THE STRUCTURE OF THE TURBULENT GAS-SOLID FLOW WITH BIDISPERSED PARTICLES

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ABSTRACT

Gas-solid flow with bidispersed particles was studied. The distribution has been obtained for the first time of the mean (time-averaged) and fluctuation velocities of bidispersed mixture moving in a turbulent flow of air in a pipe. The measurements results have demonstrated that it is possible in principle to use laser Doppler anemometers (LDA) to study velocity fields for large bidispersed particles having identical optical properties.

INTRODUCTION

Two-phase flow frequently occurring naturally and employed in technical devices is often accompanied by physicochemical processes leading to a variation in the composition of the disperse phase. Such processes include combustion, phase transitions, coagulation, fragmentation, etc. This makes it urgent to investigate of gas flows with particles which differ by their properties and, as a result, are characterized by different velocities.

Probably, there exists three type of the heterogeneous flows with bidispersed particles:

1) the flows with particles produced from same material but having the different sizes;

2) the flows with particles of same sizes but produced from different materials;

3) the flows with particles of same sizes and material but having different "effective" density, i.e. porous particles, hollow particles et al.

There are two main task in the study of the heterogeneous flows with bidispersed particles:

1) study of the bidispersed particles behavior in the carrier turbulent flow;

2) study of the bidispersed particles back influence on the characteristics of carrier phase.

As to the first task, it is clear, that the dynamics of the particles mixture will be different from that for separate parts of the particles composition due to intensive particle-particle interaction at relatively small value of the particles concentration. It is well known, that the presence of the large particles in the flow may cause an additional generation of the carrier gas turbulent energy, while the small particles presence leads to the turbulence dissipation. The common effect of the particles on the gas turbulence may be neglected at relatively large disperse phase concentration, when we have the flow with particles mixture which consist of the small and large particles. Described above examples also confirm the importance of the detailed study of the heterogeneous flows with bidispersed particles.

The objective of this study is to conduct the correct measurements of various kinds of the flows with bidispersed particles and to determine the distribution of time-averaged and fluctuation velocities of bidispersed mixture during its motion in turbulent air flow in a pipe.

EXPERIMENTAL FACILITY

A schematic diagram of our experimental facility designed for studying gas-solid flows is shown in Fig.1. The test section is a vertical pipe 1 made of stainless steel and having the internal diameter $D = 46$ mm. The pipe is 2500 mm of length and has 12 mm slot 2 in the pipe wall at a distance $L = 1380$ mm from the top end. It is designed for the inlet and outlet of the probing beams of the two-channel triple-beam LDA-10 manufactured by Dantec (Denmark) with the help of which the velocity measurements were performed. To seal the test section hermetically, the slot is covered with transparent windows attached to the pipe by tie pins. The window planes are positioned perpendicularly to the optical axis of transmitting optics 3 of the LDA. The pressurized air is produced by compressor 6 and is delivered via receiver 4 from tank 5.

To obtain an air flow with solid particles entrained we used feeder 7 operating as follows. Solid particles fed into a bottle (2 l of volume) move to the vertical pipe through pipe 8 of the feeder under the action of the force of gravity. The solid particles mass flux rate varied vs. the size of the feeder outlet aperture.

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

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 spherical glass particles with nominal diameters of 50 μm, 100 μm and 200 μm (the density of ρ_p =2550 kg/m^3), spherical iron particles of 100 μm and 150 μm (the density of ρ_p =7800 kg/m^3) were used in experiments. The standard deviations of the particles diameter were equal to about 10% of mean diameter for all types of particles.

For solid particles velocities measurements the digital exit of the Doppler signal processor (model Counter 55L90a, Dantec) was used.

In the experiments, the measuring volume had the following characteristic parameters: size, 0.091×0.091×2.28 mm; interference lattice spacing, 6.43 μm; number of spacings, 14.

