TURBULENCE MODIFICATION IN BUBBLE IMPINGING JET

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ABSTRACT

The experimental study of local structure of axisymmetric impinging jet has been performed for single-phase and two-phase conditions. On the basis of electrodiffusion measurements of flow characteristics the analysis of jet's turbulent structure was made. The effect of external periodical forcing and gas saturation on the wall shear stress values, coherent and random components of turbulence was studied. The periodical forcing of a jet at the frequencies which lie inside the range of jet's sensitivity leads to the resonant amplification of the large-scale vortex structures in the jet shear layer. The gas saturation results to a significant increase in the average friction at the impingement surface. The coherent structures in the jet shear layer suppress strongly by small gas bubbles and at large void fractions they are not discernible in the spectral distributions.

INTRODUCTION

In the gas-liquid bubble flows the bubbles can not be simply considered just like the tracers following the flow. In contrast, the nonuniformity of the flow field can result as in dispersion of bubbles as in variation of the fluid phase pulsations level. The interaction can be mutual when the particles trajectories are affected by the local non-equilibrium turbulence of the fluid phase (turbulent dispersion) and also the movement of bubbles and the wakes past them have an impact on the fluid phase turbulence (turbulence modulation).

The substantial variation of turbulence influenced by the particles has been observed in several experimental investigations. A number of experimental data on reduction or enhancement of the turbulence due to the presence of dispersed phase is referenced in literature (Serizava et al. 1975; Wang et al. 1987; Lance & Bataille 1991). Gore & Crowe (1989) have compiled most of experimental data and presented them in the form of the particle size effect on the turbulence. They concluded that the small size particles decrease the turbulence intensity while the large size ones increase it. However, this statement of Gore & Crove appeared to be valid for the centreline turbulence intensity and was not approved when overall turbulence was tested (Davis 1993). Also Yuan & Michaelides (1992) have noted in analysis that mostly the turbulence reduction is caused by the turbulent energy dissipation under the particle acceleration in relation to the fluid phase motion whereas the turbulence enhancement is caused mainly by the flow disturbances due to the motion of particles and wakes past them. In paper Taeibi-Rahni et al. (1994) the flow in the plane free shear layer in presence of large bubbles with their size approaching to the scale of large eddies has been studied on the basis of direct numerical simulation. The results have shown that the process of eddy crossing by a bubble is the main mechanism of the flow modulation which is usually characterised by decreasing of the vortex coherence and size, by the change in the fluctuation statistics and by significant variations in pairing/merging phenomena.

To understand the role of the fluid phase structures, it is firstly necessary to pay attention to the previous investigations of the large-scale structures in the single-phase flows. Essential contribution to understanding of these processes was made in experiments with instantaneous observations. Crow & Champagne (1971) have studied the response of a circular jet on the controlled axisymmetric perturbations and found that the jet shear layer is able to maintain and amplify the organised structures. Brown & Roshko (1974) and others have shown that the large-scale structures in the single-phase mixing layer are still present for the large Reynolds numbers mainly in the two-dimensional and coherent form. The two-dimensional structures (termed eddies or braids) are the basic mechanism of entrainment for such flows and maintain the largest fraction of turbulent kinetic energy. Moreover, the large-scale structures in the single-phase plane shear layer can be effectively excited by a driving frequency to yield increased coherence and grows rates at substantial distances downstream, as it is shown by Ho & Huang (1982). Thus the evolution of the free shear layer is sensitive to perturbations at proper conditions.

One of the most interesting examples of shear flows with dispersed phase is the turbulent jet. Bubble jets have wide applications such as the direct-contact heat exchangers, the pressure-suppression devices, the gas mixing and dissolution systems, etc. The characteristics of bubble turbulent jets have been studied in many papers (Goldschmidt et al. 1971; Milgram 1983; Sun & Faeth 1986), however the mutual influence between the dispersed gas phase and the large-scale structure of shear layer was not practically considered.

This paper is devoted to the experimental study of the instabilities evolution in the axisymmetric impinging jet shear layer in presence of the small-size dispersed gas phase. The main results on the flow turbulent structure are obtained with the use of the electrodiffusion technique of the wall shear stress measurements.

