11. G. J. Payne and R. G. H. Prince, "The transition from jetting to bubbling at a submerged orifice," Trans. Inst. Chem. Eng., 53, 209 (1975).

DETERMINATION OF PARTICLE DENSITY IN TWO-PHASE FLOW

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A method is proposed for determining the mass concentration of the dispersed phase in gas flows from the displacement of the Mach disk during discharge of an underexpanded stream into a vacuum.

The development of a number of fields of engineering and technology, in particular plasma metallurgy and chemistry, requires devising new methods for monitoring the mass fraction of the dispersed phase. Many methods are known for determining the content of the dispersed phase, based on the sampling of particles, the interaction of the medium with corpuscular and electromagnetic probing radiation, and the variation of the electrokinetic and aerodynamic properties of the medium [1-4]. However, the upper limit of the values of the mass fraction of the dispersed phase φ which can be measured by any of these methods is severely restricted. When aspiration methods are used in high-speed high-temperature flows with a large particle content, particles are deposited in the samplers and clog them. The radiation scattering and absorption coefficients of the medium and the variation of its electrical and aerodynamic parameters at high particle densities become nonlinear functions whose form we cannot predict theoretically. Thus, the measurement of values of the mass fraction of the dispersed phase which are near unity is a complex problem.

A method proposed in [5] is based on the determination of the effect of the dispersed phase on the position of the normal shock in an underexpanded jet. It was found experimentally [6] that the introduction of solid particles into a supersonic underexpanded gas jet emerging from a nozzle has an appreciable effect on the shape and position of shock waves. As φ is increased, the jet spreads out, and the normal shock approaches the nozzle exit.

The position of the normal shock on the jet axis can be very accurately determined with a total pressure transducer using a standard technique, or by any noncontact method. Thus, e.g., in dense streams shadow devices [7] can be used, and in diffuse gases glow discharge [8] or an electron beam [9].

The effect of the solid phase on the position of the normal shock in a supersonic underexpanded jet of a mixture can be calculated by using a flow model [10] describing the properties of the jet under the assumption that it is equivalent to two-phase flow of a gas with an effective value of the isentropic exponent given by

$$\lambda = \gamma \frac{1 + \varphi(\bar{c}_p/c_p)}{1 + \varphi\gamma(\bar{c}_p/c_p)}, \qquad (1)$$

where γ is the isentropic exponent, and $\bar{c}_p/c_p$ is the ratio of the specific heats of the particles and of the gas at constant pressure. For one-dimensional two-phase flow [11] with equal velocities and temperatures of particles and gas, the relative change of the distance from the nozzle exit to the normal shock as a function of φ and the Mach number Ma at the nozzle exit is given by

$$\frac{\overline{X}}{X_0} = \left\{\frac{\lambda^2(\lambda-1)(\gamma+1)(2\gamma-1)[1+2/(\lambda-1)\,\overline{\mathrm{Ma}}^2]}{(\lambda+1)(2\lambda-1)\gamma^2(\gamma-1)[1+2/(\gamma-1)\,\mathrm{Ma}^2]}\right\}^{1/2}\left(\frac{\overline{\mathrm{Ma}}}{\mathrm{Ma}}\right)^2, \qquad (2)$$

where $\overline{X}_0$ and X_0 are, respectively, the positions of the normal shock in pure gas and in the presence of the dispersed phase; $\overline{\mathrm{Ma}}$ and Ma are the Mach numbers at the nozzle exit under those same conditions. When the velocity of the particles in the stream is less than the velocity of the gas, i.e., for large enough particles, the position of the normal shock is given by

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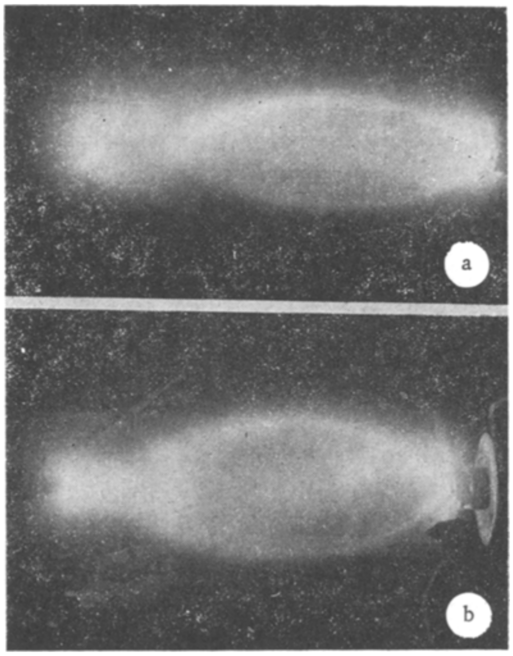

Fig. 1. Change of form of reflection of standing shock from axis of jet in the absence and presence of solid phase: a) Ma = 3, γ = 1.4, p_a/p_b = 170, φ = 0; b) same jet parameters, φ = 0.25.