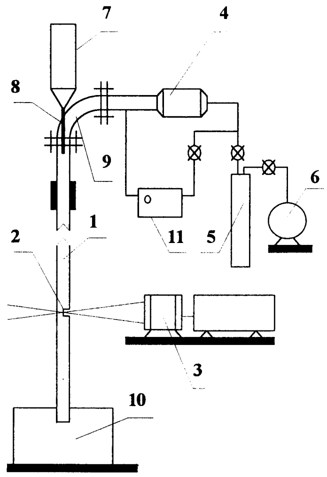

Figure 1. Experimental setup scheme: 1 - vertical pipe; 2 - slot for laser beams; 3 - optics of the LDA; 4 - receiver; 5 - air tank; 6 - compressor; 7 - solid particles feeder; 8 - feeder's pipe; 9 - turning section; 10 - particles settling tank; 11 - tracer particles generator.

The procedure of measuring the instantaneous velocity of large solid particles was described in Varaksin and Polyakov (1998, 1999).

The results described below were obtained with random scatter not exceeding the following values: for the mean velocity of air, 2%; for the mean velocity of solid particles, 4%; for the mean velocity of bidispersed particles, 6%; for the mean-square fluctuation velocity of air, 7%; for the mean-square fluctuation velocity of solid particles, 10%; and for the mean-square fluctuation velocity of bidispersed particles, 15%. Note that the foregoing values include also the systematic error due to the gradient of velocity of air and particles within the measuring volume.

RESULTS

The primary goal of a study of the behavior of bidispersed particles moving in flows is to determine the probability density function for their velocities, since it may be used to calculate the mean (time-averaged) velocity of the entire ensemble of particles, its mean-square deviation, and other statistical moments. When particles concentration in the flow is so high that due to frequent collisions between particles a quite different probability density function arises. So it becomes especially important to adjust the LDA electronic system and optimize its parameters by carrying out test measurements of the velocities of the particles (when is possible to test the results obtained by calculations) making up the bidispersed mixture.

Measurements in motionless air

Let us consider flows with particles of different sizes made from the same material. First of all, we measure the velocity of individual spherical solid particles of different sizes and particles making up a bidispersed mixture, where they undergo gravitational settling in motionless air.

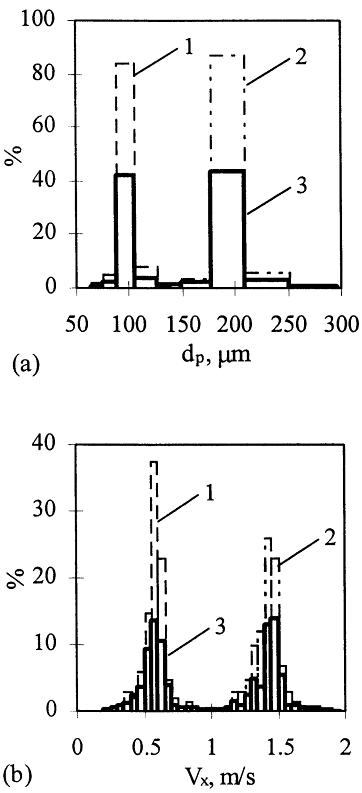

Figure 2. The distributions of (a) diameter and (b) velocity: 1 – glass particles (100 μm); 2 – glass particles (200 μm); 3 – mixture (100μm+200 μm).

In Fig.2a, we show the histograms for the mass size distribution for two kinds of spherical glass particles with nominal diameters 100 and 200 μm, obtained using sieve analysis. Since during the study we used spherical solid particles for which the mean-square deviation of the diameter is only 10% of their average diameter, their mass and number distribution functions are close. On the same figure, we also show the size distribution of a mixture obtained from glass particles of different diameters. In this case, the number of particle of each size and type was the same, while the volume and mass of large particles were eight times greater than the corresponding parameters of the small particles. The mixture obtained in this way can be considered as a bidispersed particle mixture.

