV-IT” PIV-system consisting of a double-pulse Nd:YAG laser (532 nm, pulse duration 10 ns, 50 mJ energy per pulse), CCD camera (8bits, 1240×1024 pix) and a synchronization device was used for the measurements. The system was operated by a computer with “ActualFlow” software. A laser sheet was formed by a cylindrical lens and its thickness was about 0.8 mm in the measurement area. Fluorescent tracers (mean diameter of 20 µm, the range of emission wavelength 550-700 nm) were added into the flow for carrying out PIV measurements. For shadow technique (ST) approach, a synchronized stroboscope with LED-array (100 diodes with the range emission wavelength 475±25 nm) was used. The duration of stroboscope pulse was of 10 µs. A diffuse screen was placed in front of the stroboscope matrix to achieve uniform background intensity. Band-pass filter with
450-500 nm bandwidth and high pass filter with a steep transmission edge at 560 nm and a couple of Micro Nikkor 60 lenses were used during the measurements and tests. In order to provide high enough spatial resolution (0.576 mm interrogation area size) the whole measurement area was separated into four elementary zones where the measurements were performed independently (see Figure 1b and c). For each zone, relatively high number (10,000) of image pairs was recorded to provide sufficient number of events for bubble statistics calculation.

3. PLIF approach and calibration procedure

The proposed PLIF technique is based on a fluorescent dye (Rhodamine in the present study) admixture to the working fluid. When the laser light in the form of sheet passes through the mixture, the dye re-emits as a plane with a fixed thickness. By using corresponding optical filter the emission of the fluorescent dye only is captured by a camera while the laser light, leading to flares produced by bubbles, is suppressed by the filter. Bubbles located close to the laser sheet plane form a bright ring in the image (see Figure 2a) by reflecting and refracting the light emitted from the dye. During the test application of the PLIF approach and Shadow Technique to individual bubbles it was found experimentally that the ratio between the ring diameter and actual bubble size is 1.38. The PLIF approach for bubbles diagnostics was combined with PIV in order to measure fluid flow velocity. This was done by adding fluorescent particles, which were registered as dots together with the rings from the bubbles at the same image.

![Figure 2. (a) Shadow image and (b) PLIF image of the bubbles issuing from the nozzle. (c) Liquid-phase velocity field and distribution of in-focus bubbles measured with PLIF approach. Re = 12,000; \( \beta = 2.4\% \); \( D_b = 0.85 \) mm](image)

In the present work an iterative cross-correlation algorithm with an image deformation (interrogation area size: 32´32 pixels, 50% overlap) was used for liquid velocity estimation. Then the vector fields were validated and outliers (including those caused by opacity from out-of-focus bubbles) were removed. At the first stage the signal-to-noise criteria was applied. If the highest cross-correlation peak is two times lesser than the second one, the vector is considered as outlier. At the second stage an adaptive 7´7 median filter (Westerweel and Scarano 2005) was used. For the estimation of bubble velocities, a PTV approach was applied. The pair-matching algorithm in PTV is based on the correlation similarity of bubble images in a pair. After that, the obtained vectors of bubble image displacements are refined using the correlation correction method described in Theunissen et al. (2004). In contrast to the previous work of Akhmetbekov et al. (2007), where the bubbles were identified by application of a derivative procedure, binarization and search of linked areas, in the present work the bubbles were identified by a cross-correlation approach allowing to distinguish overlapping bubbles. General steps of the applied approach are shown in Figure 3. First, cross-correlation functions of the initial image with a test function were calculated for various sizes of the test function. The test function represented a ring of a certain size with a Gaussian distribution in a radial cross-section. Then, the cross-correlation functions were averaged and the
The final correlation plane was estimated (see Figure 3b). Further, the bubbles were identified via binarization procedure and their positions were estimated with sub-pixel accuracy by approximating the cross-correlation maximum by a Gaussian fit. The bubble radii were estimated via additional cross-correlation of the initial image with the test functions located in the estimated positions (Figure 3c). At the final stage the out-of-focus bubbles, which were located far from the laser sheet were removed by analyzing width of the cross-correlation maximum (Figure 3d).

