EFFECT OF THE PARTICLES CONCENTRATION ON FLUCTUATING VELOCITY OF THE DISPERSE PHASE FOR TURBULENT PIPE FLOW

Aleksei Yu.Varaksin, Yury V.Polezhaev and Anatoly F.Polyakov
Department of Heat Transfer, Institute for High Temperatures,
Russian Academy of Sciences,
Izhorskaya 13/19, Moscow 127412, Russia

ABSTRACT

This paper presents the results of an experimental study of the solid particles fluctuation velocities distributions for case of their motion in the downward turbulent pipe flow. The glass particles with mean diameters of 50 μm and 100 μm were used as a disperse phase. The particles mass loading was varied in the range $\overline{M}$=0-1.2. The obtained results clearly showed that the particles fluctuation velocities are strongly depended on its mass loading.

INTRODUCTION

Two-phase flow is one of the most common flows of gas in the nature and industrial applications. Inspite of great number of studies in this field of physics, the knowledges about two-phase flows are very far from full understanding, and predictability of such flows with necessary level of accuracy is impossible now.

There are a number of the experimental works where the behavior of the solid particles suspended in the turbulent air flow and their back influence on the carrier phase turbulence characteristics for channel flows have been studied (Maeda *et* al., 1980; Lee and Durst, 1982; Tsuji and Morikawa, 1982; Tsuji *et* al., 1984; Rogers and Eaton, 1990; Kulick *et* al., 1994; Hosokawa *et* al., 1998; Varaksin *et* al., 1998). This paper is aimed to study solid particles behavior in the downward air turbulent pipe flow. The detailed results of the solid particles mean (time-averaged) and fluctuation velocities distributions in dependence on their mass loadings are presented.

EXPERIMENTAL SETUP AND PROCEDURE

In order to study dilute and dense gas-solid flows, an experimental facility has been developed, whose scheme is shown on the Fig.1. The test section is a vertical pipe 1 which was produced from stainless steel with inner diameter $D = 46$ mm. The pipe length is 2500 mm. A slot 2 of 12 mm wide is milled in the pipe wall at a distance $L = 1380$ mm from the top end for the inlet and outlet of the probing beams of a laser Doppler Anemometer (LDA). The velocities measurements were performed by a two-channel triple-beam LDA 10 manufactured by Dantec (Denmark). For hermetically sealing the test section, the slot is covered with transparent windows that are attached to the pipe by means of tie pins so that the window plane are positioned perpendicular to the optical axis of the transmitting optics 3 of the LDA. The air is delivered via receiver 4 from the tank 5. The pressured air is produced by the compressor 6.

In order to develop air-solid flow, a solid particles feeder 7 was used. The operating principle of the feeder follows. Solid particles are poured into 2-l bottle and move to the vertical pipe through feeder`s pipe 8 by means of their gravity force. The solid particles mass flux was varied by changing of the feeder`s outlet apertures.

After passing the receiver and the turning section 9 air flow was mixed with solid particles, and air-solid mixture entered to the test section. After passing the pipe the solid particles were utilized by the settling tank 10.

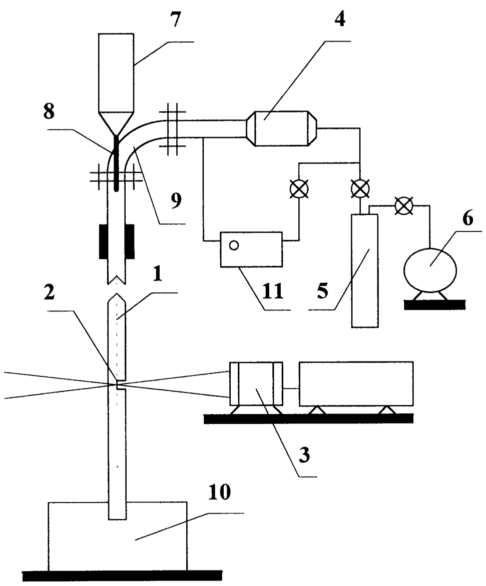


Figure 1. Experimental setup scheme: 1 - vertical pipe; 2 - slot for laser beams; 3 - optics of the LDA; 4 - receiver; 5 - air tank; 6 - compressor; 7 - solid particles feeder; 8 - feeder`s pipe; 9 - turning section; 10 - particles settling tank; 11 - tracer particles generator.