DESCRIPTION OF EXPERIMENT

The sketch of impinging jet flow is shown in Fig.1, a. The experimental set-up consisted of a test section which represented the rectangular channel, made of Plexiglas, with the dimensions of 86x162x1600 mm^3, the system of pumps and flow meters, a reservoir, connecting tubes and apparatus for measurements. A well-profiled round nozzle was inserted through the side wall of a channel. The submerged round jet issuing from the nozzle impinged normally on the opposite wall (measuring plate) of the channel. The skin friction probes were placed at the measuring plate which could be

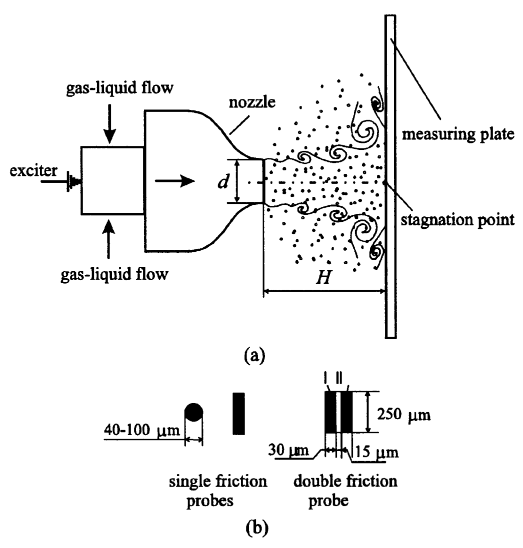

Figure 1. Sketch of impinging jet flow (a) and electrodiffusion wall shear stress probes (b)

shifted and this allowed for changing the radial position of each probe with an accuracy of 0.1 mm.

To measure the wall shear stress and liquid velocities the electrodiffusion method was applied. This method implies the use of special fluid which represents an aqueous solution having equimolar concentrations (0.01M) of potassium ferricyanide and ferrocyanide and a 0.1M-0.2M concentration of sodium carbonate. The electrodiffusion friction probes represented a platinum wire or sheet welded into the glass capillary and ground so as to be flush with the measuring plate surface (Fig.1, b). The velocity probe "blunt nose" was the platinum wire with the diameter 20-50 mm, welded into the thin glass casing. The grounded front side with the platinum circle was the probe's sensitive element. The diffusion current i in the electrochemical cell, including the microcathode (probe), large stainless steel anode and electrolyte, was related to the instantaneous values of the hydrodynamical quantities by the equations:

$$\tau = k_1 \cdot i^3 , \qquad u = k_2 \cdot i^2$$

where τ is the wall shear stress, u is the longitudinal velocity, k_1 and k_2 are the calibration coefficients.

The double friction probe (Fig1,b), proposed by Hanratty (1983) and applied for the measurements of wall shear stress in reattachment jets by Alekseenko and Markovich (1994), is intended here for determining the instantaneous value of the friction vector component along the radial direction. In the last work the details of the measurement technique are described. The electrical signals from the probes pass to the a.d. transformer through the d.c. amplifiers. A complete data processing was accomplished by a personal IBM computer. The computer program allowed us to determine the mean values of the velocity and skin friction, its rms. pulsations, spectral density of the velocity and friction pulsations and the time of existence of the flow with the given direction. For the spectral density estimation the Fast Fourier Transform technique was applied. Each array of the experimental data, which was processed by FFT, consisted of about 100 overlapped segments of 2048 points.

The excitation of flow was provided by a standard electrodynamic vibration exciter connected by the instrumentality of the siphon with the plenum chamber (Fig.1, a). The sinusoidal forcing signals destined from the generator through the power amplifier to the exciter. The initial oscillations of flow involved axisymmetric mode ($m = 0$) and their rms. value changed from $\tilde{u}/U_0 = \sqrt{\tilde{u}^2}/U_0 = 0.0001$ to 0.001 depending on the experimental conditions (these measurements were made for the single phase jet). The forcing frequency, f_f, was characterised by the Strouhal number, $\mathrm{Sh_d} = f_f \cdot d/U_0$. Test experiments showed that the imposed oscillations do not influence on flow characteristics near the nozzle edge (x/d = 0.15). In the absence of bubbles the level of natural turbulence at x/d = 0.15 was in the range of $u'/U_0 = \sqrt{\overline{u'^2}}/U_0 = 0.005 \div 0.008$ near the nozzle axis and $0.05 \div 0.06$ at the centre of shear layer. The value of