$$\frac{\overline{X}_0}{X_0} = \left\{ \frac{\lambda^2(\lambda-1)(2\gamma-1)[1+2/(\lambda-1)\overline{\mathrm{Ma}}^2]}{(2\lambda-1)(1+\varphi)\gamma^2(\gamma-1)[1+2/(\gamma-1)\mathrm{Ma}^2]} \right\}^{1/2} \left(\frac{\overline{\mathrm{Ma}}}{\mathrm{Ma}} \right)^2 . \tag{3}$$

In deriving Eqs. (2) and (3) viscous effects were not taken into account except for their contribution to the drag coefficient of the particles. An empirical relation is given in [12] for the position of the shock as a function of φ, Ma, and the ratio of the pressure p_a at the nozzle exit to the ambient pressure p_b:

$$\frac{\overline{X}_0}{d_a} = \frac{0.69\mathrm{Ma}}{1+0.197\mathrm{Ma}^{1.45}\varphi^{0.65}} \left(\gamma \frac{p_a}{p_b} \right)^{1/2} , \tag{4}$$

where d_a is the diameter of the nozzle.

A numerical procedure for investigating the shape and position of shocks in plane and axisymmetric two-phase jets under various discharge conditions was developed in [13].

Thus, the mass fraction of particles in a two-phase jet can be determined accurately enough for engineering practice from calculated or experimental relations between the position of the normal shock and the particle density.

To refine the existing procedure for determining the mass fraction of particles in transition flow ($10^{-4} < \mathrm{Kn}_d\,(p_a/p_b)^{0.5} < 10^{-2}$), experiments were performed on the effect of particles on the position and size of shocks in an underexpanded two-phase air jet. The experiments were performed on low-density gasdynamic apparatus [14] consisting of a vacuum chamber ($V \approx 100$ liters) provided with windows for photographing the jet, devices for supplying and heating the gas, a system for making the shocks visible, and an exhaust system. The apparatus described contained several mechanical and booster vapor-jet pumps with a total exhaust rate of 60 m^3/sec. The shocks in the jet were made visible by a low-power glow discharge. The working material was exhausted from the reservoir into the vacuum chamber through a supersonic nozzle with various degrees of expansion. A resistance heater in the reservoir kept the gas at 700°K to prevent its condensation. Solid particles of aluminum oxide powder 20-30 μm in diameter were fed into the nozzle through bin feeders at a known flow rate by free aeration. The flow rate of gas through the nozzle was monitored by an RS-3 flowmeter. The discharge parameters were varied over the following limits: Mach number at the nozzle exit Ma = 1.5-3, $10 < p_a/p_b < 10^3$, evaucation criterion $10^{-4} < \mathrm{Kn}_d\,(p_a/p_b)^{0.5} < 10^{-2}$, φ = 0.2-0.9. The introduction of particles into a supersonic underexpanded jet causes an increase in

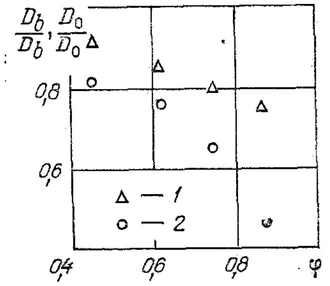

Fig. 2

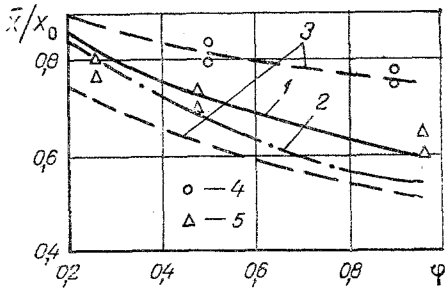

Fig. 3

Fig. 2. Dimensions of standing $D_b/\bar{D}_b$ and normal $D_o/\bar{D}_o$ shocks as functions of φ: 1) standing shock; 2) normal shock.

Fig. 3. Calculated and experimental positions of normal shock as functions of φ: 1) Eq. (2); 2) (3); 3) (4); 4) experiment for Ma = 1.5; 5) same for Ma = 3.

the diameters of the standing and normal shocks, and a transition from regular to irregular reflection — the Mach disk (Fig. 1). Figure 2 shows the diameters of the standing and normal shocks as functions of φ.

It can be seen from the figure that as φ increases, the diameter of the normal shock increases more rapidly than the diameter of the standing shock. Figure 3 shows the relative position of the normal shock as a function of φ, for various values of Ma calculated from Eqs. (2)–(4), and our experimental values. The experimental and calculated data show satisfactory agreement for Ma = 1.5 but an appreciable divergence for Ma = 3, which can be accounted for by the decrease in the drag coefficient of the particles with an increase in the Mach number for Kn = const because of the increased effect of slipping [15].

The error of the method is determined by the characteristics of the measuring systems used to record the position of the normal shock and certain features of two-phase jet flows, including condensation of the working gas and the effect of the Reynolds number on the particle drag. In measuring the position of the normal shock, e.g., by photographing the jet made visible by low-power glow discharge, the error is 2-3%. The method is limited by the dimensions of the working volume of the chamber and jet and the flow regime for $Kn_d\ (p_a/p_b)^{0.5} \gg 10^{-3}$, when there is an appreciable spreading out and thickening of the shocks, leading to a rapid increase in the error of the measurements.