![Figure 3. General steps of cross-correlation procedure for bubbles identification. (a) Initial image; (b) averaged cross-correlation plane; (c) positions and sizes of the identified bubbles; (d) in-focus bubbles.](image)

Finally, combined statistics for the void fraction, carrier, and gas phase velocities was calculated. For this purpose spatial averaging of the gas phase velocity and local void fraction was done with the parameters (i.e. size of averaging areas and percentage of their overlap) similar to cross-correlation in PIV. For the regions where bubbles were not found and the liquid phase velocity vector was identified as outlier, local void fraction $\alpha$ was considered to be unknown. Vectors of fluid velocity, for which 100% of the IA lays inside any of identified bubbles, were not considered during the statistics calculation.

To determine typical minimal distance from the bubble to the laser sheet for which the bubble was not considered to be out-of-focus and, thus, it was used in the statistics calculation, the proposed PLIF technique was calibrated by means of ST (see Akhmetbekov et al. 2007 for details). For this purpose, two cameras (each one was equipped with an appropriate filter) were used for simultaneous measurements of individual rising bubbles. Identical optical paths were achieved by using a system of a semi-transmitting mirror and reflecting mirror. The measurements were performed in the vicinity of a bubble emitter. During the tests, the distance $L$ from the cameras to the object was varied, as well as the distance $h$ from the laser sheet (focus plane for ST) to the emitter. Figure 4 demonstrates that typical ST depth of averaging (where the bubbles were identified) increases as square of $L$ and is similar to the depth of field of the lens used. For PLIF technique the depth of averaging is significantly smaller and tends to near-constant value for a large $L$ (where the lens depth of field was great). Additionally, by varying laser power, it was found that the diaphragm effect is insignificant for high values of $L$.

![Figure 4. PLIF and ST typical depth of averaging for various camera lens to object distance in comparison to the lens depth of field.](image)
The proposed PLIF based method exhibits several advantages in comparison with ST. Its depth of averaging does not depend essentially on the distance to the object if the depth of field of lens is high enough. Thus, the PLIF technique is rather local. Maximum level of gas contents at which the PLIF method can be implemented is noticeably higher comparing to ST. Additionally, the PLIF approach can be used simultaneously with PIV in case when the smallest bubble size significantly exceeds the size of the tracers, or by using two different fluorescent dyes.

4. Results and discussion
The present section describes the results of combined application of PIV, PTV and PLIF approaches for the free and impinging jets study. The effect of the dispersed gas phase on the jet structure is considered in details for the various volumetric gas content and mean bubbles size. For each measurement zone and for each experimental case, 10,000 instantaneous velocity fields of the liquid phase were calculated together with spatial distributions of the bubbles’ positions, size and velocity. After application of spatial averaging for the gas phase, spatial distributions of the statistical moments for the liquid and bubbles velocity, and local void fraction were estimated.

4.1. Free jet flow
Figures 5a and b show the examples of spatial distribution of the axial mean velocity of the liquid and gas phases, respectively, for the free jet at the highest studied volumetric gas content, i.e. $\beta = 4.2\%$. The distributions were found to be rather similar and magnitude of the bubbles velocity, $U_b$, was greater in magnitude due to buoyancy force.

Spatial distribution of the mean local void fraction $\langle \alpha \rangle$ is presented in Fig. 5c. One can observe that in the initial region of the flow, $\langle \alpha \rangle$ is quite uniform in the jet core. However, locally great value $\langle \alpha \rangle \approx 0.4$ can be observed at $r/d \approx 0.5$ $z/d \approx 0.2$ location. It was considered that this maximum is partially caused by non-uniform bubbles distribution inside of the pipe preceding the contraction nozzle. Downstream evolution of $\langle \alpha \rangle$ demonstrates fast decay of the peak and the distributions of mean void fraction become more uniform. Besides, the spatial distributions of the mean velocity
and local void fraction, second-order moments of in-plane velocity fluctuations (axial and radial components) were measured, as well. Figure 5d shows the spatial distribution of the axial component \(\langle u_b^2 \rangle\). One can observe that the second-order moment reaches a maximum value in the initial region of the flow near position of \(\langle \alpha \rangle\) maximum. Further downstream, high values of \(\langle u_b^2 \rangle\) are observed at the jet mixing layer where the fluctuations of the liquid phase (for both one-phase and two-phase jet flows) were high.