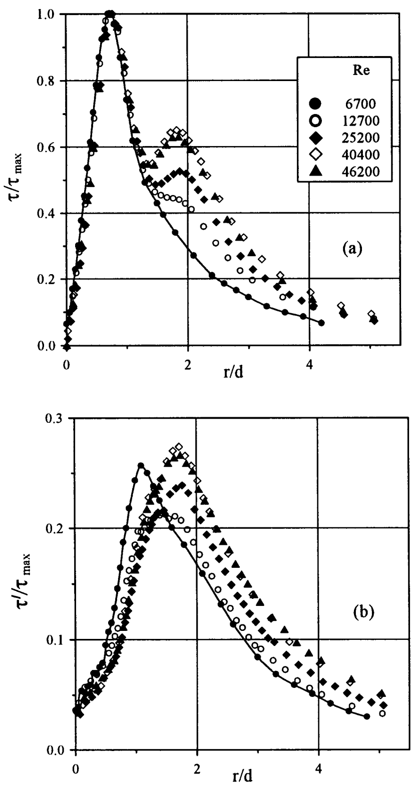

Figure 2. Distributions of wall shear stress (a) and its rms. pulsations (b) versus Reynolds number. H/d = 2; α = 0; f_f = 0.

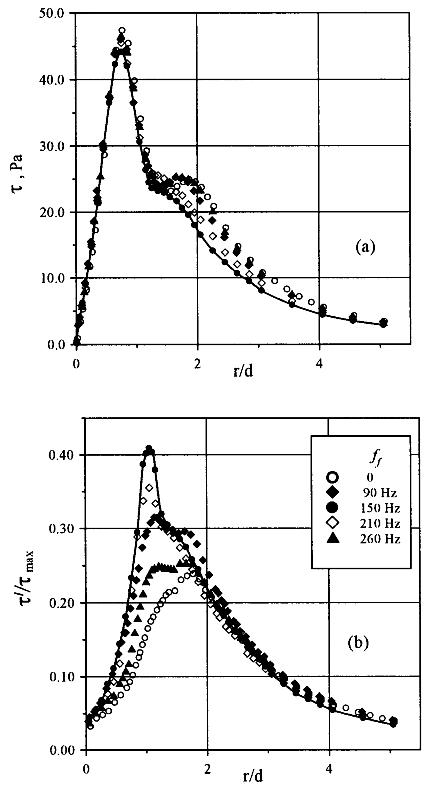

Figure 3. Distributions of wall shear stress (a) and its rms. pulsations (b) versus forcing frequency. H/d = 2; α = 0; Re = 25200.

momentum thickness θ at the nozzle exit, obtained from the measured velocity profile by the equation $\theta = \int_{r=0}^{r_{0.1}} \frac{u(r)}{u_{max}}\left(1 - \frac{u(r)}{u_{max}}\right)dr$, equals θ ≈ 0.1 mm. Here $r_{0.1}$ is the radial distance where $u(r) = 0.1 \cdot u_{max}$.

The gas (air) bubbles were supplied to the plenum nozzle's chamber from a compressor through the fine-porous plate. The air flow rate changed during the experiment from 0 to 164 l/h. For the liquid flow rate $Q_l = 0.33$ l/s (Re = 40400) this corresponds to the void fraction (gas contents) of α = 0 ÷ 12.1 %. The average bubble diameter was 200 microns and scatter in bubble dimensions was embraced as insignificant, thus the gas phase was considered as monodispersive.

During the experiments, two values of Reynolds number were tested: Re = 25200 and 40400. Here $\mathrm{Re} = U_0 \cdot d/\nu$, U_0 is the mean flow rate velocity at the nozzle exit, d is the nozzle diameter equal to 10 mm and ν is the kinematic viscosity of solution equal to $1.04 \cdot 10^{-6}$ m^2/s. The distance H between the edge of a nozzle and plate did not change in the experiments and was equal to 20 mm ($H/d = 2$).

