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THE EFFECT OF PARTICLES ON THE GAS VELOCITY IN A FREE TURBULENT FLOW

M. B. Stakić and D. Z. Milojević

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The article describes experimental studies carried out to investigate the interaction between gas and particles in a free turbulent two-phase flow at the outlet from a rather long vertical tube.

Investigation of phenomena occurring in a two-phase flow of gas and admixtures and knowledge of the velocity, temperature, and concentration fields are important for many plants of chemical industry and power production. The effect of the disperse phase (particles and drops) on the gas flow is especially important. In the present work experimental studies have been carried out to investigate the velocity of the gas phase and return effect of the particles on the velocity of the gas phase in a two-phase flow.

The experimental setup (Fig. 1) consists of a vertical tube 1 with an inside diameter of 10.9 mm and a length of 950 mm (more than 80 diameters, which ensures a fully developed flow at the outlet from the tube). Particles of quartz sand are introduced into tube 1 from a fluidized bed 2. Air is supplied to the tube from a heater in which fine control of the air flow rate is provided with the use of a by-pass input. A Pitot probe 3 connected to a differential manometer 4 served to measure dynamic pressures, and then the velocities of the air flow were calculated at different distances from the tube outlet x along the radius r.

Two experiment series were conducted with quartz sand particles of various sizes. In the first series sand particles of 0.25–0.3 mm were used, and in the second series the particle size was 0.8–1.0 mm. As the sand-particle size could be reduced in the experiment, the sand was sieved continuously, which hampered conduction of the experiment but eliminated errors that could be induced by a decrease in the particle size. Problems caused by charging of the quartz sand particles, clogging and erosion of the Pitot probe were eliminated with suitable means.

The consumption of sand was determined from changes in the mass of sand collected within a certain time interval, and the air flow rate was calculated in terms of the velocity measured at the tube outlet ($x = 0$) from the expression

$$\dot{u} = \frac{d_c^2 \pi}{4} u_0 + 2\pi \int_{r_1}^{r_n} urdr . \tag{1}$$

Figure 2 shows measured air velocity profiles along the flow of pure air and air with particles for the same volume flow rates of the air. One can see clearly that the presence of particles deforms the velocity profile in a two-phase flow. It is especially interesting to note the difference in the effects of the particles on the characteristics of the air flow:

a) Air velocities in the core (central part) of a two-phase flow with particles of 0.25–0.3 mm are higher than those in the core of the flow without particles (for the same initial air flow rate); the inverse relationship was observed on the periphery of the flow.

b) Air velocities in the core of a two-phase flow of air with particles of 0.8–1.0 mm are lower than those in the core of an air flow without particles (for the same initial air flow rate); the inverse relationship is observed on the periphery.

Institute of Nuclear Research Vinča, Laboratory of Thermal and Power Engineering, Belgrade, Yugoslavia.
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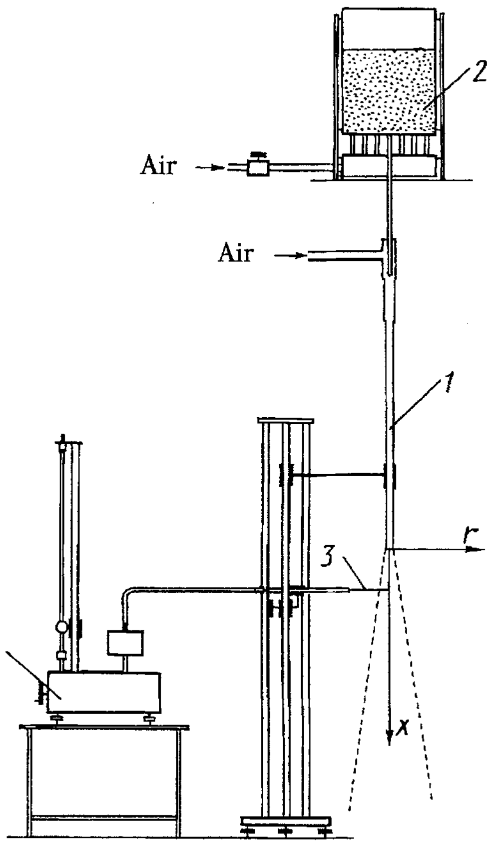