The results of measurements of the particle velocity distribution are shown in Fig.2b. The experimentally obtained probability density

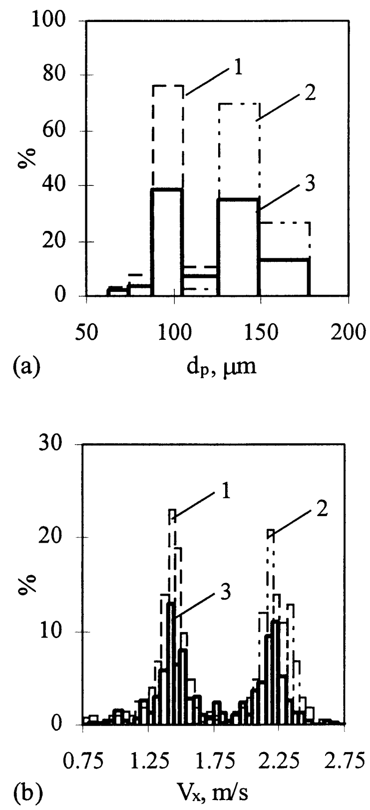

Figure 3. The distributions of (a) diameter and (b) velocity: 1 – iron particles (100 μm); 2 – iron particles (150 μm); 3 – mixture (100μm+150 μm).

functions for the velocity were used to determine the mean velocity of the particles and the bidispersed mixture and their mean-square deviations. The corresponding parameters for polydisperse particles and the mixture obtained from them were also determined by calculation. The differences identified were 4% and 12% for the mean velocities and mean-square deviations, respectively. Thus our measurements clearly showed that it is possible to use LDA to study the velocity fields of a bidispersed mixture of glass particles.

After successfully measuring the velocities of bidispersed glass particles, we attempted to make analogous measurements for spherical iron particles. The size distributions of the spherical iron particles are shown in Fig.3a. Here we also show the size distribution of a bidispersed mixture obtained from the original iron particles with nominal diameters 100 and 150 μm in such a way that the numbers of particles of each size were the same. Obviously, the iron particles, due to their optical properties, scatter light significantly more poorly than the glass particles. Nevertheless, the velocity of such particles also can be measured using LDA. In Fig.3b, we show the results of measurements of the velocities of polydisperse iron particles, and also a bidispersed mixture. The difference between the experimental data and the calculations was within 5% and 15% for the mean and the mean-square deviations, respectively. Thus we have demonstrated the feasibility in principle of making correct LDA measurements of velocities also for bidispersed iron particles.

Measurements in turbulent flow

All measurements were performed in a single cross section of the pipe. The distance from the pipe inlet to the measuring cross section was L=1380 mm, which corresponds to L/D=30. The Reynolds number was Re_D=12300. The mass concentration of particles averaged over the pipe cross section, defined as the ratio between the mass flow rates of the phases, was M=0.02.

An attempt was made at studying the fields of averaged and fluctuation velocities of solid particles and of a bidispersed mixture of particles for the case when the inter-particle collisions and the effect of the disperse phase on the characteristics of carrier air flow may be ignored. These requirements were satisfied by the choice of the foregoing value of the mass concentration of particles (as corroborated by the available experimental data by Tsuji and Morikawa (1982), Tsuji *et* al. (1984), Rogers and Eaton (1991), Kulick *et* al. (1994), Varaksin *et* al. (2000)).

Described below are the results of measurements of the distribution of velocity of solid particles and of a bidispersed mixture of particles. This mixture was prepared from glass particles of different diameters with equal amounts of particles of each size. Histograms of the size distributions of glass particles and of the bidispersed mixture of these particles are given in Fig.4a. Note that the volume and mass of large glass particles (d_p=100 μm) in the mixture are eight times greater those of smaller particles (d_p=50 μm).