EXPERIMENTAL RESULTS

Single-phase jet

The main results were obtained with the help of measurement of the averaged and pulsation values of wall shear stress as well as the spectral characteristics at the obstacle. These data allow us to get the information concerning the flow turbulent structure in a near-wall area. First of all, let's consider a single phase impinging jet for the case when the nozzle's edge is placed at a distance equal to the doubled nozzle's diameter from the wall ($H/d = 2$). One of the main aims of the current study is to explore how the dispersed phase (gas bubbles) effects the large-scale structures which develop in the jet mixing layer. In the case of a single phase, the large vortex structures are coherent in the area of the jet turn and attachment. That's why we chose such a distance between the nozzle and the wall. The distributions of the average and pulsation values of the wall shear stress are shown in Fig. 2 a, b depending on the Reynolds number. For the relatively low Re (Re < 10^4), the average friction increases with a distance from the critical point. Then after point with maximum friction at $r/d = 0.75$, it starts decreasing monotonously. This fact corresponds to calculations according to the laminar integral model

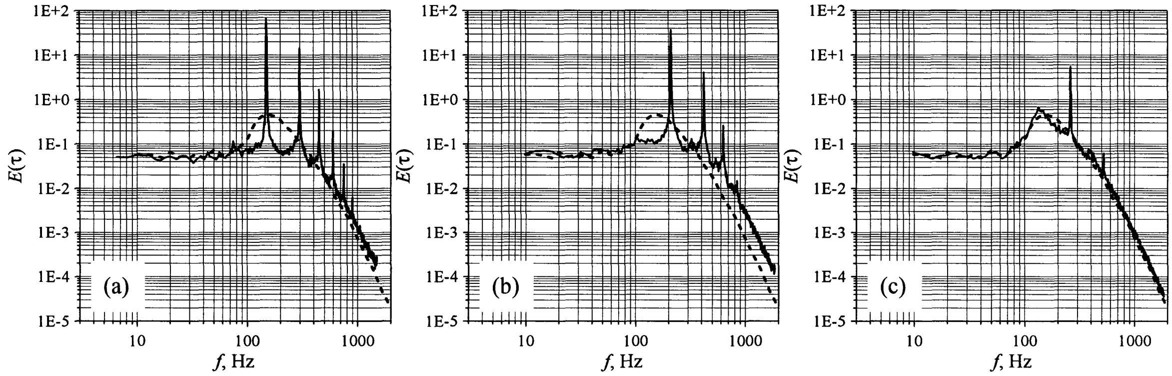

Figure 4. Power spectra of wall shear stress pulsations. Dashed lines - unforced jet, black lines - forced jet. H/d = 2; α = 0, r/d = 1.1, Re = 25200. (a) - f_f = 150 Hz (Sh_d= 0.57); (b) - f_f = 210 Hz (Sh_d= 0.8); (c) - f_f = 260 Hz (Sh_d= 1.0).

(Alekseenko & Markovich, 1994). With a rise of Reynolds number, the monotony of the friction decrease breaks in the area of r/d > 1.2, and the second small maximum appears there. As usual its appearance is caused by the change of the laminar boundary layer flow regime to the turbulent one (Baines & Keffer, 1976; Kataoka & Mizushina, 1974). The maximum of the friction pulsations shifts downward the flow from the point r/d = 1 for Re = 6700. With a further increase in Re, the wall shear stress and pulsation's profiles become self-similar. In a dimensionless form they almost coincide with each other for Re > 40000. With increase of the nozzle-to-wall distance, the distributions of the average friction change also for the high Re. For H/d > 6, the second maximum disappears because the turbulization of the boundary layer begins directly at the critical point and here the maximum of the r.m.s. pulsations takes place for given conditions.

The jet flows like the majority of the shear flows are sensitive to the external perturbations. Particularly, it is well known from Crow & Champagne (1971) and other relevant studies that if the jet shear flow is excited by the periodic acoustic or mechanical oscillations of a small amplitude with certain frequencies, one can achieve the resonant amplification of the large-scale vortex structures. Without the external forcing these structures are weak and quasi regular. For the impinging jets there are only a few works devoted to the development of instabilities under the effect of external oscillations (Ho & Nosseir, 1981; Alekseenko et al., 1997).