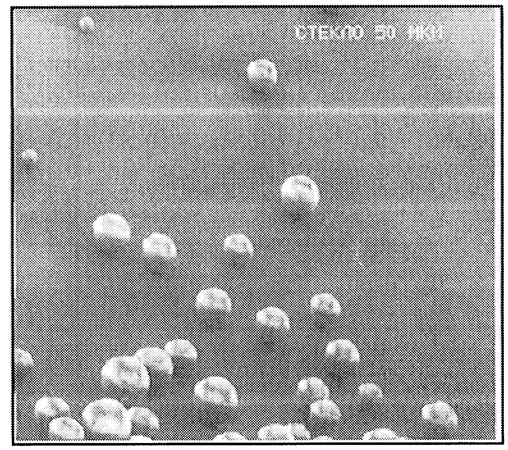
The spherical glass particles with nominal diameters of 50μm and 100 μm with density of ρ_p=2550 kg/m^3 were used in experiments. The standard deviations of the particles diameter were equal 5μm and 8μm for small and large particles respectively. The photos of the used particles are shown on the Fig.2.

A micron-particle generator 11, manufactured by Dantec (Denmark) and using a glycerin-water mixture, was applied to seed the flow with tracer particles simulating the air motion. The generated particles were 2-3 μm in diameter. The pipe section was scanned by use of the traversing system by Dantec, making it possible to automatically move the measuring volume (measurement point) with the accuracy of 10 μm along a horizontal axis. The main measuring volume characteristics were follows: dimension - 0.091x0.091x1.32 mm; interference fringe size - 3.63 μm; number of the fringes - 25.

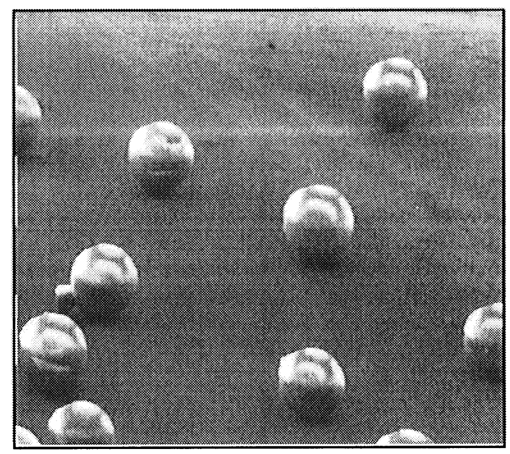
For solid particles velocities measurements the digital exit of the doppler signal processor (model Counter 55L90a, Dantec) was used. A particles relative local concentration was defined by use of data rate of the doppler signals from the disperse phase and mean particles loading determined by the weighting way.

The created measuring system allowed to measure the mean (time-averaged), r.m.s. fluctuation particles velocities and particles local concentration with uncertainties of 2%, 8% and 20% respectively.

The task of the solid particles back influence on the carrier air parameters was not study in the present work, therefore,



a)



b)

Figure 2. Used glass particles photo: a) 50 μm; b) 100 μm.

the air and particle velocities distributions were measured separately.

RESULTS AND DISCUSSION

All described measurements were conducted for centerline air mean velocity of 5.2 m/s. Reynolds number based on the pipe diameter was $\mathrm{Re}_D = 15300$. The distance from the particles entrance section to the measuring section was equal $L = 1380$ mm ($L/D = 30$). This distance was enough for creation of quasi-stationary air-solid flow, because the acceleration of the used solid particles in the mean (time-averaged) motion to the measuring section has been finished.

The obtained experimental results on the particles mass concentration, mean and fluctuation particles velocities

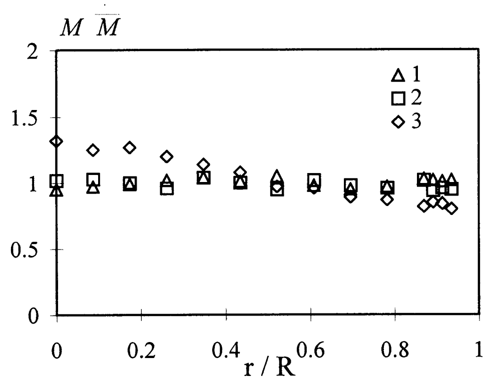


Figure 3. Mass concentration distributions for 50 μm glass particles: 1 - $\bar{M} = 0.05$; 2 - $\bar{M} = 0.35$; 3 - $\bar{M} = 1.2$.