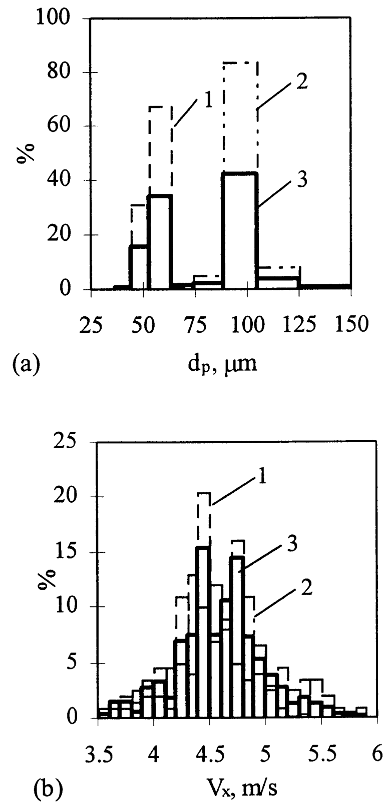

Figure 4. The distributions of (a) diameter and (b) velocity: 1 – glass particles (50 μm); 2 – glass particles (100 μm); 3 – mixture (50μm+100 μm).

An example of the measured distribution of the velocity of glass particles of different sizes and of a bidispersed mixture of particles on the pipe axis is given in Fig.4b. The figure demonstrates the presents of two maxims in the distribution of velocity of bidispersed particles.

The measured distributions of the velocity were used to derive the fields of mean velocities and their mean-square deviations. Figure 5 gives the distribution of time-averaged velocity for air, U_x, and for solid particles and bidispersed mixture of particles, V_x, over the pipe cross section (U_{xc} is the mean velocity of air on the pipe axis). This figure demonstrates that the velocities of particles and of bidispersed mixture of particles exceed that of carrier air over the entire cross section of the pipe. One can see that the profile of averaged velocity of particles is flatter compared with the respective profile for the continuous phase. The flatness of the velocity profile increases with the inertia of the particles. The maximum difference

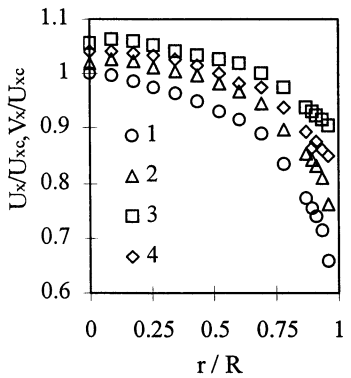

Figure 5. The distributions of mean velocity: 1 – air; 2 –glass (50 μm); 3 – glass (100 μm); 4 – mixture (50μm+100μm).

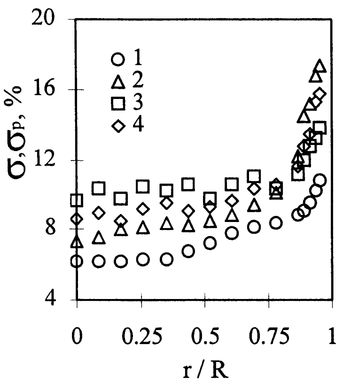

Figure 6. The distributions of the velocity fluctuations intensity: 1 – air; 2 –glass (50 μm); 3 – glass (100 μm); 4 – mixture (50μm+100μm).

between the velocities of the gas and disperse phases is observed in the wall region. An important characteristic of heterogeneous flow, namely, the Reynolds number determined by the particle diameter and slip in time-averaged motion, varies in the range of Re_p=0.3–0.5, Re_p=1.7–7.7, and Re_p=1.1–5.0 for glass particles 50 and 100 μm in diameter and for a bidispersed mixture of particles, respectively.

Figure 6 gives the distribution of the longitudinal fluctuations intensity of the velocity of air, solid particles, and a bidispersed mixture of particles in the pipe cross section. One can see in the figure that the intensity of fluctuations for air on the pipe axis is $\sigma = (\overline{u_x'^2})^{1/2} / U_{xc} \cong$ 6%. On approaching the wall, this characteristic of air flow increases and reaches the value of $\sigma \cong$11% at a distance of 1 mm from the wall (the coordinate of the last point of measurement).