The distributions of the wall shear stress and r.m.s. friction pulsations are shown in Fig. 3 a, b for the excited impinging jet versus the forcing frequency. It was already mentioned in our previous work (Alekseenko et al., 1997) that if the forcing is carried out at a frequency which is close to the frequency f_{mp} (the most probable frequency for given conditions), the coherent structures would resonantly enhance at this frequency. In the case of Re = 25200 the sensitivity range is $120 < f_f < 210$ Hz ($0.45 < Sh_d < 0.8$), where f_f is the forcing frequency. The excitation at the most probable frequency $f_f = f_{mp}$ = 150 Hz (Sh_d = 0.57) leads to a 30% and more decrease of friction. The pulsation's level is increased twice, mainly due to the growth of the coherent component. Thus, in a zone of intense penetration of the structures into the near-wall area, the spectral density of pulsations at the resonant frequency sharply increases and becomes in two orders of magnitude larger to compare with undisturbed jet (see Fig. 4, a, b). The second friction maximum disappears under the resonant regimes. The

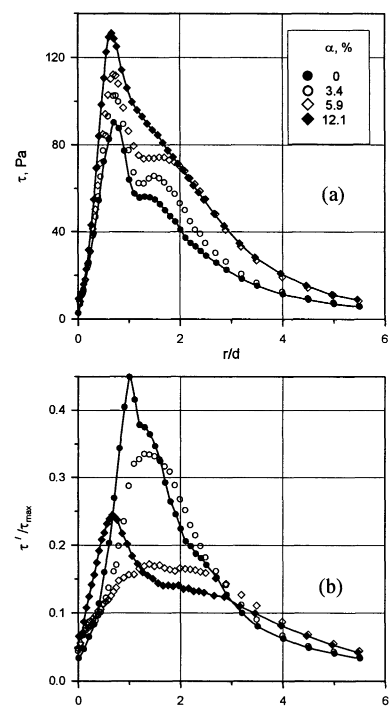

Figure 5. Distributions of wall shear stress (a) and its rms. pulsations (b) versus void fraction. H/d = 2; Re = 40400; f_f = 250 Hz (Sh_d = 0.6).

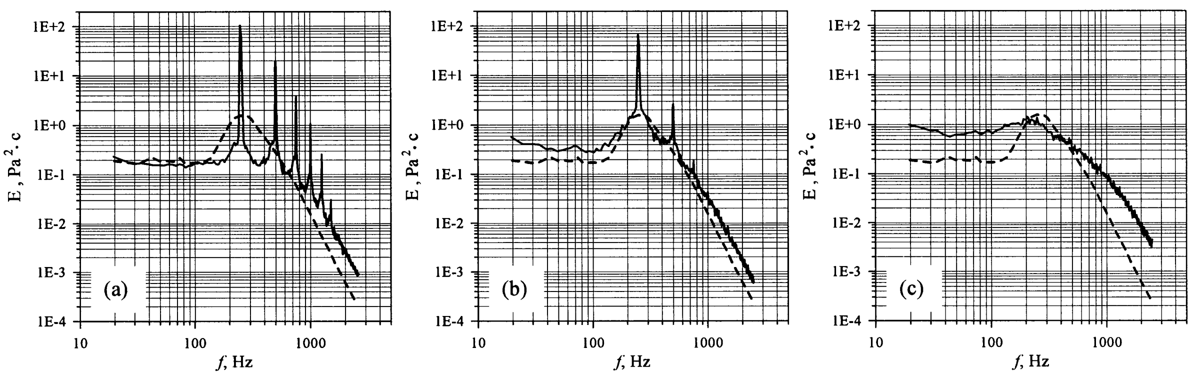

Figure 6. Power spectra of wall shear stress pulsations. Dashed lines - unforced single-phase jet, black lines - forced gas-saturated jet. H/d = 2, Re = 40400, f_f = 250 Hz (Sh_d= 0.6); r/d = 1.1. (a) - α = 0; (b) -3.4 %; (c) - 10.1 %.

distributions of the jet characteristics become similar to the distributions for the low Reynolds numbers (Fig. 2). Besides, we can conclude from the spectral dependencies that a considerable part of stochastic friction pulsations is suppressed in a range of the moderate frequencies. Thus, we can speak about the effect of quasilaminarization of the flow during the resonant enhancement of the large-scale vortex structures. If the jet is excited at the frequencies which lie higher than the range of maximal sensitivity, one can observe only a slight enhancement of the main harmonics which does not change the main characteristics of the flow (Fig. 4, c). The excitation at the low frequencies provides the enhancement of the multiple harmonics $2f_f$, $3f_f$, and so on, if they lie in the range of maximal sensitivity (Ho & Huang, 1982; Alekseenko et al., 1997). The amplitude of the superimposed oscillations does not influence the flow characteristics in the studied range.