It was found that the influence of the bubbles presence on the mean velocity of the liquid phase was found to be rather low (increase of \(\beta\) caused greater values of \(U\), while the shape of the distributions was almost unchanged). However, the influence of the bubbles on turbulent characteristics of the liquid phase was found to be more pronounced. As an example, the distributions of radial component of turbulent kinetic energy of the liquid phase are presented in Figure 6 for the various value of \(\beta\). Increase in volume gas content (bubble diameter was maintained at \(D_b = 0.85\) mm) significantly affected the development of the shear layer. One can observe that values of \(\langle u_l^2 \rangle\) decrease in the initial region of the jet and maximum of \(\langle u_l^2 \rangle\) shifts upstream. At the same time, no significant distinction was observed at the edge of tested area (\(z/d \sim 4\)). Moreover, comparing second-order moments of velocity fluctuations for the liquid and gas phases at the far region of the flow at \(\beta = 4.2\%\), one can clearly observe strong correlation between the moments. Thus, one can conclude that far downstream the bubbles velocity fluctuations are mainly governed by the liquid turbulence, while the bubbles effect is the most pronounced in the initial region of the mixing layer.

![Figure 6](image URL)

Figure 6. Spatial distributions of the radial component of TKE of liquid for free jets at \(Re = 12,000\) and \(D_b = 0.85\) mm; (a) \(\beta = 0\%\); (b) \(\beta = 1.2\%\); (c) \(\beta = 2.4\%\); (d) \(\beta = 4.2\%\).

Figure 7a shows profiles of \(\langle u_l^2 \rangle\) along the jet shear layer \((r/d = 0.5)\) for various volumetric gas content \(\beta\). In all cases exponential grows with \(z\) is observed. However, the presence of the bubbles results rapid increase of \(\langle u_l^2 \rangle\) in the vicinity of the nozzle edge \((z < 0.1d)\). Downstream, the growth is less pronounced and one can conclude that values of \(\langle u_l^2 \rangle\) are inversely proportional to \(\beta\). This fact can be explained by additional influence of turbulence enhancement mechanisms by large bubbles (wakes behind the bubbles, oscillation of interface, etc.). Similar comparison is shown in Figure 7b for the same \(\beta\), but different mean diameter of the bubbles. One-phase flow is also shown for comparison. The effect of the bubble size is observed in the initial region of the jet and it
becomes less pronounced downstream. Comparatively higher growth rate of the radial component of TKE is observed with decrease of the bubble size. Besides, comparing Figure 7a, showing the results for the different $\beta$ but the same bubble size it is clear that for the studied range of $\beta$ and $D_b$ only the bubble size noticeably affects the growth rate of TKE in the initial region of the jet.

The examples of the third-order moments spatial distributions, namely $\langle u_l^3 \rangle$, corresponding to the radial flux of the radial component of turbulent energy, are presented in Figure 8 for the same flow conditions as in Figure 6. These moments are usually modeled in CFD approaches and are important to be estimated because they contribute to the turbulent diffusion of the Reynolds stresses. Similarly to $\langle u_l^2 \rangle$ distributions, the presence of the gas phase leads to significantly lesser magnitude of $\langle u_l^3 \rangle$ in the initial region of the jet, while the shape of the distributions remained unchanged. The difference between maximum values of the second- and third-order moments for single phase jet and gas-saturated jet at $\beta = 4.2\%$, can reach about 20-30% and 60-70%, respectively.

![Figure 7](image1.png)

**Figure 7.** Distribution of radial component of TKE of liquid along jet shear layer ($r/d = 0.5$). (a) Effect of volumetric gas content for $D_b = 0.85$ mm; (b) effect of bubbles mean size.