Figure 6 demonstrates that the intensity of longitudinal fluctuations of the velocity of particles of all varieties and of a bidispersed mixture of particles $\sigma_p = (\overline{v_x'^2})^{1/2} / V_{xc}$ (V_{xc} is the time-averaged velocity of particles and mixture of particles on the pipe axis) exceeds the respective characteristic for the flow of air in the entire cross section of the pipe. This fact is worthy of special attention. As to turbulent heterogeneous flows with particles, quite a number of reasons are responsible for the emergence of particle velocity fluctuations observed at the given point of space. We will identify the main ones of these reasons for the case of weakly dust-laden flow (the particle interaction with one another is negligible): (1) the emergence of turbulent fluctuations proper of the velocity of particles, which are associated with the involvement of particles in the fluctuation motion by turbulent vortexes of the carrier gas phase; (2) the emergence of fluctuations of the velocity of particles due to their polydispersity, i.e., the presence in the flow of particles which have different diameters and, consequently, are characterized by different time-averaged velocities; (3) the emergence of fluctuations of particles during their transverse motion in the region with different characteristic values of averaged velocity of disperse phase.

The experimentally observed intensities of longitudinal fluctuations of velocity of solid particles on the pipe axis were $\sigma_p \cong$7.5%, $\sigma_p \cong$9.5%, and $\sigma_p \cong$8.5% for glass particles 50 and 100 μm in diameter and for a bidispersed mixture of particles, respectively (see Fig.6).

Apparently, the fluctuations of velocity of the disperse phase in the axis region are due to the first two of the above-mentioned reasons.

In analyzing Fig.6, one can see that, on approaching the wall, the intensity of longitudinal fluctuations of the particle velocity increases. An especially significant rise of the particle velocity fluctuations is observed in the $r/R > 0.8$ range. The particle velocity fluctuations reach their maximum values at $r/R \cong 0.96$ (the last point of measurement). The measured intensity of velocity fluctuations in the vicinity of the wall was $\sigma_p \cong 17.5\%$, $\sigma_p \cong 13.5\%$, and $\sigma_p \cong 15.5\%$ for glass particles 50 and 100 μm in diameter and for a bidispersed mixture of particles, respectively. The rise of fluctuations of the velocity of particles on approaching the wall was probably due to the third one of above-mentioned reasons, namely, to transverse "hovering" of particles in a region with a relatively high gradient of mean velocity of the disperse phase (see Fig.5). As one can see in Fig.6, the rise of intensity of velocity fluctuations for smaller particles was much greater than for inertial particles. This may probably be attributed to two reasons. First, the gradient of mean velocity of less inertial particles exceeds that for larger particles (see Fig.5). Second, the less inertial particles are more readily involved into fluctuation motion by turbulent vortexes, which favors their motion in the transverse direction.

The distribution of longitudinal fluctuations of velocity of bidispersed particles (as well as the distribution of averaged velocity) was found to lie between the respective distributions of particles which made up the given mixture. This was due to the fact that, for the conditions of our investigation, the functions of probability density of particle velocities (see Fig.4b) were close to one another. We will speculate that, for flows with bidispersed particles, the probability density functions of whose velocities do not exhibit intersections, one can expect a substantial rise of velocity fluctuations.

The question (which we did not touch upon in this paper) remains open of the study into the frequency spectrum of fluctuations of velocity of solid particles in general and bidispersed particles in particular.

CONCLUSION

We have demonstrated the possibility of using laser Doppler anemometers to investigate the characteristics of turbulent heterogeneous flows which carry solid bidispersed particles. The distribution has been obtained for the first time of the time-averaged and fluctuation velocities of bidispersed particles moving in a turbulent flow of air in a pipe.

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