ACCELERATION AND INTERACTION OF MULTIPHASE STREAMS

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Investigations of nonequilibrium multiphase flows are interesting in connection with various applications, particularly with the creation of high-enthalpy installations [1], gas-dynamic lasers (GDL) [2], active means of thermal shielding, etc. As follows from [2], multiphase lasers possess a number of advantages over the GDL usually investigated, particularly in the specific energy characteristics. However, the realization of these advantages is essentially connected with the solution of complex gas-dynamic problems which have not come up in traditional GDL. Some gas-dynamic problems of hypersonic multiphase lasers were examined in [3, 4]. These investigations are continued in the present report.

Let us consider the problem of the maximum possible acceleration of particles of the solid or liquid whose flux $\hat{\rho}\hat{v}$ comprises a significant amount, comparable with the flux ρv of the carrier gas $\rho v(\varepsilon = \widehat{\rho v}/\rho v \sim 1)$. Light gases such as hydrogen or helium can be used as the carrier. Such a problem was first analyzed in a two-dimensional formulation in [3]. It was shown that it is advisable to accomplish the acceleration in nozzles having an extended transonic section and a supersonic section with a small expansion angle. The exchange of momentum between the accelerating gas and the particles occurs most intensely under these conditions, since the characteristic time of relaxation of the particle velocity (for the most probable size in the mass spectrum) relative to the gaseous phase is much less than the principal gas-dynamic time of flow, and the parameters of the mixture approach the equilibrium values corresponding to the effective adiabatic index $\hat{\varkappa} = (\varkappa + \varepsilon c)/(1 + \varepsilon c)$ $(c = c^{\circ}/c_V$ is the relative heat capacity of the particle material). If the mass spectrum of the particles being accelerated is such that the equilibrium conditions are reached, the parameter $\hat{\varkappa}$ can be used for an upper estimate of the possible velocities for acceleration by different gases. Although light gases (such as hydrogen or helium) are the best, other conditions being equal, their use can be inconvenient for a number of technological reasons. Therefore, other gases such as methane or air are also of interest. Comparative data on acceleration in different gases as a function of ε under equilibrium conditions are presented in Fig. 1. The expression $v_m^e = \left[\frac{2R_0T_0(\varkappa + \varepsilon_c)}{\mu(\varkappa - 1)(1 + \varepsilon)}\right]^{1/2}$ for the maximum velocity was obtained from the energy equation with the condition that expansion of the disperse mixture proceeds until its complete cooling (μ is the molecular weight, R is the universal gas constant, $c^{\circ} \approx 1.35 \cdot 10^3$ J/kg·deg for CO_2 particles, and $T_0 = 250$°K). The data obtained indicate that without the use of light gases (H_2, He) it is impossible to accelerate particles to velocities of $>10^3$ m/sec without increasing the initial temperature. But the temperature can only be increased when nonvaporizing particles are accelerated.

A strange result, at first glance, follows from the data presented in Fig. 1, indicating that air accelerates particles better, the higher the mass ratio ε. This originates in the cooling owing to the heat capacity of the particles, the contribution of which becomes considerable at large values of ε and hence large absolute amounts of the solid phase.

Allowance for phenomena associated with vaporization in the process of acceleration is also an important task, since this process can lead to worsening of the carrier properties of the light gas. The solution of this problem was obtained on the basis of the program of [5, 6] with allowance for the diffusional mechanism of particle vaporization and condensation. In Figs. 2 and 3 we show the results of calculations of the acceleration of spherical CO_2 particles with initial radii $\hat{a}_0$ = 1-15 μm by hydrogen at a forechamber pressure p_0 = 7 MPa, a gas temperature T_0 = 250°K, and a particle temperature $\hat{T}_0$ = 170°K in a nozzle having a critical cross section with a half-width $y_* = 10^{-3}$ m and an extended transonic section.