![Figure 8](image2.png)

**Figure 8.** Spatial distributions of third-order moments (liquid phase) for free jets at $Re = 12,000$ and $D_b = 0.85$ mm; (a) $\beta = 0\%$; (b) $\beta = 1.2\%$; (c) $\beta = 2.4\%$; (d) $\beta = 4.2\%$. 
4.2. Impinging jet flow

Spatial distributions of the axial component of TKE for the impinging jet are shown in Figure 9 for the various $\beta$ and the fixed mean bubbles diameter. For the initial region of impinging jet, $\langle u_l^2 \rangle$ shows similar behavior to $\langle u_l^2 \rangle$ (not shown in the present paper) and $\langle v_l^2 \rangle$ for the free jet flow: development of mixing layer at $z/d > 0.4$ is suppressed in some degree. However, opposite effect of bubbles on fluctuation intensity of the liquid phase is observed near the impinging plate. The value of $\langle u_l^2 \rangle$ for bubble impinging jet with the highest volumetric gas content has a local maximum at $z/d = 2.8$, $r/d = 0.5$. Besides, growth of $\langle v_l^2 \rangle$ values with increase of $\beta$ was observed in the near wall region (not shown in the present paper).

![Figure 9](image_url)

Figure 9. Spatial distributions of the axial component of TKE of liquid for impinging jet at $Re = 12,000$, $D_b = 0.85$ mm; (a) $\beta = 0\%$; (b) $\beta = 1.2\%$; (c) $\beta = 2.4\%$; (d) $\beta = 4.2\%$.

Figure 10 demonstrates the effect of the bubbles on the third-order moment $\langle u_l^3 \rangle$ of the liquid phase velocity fluctuations. Similarly to $\langle u_l^2 \rangle$, increase of $\beta$ leads to decrease of $\langle u_l^3 \rangle$ magnitude between the jet nozzle and impinging plate. Similarly, great magnitude of $\langle u_l^3 \rangle$ is observed near the wall, where $\langle u_l^2 \rangle$ is high.

To demonstrate the effect of the bubbles on the asymmetry of velocity fluctuations of the liquid phase, skewness factor of $u_l$ was calculated for the most representative cases of the volumetric gas content, namely $\beta = 0$ and 4.2%. The skewness distributions are shown in Figure 11. The main difference between these two cases can be observed in the initial region of the jet mixing layer.
$z/d < 0.5$ and near the stagnation point. One should note that in spite that the highest magnitudes of $\langle u_l^2 \rangle$ and $\langle u_l^3 \rangle$ were observed at $r/d = 0.5$ and 0.3, respectively, the skewness factor is almost not affected by the dispersed phase in these regions. The most pronounced effect on the asymmetry of the liquid phase velocity fluctuation is observed near the jet axis at $0.3d$ from the impinging plate.

Figure 10. Spatial distributions of the third-order moment (liquid phase) for impinging jet at $Re = 12,000$, $D_b = 0.85$ mm; (a) $\beta = 0$%; (b) $\beta = 1.2$%; (c) $\beta = 2.4$%; (d) $\beta = 4.2$%.

Figure 11. Spatial distributions of skewness of axial velocity fluctuations (liquid phase) for impinging jet at $Re = 12,000$; $D_b = 0.85$ mm; (a) $\beta = 0$%; (b) $\beta = 4.2$%.
5. Conclusions
The present paper reports the results of the combined application of PIV, PTV and PLIF techniques for experimental study of the bubbles effect on structure of gas-saturated free and impinging jets at Re = 12,000 and the range of volumetric gas content $\beta = 0$ - 4.2%. Spatial distributions of instantaneous liquid and gas velocity and void fraction were obtained as well as the set of statistical moments (up to the third-order). It is demonstrated that the gas phase influences mainly on the turbulent structure of the flow while the averaged flow velocity remained almost unchanged. It is shown that in the initial region of the jet shear layer ($z/d < 0.2$) the introduction of the bubbles leads to a faster growth of liquid-phase velocity fluctuations. The growth rate was found to be greater for the lesser bubble size. Further downstream ($z/d > 0.3$), the bubbles presence suppressed the liquid-phase velocity fluctuations and the difference was clearly observed until $z/d < 3.5$. In this region, the suppression of turbulence intensity was found to be less pronounced for the case of larger bubbles. For the impinging jet flow, similar observations were made for the region near the nozzle exit and for the jet mixing layer. Additionally, it was found that the bubbles strongly affect turbulence characteristics in the near-wall region: magnitude of the second- and third-order moments of liquid velocity fluctuations dramatically increased with increase of the volumetric gas content. From estimated skewness factor of the liquid-phase velocity fluctuations it was found that the bubbles produce strong asymmetry of the liquid velocity fluctuations near the jet axis at 0.3$d$ distance from the impinging plate.

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References