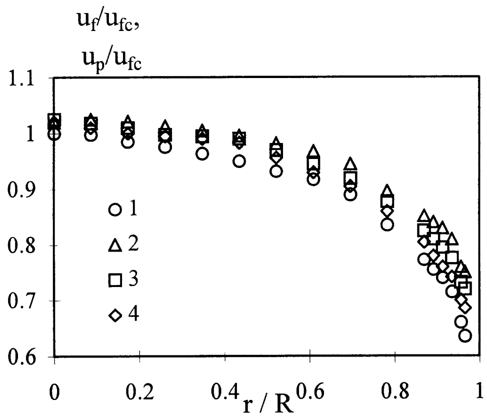


Figure 4. Mean velocities distributions for air and 50 μm glass particles: 1 - air ($\bar{M} = 0$); 2 - particles ($\bar{M} = 0.05$); 3 - particles ($\bar{M} = 0.35$); 4 - particles ($\bar{M} = 1.2$).

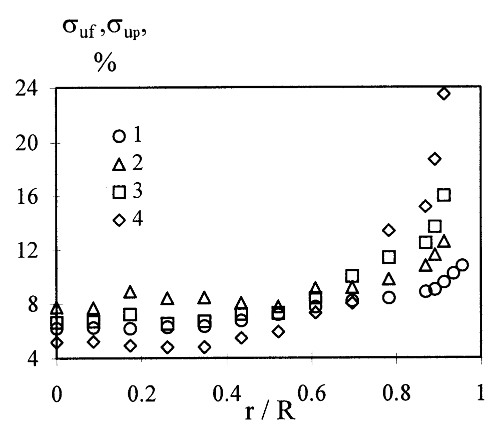


Figure 5. Streamwise fluctuations intensity distributions for air and 50 μm glass particles: 1 - air ($\bar{M} = 0$); 2 - particles ($\bar{M} = 0.05$); 3 - particles ($\bar{M} = 0.35$); 4 - particles ($\bar{M} = 1.2$).

distributions will be described below. At the beginning consider the results for flow with small solid particles.

Figure 3 shows the distributions of the particles local mass concentration in dependence on their mean (throughout pipe) mass loading. It can be seen, that the particles distribution is almost uniform excepting the case when $\bar{M} = 1.2$. For this mass loading the particles local concentration becomes higher (compared with the mean particles loading) in the region near pipe axis and becomes lower near the pipe wall. The reason of this phenomenon is length of the pipe which was not enough for creation of the nearly uniform distribution of the particles by turbulent flow.

Figure 4 demonstrates the profiles of the mean velocities for air and solid particles. We can see, that the particles velocity is greater than air velocity across all pipe section. This fact confirms, that the acceleration of the particles to the measuring section was finished, therefore, the quasi-stationary air-solid flow has been created. Fig.4 also shows that the particles mean velocities distributions are more flat compared with air velocity distribution. The velocity of the particles in the near-wall region is decreased, and it is strongly depended on their mass loading. Perhaps, the main reason of this effect is particles impulse lost due to their interaction with the pipe wall.

Figure 5 shows the streamwise fluctuations intensity distributions for single air and for solid particles. As to solid particles velocity fluctuations that there are a number of the reasons of their appearance:

1) appearance of the particles turbulent velocities fluctuations due to their involving in the fluctuating motion by the turbulent eddies of the carrier air;

2) appearance of the particles velocities fluctuations due to use in the experiments of the polydisperse particles, i.e. the particles with different sizes (such particles has different time-averaged velocities that are observed as fluctuations velocities);

3) the particles velocities change due to the particle-particle collisions (this effect is increased with particles mass loading increasing);

4) the particles velocities change due to the particles-wall interaction.

Note, that the observed velocities fluctuations of the solid particles also may be directly connected with the experimental uncertainty which is greater than for case of the single air velocities measurements. As to present experiments the contribution of the measurement error is determined by the value of the solid particles fluctuation velocity measurement uncertainty - 8%.