Two-phase jet

The two-phase jet's diagnostics was carried out for two Reynolds numbers Re = 25200 and 40400. In general, results for these two regimes do not differ, except the fact that for the horizontal orientation of the nozzle, the bubbles floating is more essential for the low Reynolds numbers and the flow characteristics depend on the ratio of liquid velocity and slip velocity of bubbles and their agglomerates for each point. For the high Re and small bubbles, these phenomena are insignificant. Thus, for Re = 40400, the difference between the values of wall shear stress (measured in the points symmetrical to each other relative to the horizontal axis of the flow - the upper and lower ones) was not larger than 5% for all studied void fractions. The distributions of the mean wall shear stress and friction pulsations for the jet forced at resonant frequency are shown in Fig. 5 versus the void fraction. For the unforced case effects are similar. The gas saturation leads to a significant increase in the average friction, however, the flow character is unchangeable for the void fraction of up to α = 8÷9 %. The value of the r.m.s. friction pulsations related to the friction maximum for the corresponding void fraction decreases monotonously within the whole impingement area, excluding the vicinity of the critical point where the absolute level of pulsation increases. For α > 8÷9 %, the flow structure changes. For the unforced jet the second friction maximum disappears, and pulsation maximum shifts closer to the critical point both for forced

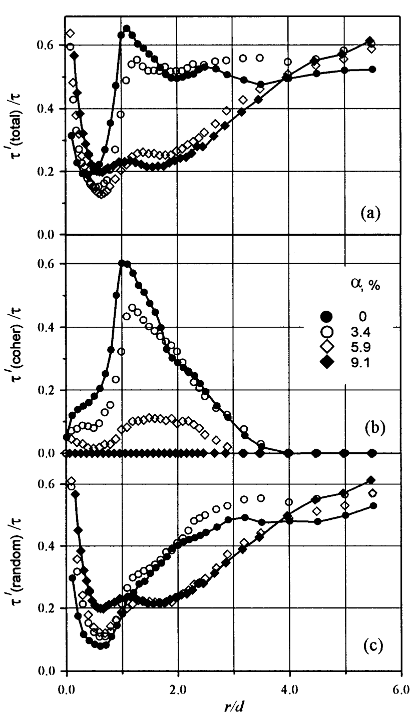

Figure 7. Total (a), coherent (b) and broad-band (c) components of wall shear stress pulsations versus the void fraction. H/d = 2; Re =40400; f_f = 250 Hz (Sh_d= 0.6).

and unforced conditions. A comparison of distributions of the spectral density is presented in Fig. 6 for the point on obstacle where the large-scale vortex structures penetrate from the free jet mixing layer with the highest intensity ($r/d = 1.1$). The suppression of the pulsation's coherent component with a rise of void fraction is obvious. Dashed lines in the Fig. 6 are the spectral distributions for the unforced single-phase impinging jet. For the sufficiently large void fractions the coherent component in spectra practically disappears for each distance r/d (Fig. 6, c). In Fig. 7 the evolution of coherent and broad band components of pulsations is presented for different values of void fraction. The pulsation components are related here to the local mean friction, thus the relative contributions of coherent and random parts to the total turbulence level are compared here for each point. It is clearly seen that the coherent component of pulsations is substantial here only for restricted range of radial distances ($0.5 < r/d < 3$) and decrease almost up to zero at large void fractions ($\alpha > 8$ %). In the region with $r/d > 3$ the broad band component yield the main contribution into the turbulent energy. The level of random turbulence change weakly in this area versus gas contents because the surrounding of the jet is free from the bubbles and local void fraction decrees with the distance.

CONCLUSIONS

The experimental study of local structure of axisymmetric impinging jet has been performed for single-phase and two-phase conditions. The effect of external periodical forcing and gas saturation on the jet's turbulent structure was studied. The main conclusions have been made on the basis of analysis of wall shear stress values. The periodical forcing of a jet at the frequencies which lie in the range of jet's sensitivity leads to the resonant amplification of the large-scale coherent structures in the jet shear layer. The gas saturation up to $\alpha \approx 10 \div 12$ % results to a significant increase in the average friction at the impingement surface. The coherent structures in the jet shear layer are suppressed strongly by small gas bubbles and at large void fractions they are not discernible in the spectral distributions.