The error in determining the mass fraction of particles can be considerably reduced by calibrating the apparatus used to realize the proposed method in a specific range of working parameters.

LITERATURE CITED

1. B. I. Leonchik and V. L. Mayakin, Measurements in Dispersed Flows [in Russian], Energiya, Moscow (1971).
2. A. P. Klimenko, Methods and Devices for Measuring Concentrations of Dust [in Russian], Khimiya, Moscow (1978).
3. S. P. Belyaev et al., Optical-Electronic Methods of Measuring Aerosols [in Russian], Energiya, Moscow (1979).
4. B. S. Rinkevichyus and G. A. Saltanov, "Optical methods for investigating two-phase flows," in: Vapor-Liquid Flows [in Russian], Nauka i Tekhnika, Minsk (1977), pp. 176-194.
5. S. A. Senkovenko and A. G. Sutugin, "A method for measuring the concentration of particles in dispersed flow," Favorable decision of VNIIGPE on claim No. 2267463/25 of April 25, 1979.
6. S. A. Senkovenko and N. I. Yushchenkova, "Effect of condensation and the solid phase on the structure of a supersonic underexpanded CO_2 jet," Data of Second All-Union Conference on Problems of Evaporation, Heating, and Gas Dynamics of Dispersed Systems [in Russian], Odessa State University (1972), p. 60.
7. L. A. Vasil'ev, Shadow Methods [in Russian], Nauka, Moscow (1968).

8. M. J. McCroskey and J. G. McDougall, "Shock wave shapes on a sharp flat plate in rarefied hypersonic flow," AIAA J., 4, 184 (1966).
9. D. E. Rothe, "Flow visualization using a traversing electron beam," AIAA J., 3, 1945 (1965).
10. R. E. Hoglund, "Recent advances in gas-particle nozzle flows," ARS, 32, 662 (1962).
11. A. B. Bauer, "Normal shock location of underexpanded gas-particle jet," AIAA J., 3, 1187 (1965).
12. C. H. Lewis and D. J. Carlson, "Normal shock location of underexpanded gas and gas-particle jets," AIAA J., 2, 776 (1964).
13. V. I. Blagosklonov and A. L. Stasenko, "Two-dimensional flows of a multiphase mixture in a nozzle and jet exhausting into a flooded space," Uch. Zap. TsAGI, 8, No. 1, 32 (1977).
14. S. A. Senkovenko, "Structure of an underexpanded supersonic CO_2 jet," Proc. of Second Republican Conference on Aerodynamics and Heat and Mass Transfer, Section: Aerodynamics at High Velocities [in Russian], Kiev (1971), pp. 154-160.
15. G. V. Tsiklauri, V. S. Danilin, and L. I. Seleznev, Adiabatic Two-Phase Flows [in Russian], Atomizdat, Moscow (1973).

EXTERNAL EXCHANGE IN A DISPERSE BED

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The time-varying convective heat or mass transfer from objects immersed in a filtering granular bed is analyzed. Absorption of the heat or mass in the bed is taken into account.

Heat and mass transfer between a bed and the surface of objects immersed in the bed is important in many processes involving heat treatment or diffusion treatment of articles in still or fluidized granular beds, during the cooling of furnaces and reactors with granular beds caused by inserting special heat exchangers into them, etc.

If the characteristic linear dimension of the immersed object is much larger than the characteristic dimension of the microstructure of the bed (e.g., the grain diameter) it is natural to use the continuum transport equations in the various phases in the bed to describe these processes. In several important cases these two equations can be replaced by a single transport equation; this approach corresponds to adopting a model for the disperse system around the object consisting of a homogeneous continuous medium which is described by appropriate effective thermal and diffusion properties. It is important to note that in general the effective thermal diffusivity and diffusion coefficient, which represent not only molecular transport but also the transport due to the convective heat and mass dispersion in the discontinuous pore space of the filtering granular bed, are inhomogeneous and depend on the local filtration velocity of the continuous phase in the bed.

The problems of the steady-state convective transfer from objects in a granular bed penetrated by a filtering flow were first formulated and solved in [1, 2], where absorption of heat or mass was neglected. Absorption has been taken into account in these problems on the basis of the film or penetration theory, as a rule; i.e., absorption has been taken into account by ignoring convection, in accordance with mass-transfer systems in which chemical reactions are occurring (see, e.g., the review in [3, 4]). In [5] there is an example of the application of a penetration theory to the analysis of external heat transfer in a fluidized bed. In the first case, as is usual in convective-diffusion processes, the surface in the flow is far from uniformly accessible with respect to diffusion; in the second case, it is uniformly accessible.

In actual granular-bed installations it is extremely common to find situations in which the convective transport and the acceleration of this transport caused by the absorption of

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