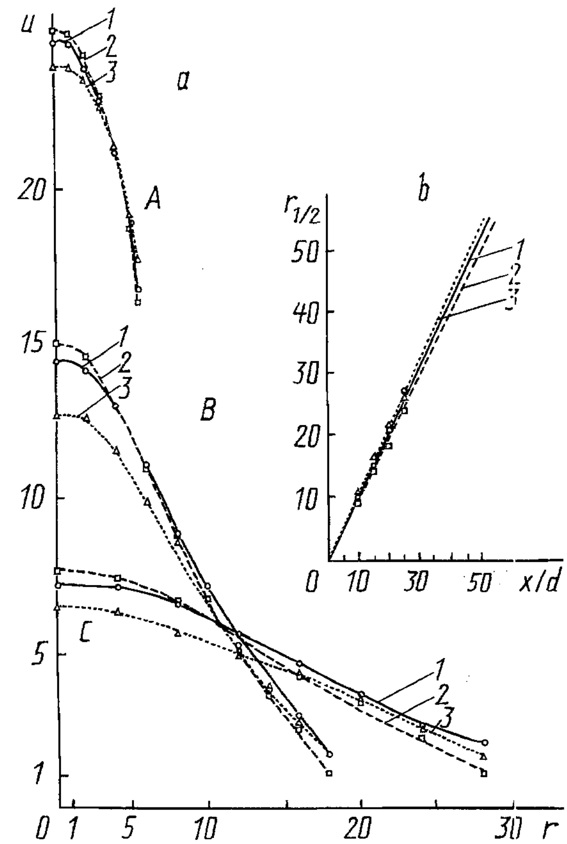

Fig. 1. Experimental setup for determination of hydrodynamic characteristics of a vertical two-phase free flow of air with particles: 1) vertical tube; 2) fluidized bed; 3) Pitot probe; 4) differential manometer.

Fig. 2. Measured air velocity profiles along the flow of pure air and air with particles (at the same volume flow rates of air u_{av} = 21.22 m/sec) (a) and the normal distance from the flow axis to the point at which the velocity is equal to the half of the axial velocity (expansion angle) (b): 1) pure air; 2) air with sand particles 0.25–0.3 mm (k_0 = 1.49); 3) air with sand particles 0.8–1.0 mm (k_0 = 2.11); A) x = 0d; B) = 10d, C) 20d. u, m/sec; r, $r_{1/2}$, mm.

In Fig. 2 one can also see changes in the distance from the flow axis $r_{1/2}$ at which the velocity of the air is half of the air velocity on the flow axis ($u = 0.5u_{fa}$) as a function of x/d for the case of a flow of pure air and for a flow of a two-phase mixture of air with particles. One can see that the expansion angle (the ratio $r_{1/2}/x$) is lower for the case of a two-phase flow of air with particles of 0.25–0.3 mm as compared with the expansion angle of the flow of air without particles. The relationship is inverse in the case of a two-phase flow of air with particles of 0.8–1.0 mm.

In the general case we can consider the effect of particles of three different sizes (small, medium, and large) on a gas flow.

Small particles (of several micrometers) in a two-phase flow follow the gas flow quite well and "respond" to turbulent fluctuations of the gas flow. Because of their small mass and inertia, their return effect on the gas is insignificant; therefore small particles (of about 1 μm) are used in laser-Doppler measurements of gas phase velocities [1, 2]. In the present work their effect is not considered.

Medium particles (for example, of 0.25–0.3 mm) induce an increase in the gas velocity on the axis u_{fa} and in the core of a two-phase flow. Simultaneously, a two-phase flow is narrowed and disappears slowly in comparison with a gas flow without particles, i.e., such particles "entrain" the surrounding gas and accelerate the flow. It can be explained by the fact that due to mass inertia medium-size particles entrain gas particles and accelerate the core