It can be seen from Fig.5, that the particles streamwise velocity fluctuations intensity is about $\sigma_{up} \approx 8\%$ at the pipe axis for small mass loading ($\bar{M} = 0.05$). This value exceeds the respective value for single air which equal about $\sigma_{uf} \approx 6\%$. The particles velocities fluctuations intensities are decreased with particles mass loading increase. So, particles fluctuations intensities are $\sigma_{up} \approx 7\%$ and $\sigma_{up} \approx 5\%$ for mass loadings $\bar{M} = 0.35$ and $\bar{M} = 1.2$ respectively. The 50 μm particles relaxation time is very

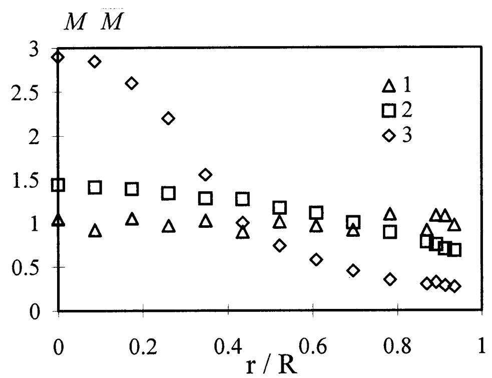


Figure 6. Mass concentration distributions for 100 μm glass particles: 1 - $\bar{M} = 0.05$; 2 - $\bar{M} = 0.57$; 3 - $\bar{M} = 1.2$.

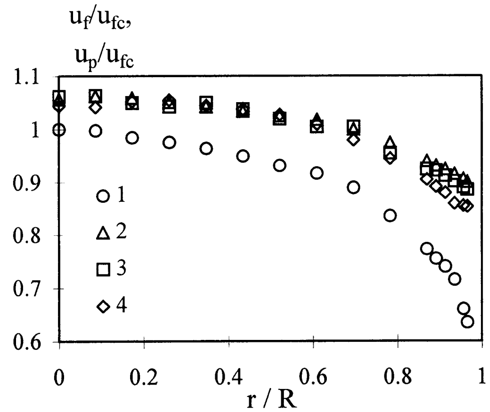


Figure 7. Mean velocities distributions for air and 100 μm glass particles: 1 - air ($\bar{M} = 0$); 2 - particles ($\bar{M} = 0.05$); 3 - particles ($\bar{M} = 0.57$); 4 - particles ($\bar{M} = 1.2$).

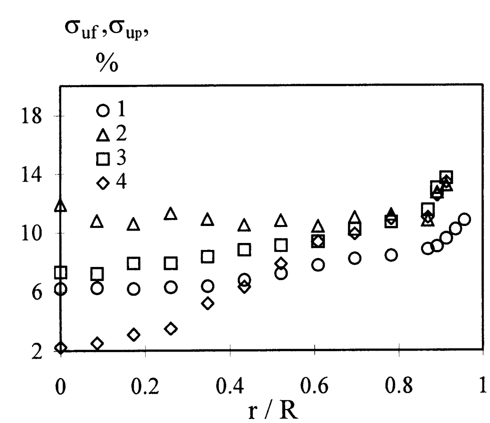


Figure 8. Streamwise fluctuations intensity distributions for air and 100 μm glass particles: 1 - air ($\bar{M} = 0$); 2 - particles ($\bar{M} = 0.05$); 3 - particles ($\bar{M} = 0.57$); 4 - particles ($\bar{M} = 1.2$).

close to the characteristic time of the energy-containing turbulent eddies of the carrier phase. It means, that such particles are effectively involved in the fluctuation motion. Therefore, the fluctuation velocity of the air is decreased due to the turbulent eddies energy lost. This effect increases with increasing of the particles mass loading. Probably, described above reason is the main dominant fact of the particles velocity fluctuations decrease in the region of the pipe axis.