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REFERENCES

Alekseenko, S.V., and Markovich, D.M., 1994, "Electrodiffusion diagnostic of wall shear stresses in impinging jets," *J. Appl. Electrochemistry*, Vol. 24, pp. 626-631.

Alekseenko, S.V., Markovich, D.M., and Semenov, V.I., 1997, "Effect of external disturbances on the impinging jet structure," *Proceedings, 4th World Conference on Experimental Heat Transfer, Fluid Mech. and Thermodynamics*, Brussels, June 2-6, 1997, Vol. 3, pp. 1815-1822.

Baines, W.D., and Keffer, J.F., 1976, "Shear stress and heat transfer at a stagnation point," *Int. J. Heat and Mass Transfer*, Vol. 19, pp. 21-26.

Brown, G.L., and Roshko, A., 1974, "On density effects and large scale structure in turbulent mixing layer," *J. Fluid Mech,*, Vol. 64, pp. 775-816.

Crow, S.C., and Champagne, F.H., 1971, "Orderly structure in jet turbulence," *J. Fluid Mech,*, Vol. 48, pp. 547-591.

Davis, F., 1993, "Visualisation of turbulence modulation with large particles," M.S. Thesis, Department of Aeronautical and Astronautical Engineering, University of Illinois at Urbana-Champaign. (according to the reference in Taeibi-Rahni et al. 1994)

Goldschmidt, V.W., Householder, M.K., and Chuang, S.C., 1971, "Turbulent diffusion of small particles suspended in turbulent jets," *Progress in Heat and Mass Transfer*, Vol. 6, pp. 487-508. Pergamon, Oxford.

Gore, R.A., and Crowe, C.T., 1989, "Effect of particle size on modulating turbulent intensity," *Int. J. Multiphase Flow*, Vol. 15, pp. 279-285.

Hanratty, T.J., and Campbell, J.A., 1983, "Measurements of wall shear stress," in *Fluid Mechanics Measurements*, pp. 559-615, Washington, Hemisphere.

Ho, C.M., and Huang, L.S., 1982, "Subharmonics and vortex merging in mixing layers," *J. Fluid Mech,*, Vol. 119, pp. 443-473.

Ho, C.M., and Nosseir, N.S., 1981, "Dynamics of an impinging jet. Part I. The feedback phenomenon," *J. Fluid Mech*, Vol. 105, pp. 119-142.

Kataoka, K., and Mizushina, T., 1974, "Local enhancement of the rate of heat transfer in an impinging round jet by free stream turbulence," *Proceedings, 6th Int. Heat Transfer Conference*., Tokyo: Jap. Soc. Mech. Eng., 1974, pap. B-3, pp. 305-310.

Lance, M., and Bataille, J., 1991, "Turbulence in the liquid phase of a uniform bubble air-water flow," *J. Fluid Mech.*, Vol. 222, pp. 95-118.

Milgram, J.H., 1983, "Mean flow in round bubble plumes," *J. Fluid Mech.*, Vol. 85, pp. 345-376.

Serizava, A., Kataoka, I., and Michigoshi, I., 1975, "Turbulence structure of air-water bubbly flow -II. Local properties," *Int. J. Multiphase Flow*, Vol. 2, pp. 235-246.

Sun, T-Y., and Faeth, G.M., 1986, "Structure of turbulent bubbly jets - part I, II," *Int. J. Multiphase Flow, Vol.* 12, pp. 99-126.

Taeibi-Rahni, M., Loth, E., and Tryggvason, G., 1994, "Flow modulation of planar free shear layer with large bubbles - direct numerical simulations," *Int. J. Multiphase Flow*, Vol. 20, pp. 1109-1128.

Wang, S.K., Lee, S.J., Jones, O.C., and Lahey, R.T., 1987, "3-D turbulence structure and phase distribution measurements in bubbly two-phase flows," *Int. J. Multiphase Flow*, Vol. 13, pp. 327-343.

Yuan, I., and Michaelides, E.E., 1992, "Turbulence modulation in particulate flows - a theoretical approach," *Int. J. Multiphase Flow*, Vol. 18, pp. 779-785.