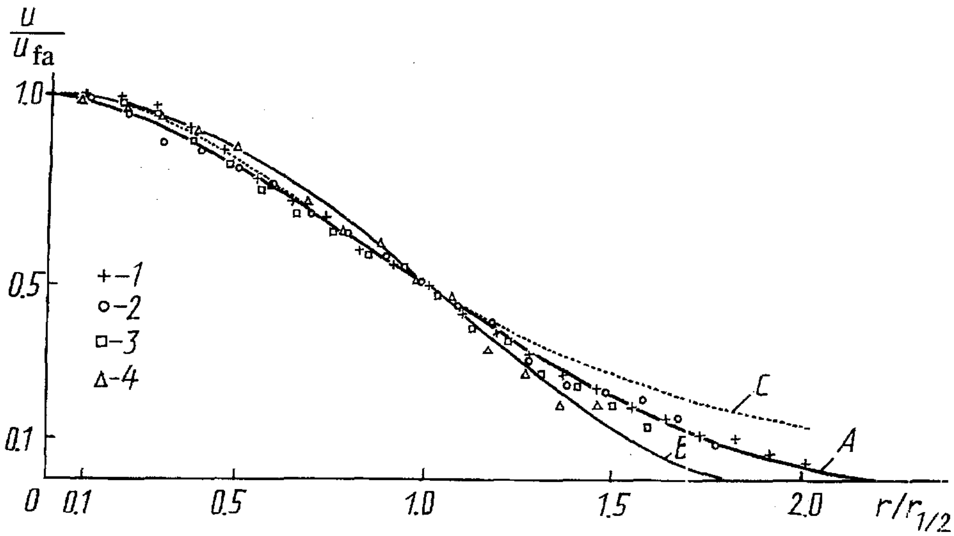

Fig. 3. Dimensionless relation between the velocity ratio and the dimensionless coordinate. Experimental data: 1) $x = 10d$; 2) $20d$; 3) $30d$; 4) $40d$; calculation [4]: A) by Eq. (2); B) by Eq. (3); C) by Eq. (4).

of the gas flow. This phenomenon is exhibited to a greater extent for a large mass ratio of the gas and particles in a two-phase flow.

Large particles (for example, of 0.8–1.0 mm) induce a decrease in the gas velocity on the axis and in the core of a two-phase gas flow with particles and expansion and rapid disappearance of the two-phase flow in comparison with the gas flow without particles. It can be explained by the substantial mass of the particles and the large momentum (kinetic energy) spent on their acceleration, which leads to a decrease in the gas velocity. In this case large particles do not have enough time to attain a sufficient velocity and entrain the gas phase, therefore it can be assumed that the gas phase is accelerated in the areas that follow those in which the gas velocity was measured.

Similar experimental data were obtained in [3], but the conclusions drawn from them were contradictory to our results on the effect of medium and large particles on the gas velocity in a two-phase flow.

It is known from the literature that the velocity field in a free flow can be expressed by a dimensionless relation between the velocity ratio and the dimensionless coordinate. Thus, the following relations are used for changes in the velocity profile at a certain distance from the flow outlet [3]:

$$\frac{u}{u_{fa}} = \left[1 - 0.292\left(\frac{r}{r_{1/2}}\right)^{1.5}\right]^2, \tag{2}$$

$$\frac{u}{u_{fa}} = 1 - \left[1 - \left(1 - 0.56\frac{r}{r_{1/2}}\right)^{1.5}\right]^2, \tag{3}$$

$$\frac{u}{u_{fa}} = \frac{1}{\left[1 + 0.414\left(\frac{r}{r_{1/2}}\right)^2\right]^2}. \tag{4}$$

Comparison of the obtained results with the given relations (Fig. 3) shows that the best agreement is obtained with the use of relation (2).