It can be seen from the Fig.5, that the particles fluctuation velocity intensities are increased to the pipe wall direction. So, the particles fluctuation velocity intensity near pipe wall (2 mm from the pipe wall) is about $\sigma_{up} \approx 12\%$ for low particles mass loading ($\bar{M} = 0.05$). This value exceeds the fluctuation velocity value for carrier air which equal about $\sigma_{uf} \approx 10\%$ at this point. The particles velocities fluctuations are icreased with increasing of their mass loading. So, particles velocities fluctuations intensities in the pipe wall region are $\sigma_{up} \approx 16\%$ and $\sigma_{up} \approx 24\%$ for mass loadings $\bar{M} = 0.35$ and $\bar{M} = 1.2$ respectively. It is neccessary to note, that the relative inertia of the particles (particles Stokes number) is strongly decreased in the region of the pipe wall, because the energy-containing turbulent eddies characteristic time is decreased compared with its value at the pipe axis. Therefore, the degree of the particles involving in the fluctuating motion can not be significant. In this case it is difficult to explain the high values of the particles velocities fluctuations near the pipe wall observed in the experiments. Probably, the motion of the particles in this region (where the high gradients of the carrier air velocity take place) is determined additionally by the Saffman's and Magnus forces action. The influence of these forces lead to the particles motion in the direction to the pipe wall for case of the downward flow. The particles-wall interaction is a probable reason of the appearance of particles velocities fluctuations high values.

Now, about received results for flow with particles of 100μm in diameter. Figure 6 demonstrates the distributions of the particles local mass concentration in dependence on their mean mass loading. It can be seen, that the non-uniformity of the large particles concentration is bigger than for flow with small particles. The reasons of this phenomenon are relatively short pipe length and relatively big inertia of these particles. Such non-uniform particles concentration distributions were used in present experiments to clarify the effect of the particles concentration on their fluctuation velocities.

Figure 7 demonstrates the profiles of the mean velocities for air and solid particles. We can see, that the particles velocity is greater than air velocity across all pipe section and particles velocity profile is more flat compared with single air and small particles velocity profiles. The velocity of the particles in the near-wall region is decreased with mass loading increase.

The streamwise fluctuations intensity distributions for single air and for particles of 100μm in diameter are shown on the Fig.8. We can see, that the large particles fluctuations intensity at the pipe axis for small mass loading($\bar{M} = 0.05$)

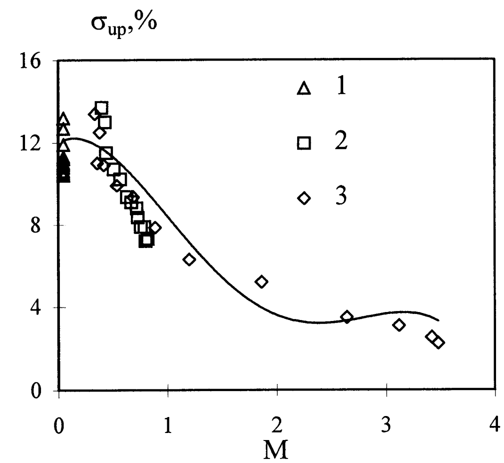


Figure 9. Streamwise turbulence intensity distribution for 100 μm glass particles in dependence on the mass concentration: 1 - $\bar{M} = 0.05$;2 - $\bar{M} = 0.57$; 3 - $\bar{M} = 1.2$.

is about $\sigma_{up} \approx 11\%$. This value is decreased with particles mass loading increase. So, particles velocities fluctuations intensities at the pipe axis are $\sigma_{up} \approx 7\%$ and $\sigma_{up} \approx 2\%$ for mass loadings $M = 0.57$ and $M = 1.2$ respectively.

The main reason of large particles velociites fluctuations appearance is the fact, that the particles in the flow has different diameters due to dispersion of their sizes. It leads to the existance in the flow the particles with different values of the velocities. The degree of the particles involving in the fluctuating motion is small, because the inertia of these particles is relatively big. Thus, the particles fluctuating velocities connected with turbulence of the surrounding air should be much more smaller than the respective fluctuating velocity of the continious phase. But, it was not observed in experiments.

It can be seen from the Fig.8, that fluctuation velocities of the particles are decreased in the direction to the pipe axis for the flow with relatively high mass loadings of particles. The reason of this effect is the growth of local concentration of the particles in this direction (see Fig.6) and beginning of the intensive interaction between the particles. The particle-particle collisions lead to the impulse exchange between the particles (more large particles accelerate more small particles). The particles velocity probability density function becomes more narrow and, therefore, particles fluctuations velocities become smaller due to this impulse exchange.