From the condition of conservation of momentum of a two-phase flow

$$\int_0^A \rho_g u^2 (1 + k)\, dA = I_i, \tag{5}$$

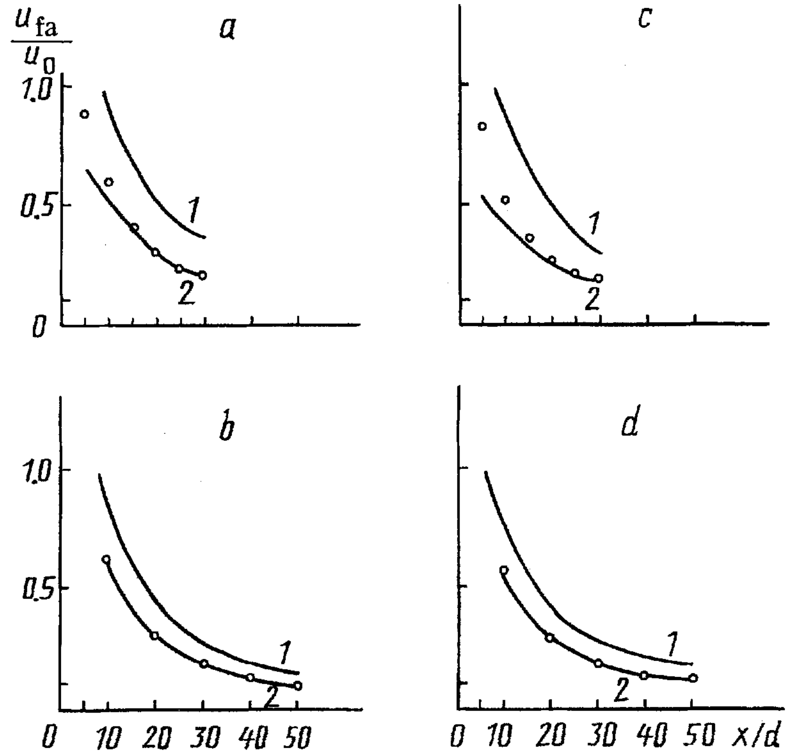

Fig. 4. Comparison of theoretical relation (7) with the experimental results obtained for a two-phase flow of air with particles for the boundary cases $u_{av} = u_p = u_0$ (1) and $u_{av} = u_0$, $u_p = 0$ (2): a) $d_p = 0.25-0.3$ mm; $u_{av} = 21.22$ m/sec ($k_0 = 1.49$); b) $d_p = 0.25-0.3$ mm; $u_{av} = 36.41$ m/sec ($k_0 = 0.72$); c) $d_p = 0.8-1.0$ mm; $u_{av} = 21.22$ m/sec ($k_0 = 2.11$); d) $d_p = 0.8-1.0$ mm; $u_{av} = 36.41$ m/sec ($k_0 = 0.91$).

where

$$I_i = m_g u_g + m_p u_p ,$$

and from the condition of conservation of particle mass in the flow

$$\int_0^A \rho_g k u dA = m_p \tag{6}$$

an equation relating the dimensionless gas velocity u_{fa}/u_0 to $r_{1/2}/r_0$ can be derived:

$$\frac{u_{fa}}{u_0} = 2.24 js \frac{1}{(R/r_0)^2} \left(\sqrt{\left(1 + \frac{1.49}{js^2} \left(\frac{R}{r_0} \right)^2 \right)} - 1 \right), \tag{7}$$

where

$$s = \frac{m_p u_0}{I_i}; \quad j = \frac{I_i}{\rho_g u_0^2 A_0}.$$

Since the velocity of the particles at the nozzle outlet u_g is most often known, two boundary cases will be considered:

1. If a homogeneous two-phase mixture flows out of the nozzle, when $u_p = u_g = u_0$, then we obtain

$$j = 1 + k_0 , \quad s = k_0/(1 + k_0) ;$$

2. If gas flows out of the nozzle and at the outlet it is mixed with particles without the initial velocity, i.e., if $u_g = u_0$, $u_p = 0$, we have

$$j = 1, \quad s = k_0.$$

A comparison of theoretical relation (7) for the two aforesaid boundary cases with the experimental results obtained for a two-phase air flow with particles is shown in Fig. 4. One can see that as the initial mass ratio of particles k_0 decreases, the difference between the dimensionless ratios of the velocities u_{fa}/u_0 for the two aforesaid boundary cases diminishes. Thus, if $k_0 \to 0$, the value of u_{fa}/u_0 obtained from Eq. (8) is close to the values for a gas flow without particles.

Values of u_{fa}/u_0 obtained from experimental results either lie between u_{fa}/u_0 obtained from Eq. (7) for the first and second boundary cases or coinside with the latter. It shows that in a tube at low initial gas velocities, particles are accelerated to a greater extent as compared with the gas, i.e., the difference in the velocities of the gas and particles at the tube outlet is smaller at lower initial gas velocities. At higher initial gas velocities this difference is higher.

For complete verification of the conclusions made here it is necessary to investigate the measured particle velocity at the nozzle outlet and in the flow. It is also important to obtain data on the velocity of gas and particles in a two-phase flow with modern measuring methods (for example, laser-Doppler measurement) and compare them with the present results.

NOTATION

A, cross-sectional area of the flow; A_0, initial cross-sectional area of the flow; d, diameter of the flow; d_p, average diameter of particles; I_i, initial momentum of the two-phase flow; k, mass ratio of particles and gas ($k = m_p/m_g$); k_0, mass ratio of particles and gas in the initial cross-section of the two-phase flow ($x = 0$); m_g, mass flow rate of gas; m_p, mass flow rate of particles; r, instantaneous radius of the flow; r_0, radius of the initial cross-section of the flow; $r_{1/2}$, normal distance from the flow axis to the point at which the velocity of gas is equal to the half of the axial velocity; R,cross-sectional radius of the flow; u, velocity; u_a, air velocity; u_{fa}, gas velocity on the flow axis; u_g, gas velocity; u_{av}, average gas velocity in the initial cross-section for two-phase and single-phase flows; u_0, gas velocity on the axis of the initial cross-section of the flow; u_p, particle velocity; x, distance along the axis from the original of coordinates; ρ_g, gas density.

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