Figure 9 generalizes the experimental data on intensity of 100 μm particles velocities fluctuations in dependence on their local mass concenbtration. It is clear seen, that the particle-particle interaction (which leads to the decrease of their velocity fluctuations) is started at the mass loading $M \approx 0.5$ (corresponding particles volume fraction is $\Phi \approx 2.4 \cdot 10^{-4}$). This boundary particles concentration determines the kind of the interaction between the particles and surrounding gas turbulence and transition from so-called "two-way coupling" to "four-way coupling". Following conclusions from review (Elghobashi, 1991) the volume fraction of particles, when the particle-particle collisions take place is $\Phi \geq 10^{-3}$. Thus, the present experiments show, that the intensive particle-particle interactions start to play important role at more small particles volume concentration.

CONCLUSION

The effect of the solid particles concentration on their velocities fluctuations intensities for case of downward turbulent air-solid pipe flow has been experimentally studied. The boundary value of the particles mass loading and corresponding particles volume fraction, when the particle-particle collisions start to take place, were found.

Acknowledgements - The authors were partly supported by the Russian Foundation for Basic Research (project No. 98-02-17323) and President Grant for leading scientific school (Prof. Yu.V.Polezhaev).

NOMENCLATURE

R - pipe radius;
r - distance from pipe axis;
M - particles local mass concentration;
$\bar{M}$ - mean (across the pipe) particles mass concentration;
Φ - particles volume fraction;
u_f - mean (time-averaged) air velocity;
u_p - mean (time-averaged) particles velocity;
$(\overline{u_f'^2})^{1/2}$ - air streamwise fluctuation velocity;
$(\overline{u_p'^2})^{1/2}$ - particles streamwise fluctuation velocity;
$\sigma_{u_f} = (\overline{u_f'^2})^{1/2} / u_{fc}$ - air streamwise turbulence intensity;
$\sigma_{u_p} = (\overline{u_p'^2})^{1/2} / u_{pc}$ - particles streamwise fluctuations intensity;
"c" - parameters at the pipe axis.

REFERENCES

Elghobashi, S., 1991, "Particle-Laden Turbulent Flows: Direct Simulation and Closure Models," *Applied Scientific Research,* Vol.48, pp.301-314.

Hosokawa, S. et al., 1998, "Influences of Relative Velocity on Turbulent Intensity in Gas-Solid Two-Phase Flow in a Vertical Pipe," *Third Int. Conf. on Multiphase*

Flow, Lyon, France, Paper No.279, pp.1-7.

Kulick, J.D. et al., 1994, "Particle Response and Turbulence Modification in Fully Developed Channel Flow," *J. Fluid Mechanics*, Vol.277, pp.109-134.

Lee, S.L., and Durst, F., 1982, "On the Motion of Particles in Turbulent Duct Flows," *Int. J. Multiphase Flow*, Vol.8, pp.125-146.

Maeda, M. et al., 1980, "Velocity Distributions of Air-Solid Suspension in Upward Pipe Flow (Effect of Particles on Air Velocity Distributions)," *Trans. Jap. Soc. Mech. Engrs, Ser. B*, Vol.46, pp.2313-2320.

Rogers, C.B., and Eaton, J.K., 1990, "The Behavior of Solid Particles in a Vertical Turbulent Boundary Layer in Air," *Int. J. Multiphase Flow*, Vol.16, No.5, pp.819-834.

Tsuji, Y., and Morikawa, Y., 1982, "LDV Measurements of an Air-Solid Two-Phase Flow in a Horizontal Pipe," *J. Fluid Mechanics*, Vol.120, pp.385-409.

Tsuji, Y. et al., 1984, "LDV Measurements of an Air-Solid Two-Phase Flow in a Vertical Pipe," *J. Fluid Mechanics*, Vol.139, pp.417-434.

Varaksin, A. Yu. et al., 1998, "Experimental Study of the Direct Influence of the Small Particles on the Carrier Air Turbulence Intensity for Pipe Flow," *Third Int. Conf. on Multiphase Flow*, Lyon, France, Paper No.368, pp.1-8.