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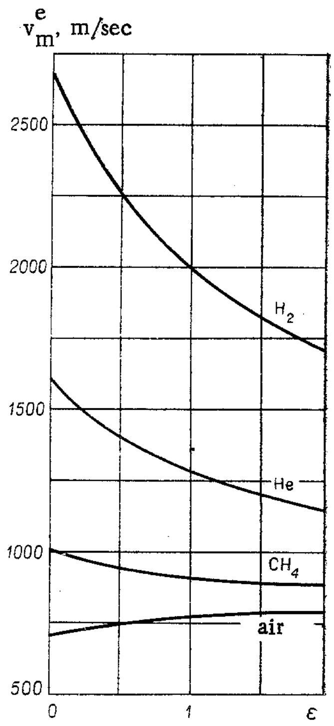

Fig. 1

The aperture half-angle of the supersonic section of the nozzle is 5° and $\varepsilon \ll 1$. It was assumed that in the converging section of the nozzle the outermost particle trajectories are directed along the walls. The calculations showed that particle vaporization during acceleration is insignificant. The relative variation in the radii $\hat{a}_i/\hat{a}_{i_0}$ of particles of different fractions in the process of vaporization along the nozzle is shown by dashed lines in Fig. 2. We emphasize that under these conditions vaporization plays a minor role owing to the low values of T_0 and hence the low final rates of particle acceleration. It is seen, in particular, that the relative change in radius for the finest particles of ~1 μm is $\Delta\hat{a}/\hat{a}_0 \leqslant$ 5% at distances of $x/y_* \leqslant 10^2$ from the critical cross section. Therefore, if $\varepsilon \leqslant 1$ and particles with $\hat{a}_0$ ~ 5-10 μm comprise the basis of the mass spectrum,† the influence of the vaporized mass on the parameters of the carrier gas can be neglected under these conditions. It is also seen from the data of Fig. 2 that large particles ($\hat{a}_0 \gtrsim 9$ μm) are unable to turn away from the axis after passing through the critical cross section and can strike the opposite wall. Refinement of the model of the interaction of particles with solid surfaces and the boundary layer is needed for an investigation of their further evolution.

The velocity distribution over the particle spectrum in the cross section $x/y_* = 10^2$ is shown in Fig. 3, from which follows the considerable velocity scatter (~10^3 m/sec) of the different fractions $\hat{a}_i$. The horizontal lines correspond to the gas velocities in this cross section.

Thus, under actual conditions, with a particle size distribution function present, equilibrium conditions with respect to velocity in the entire spectrum cannot be achieved even in nozzles with small stream-expansion angles. A comparison of calculations on the acceleration of particles by helium and hydrogen under the same initial conditions shows that a higher absolute particle velocity is reached in the latter case (Fig. 3), despite the lower molecular weight and density of hydrogen.

The results of a numerical calculation of the flow of a hydrogen mixture with a high content of carbon dioxide particles ($\varepsilon = 1$) under the assumption that the suspension is monodisperse ($a_0 = 5$ μm) and with an expansion angle $\theta_1 = 5°$ in the supersonic section are shown by solid lines in Fig. 4. On the left side of Fig. 4 we give the distributions of the "axial" component of the velocities of the particles ($\hat{u}$) and the gas ($u(0)$ and u_b) along the plane $y = 0$ and the nozzle boundary y_b, respectively, and on the right side we give the transverse distributions of the same quantities in one of the cross sections ($x = 130$). The

†As shown in [3, 4], such sizes offer the greatest interest for the creation of population-inverted media.

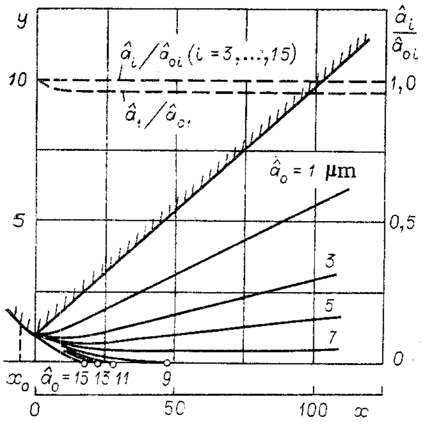

Fig. 2

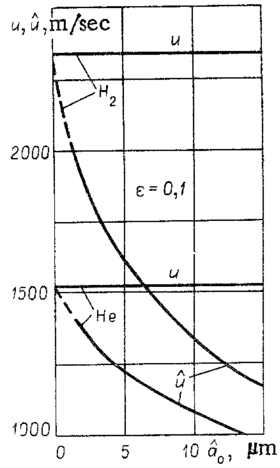

Fig. 3

effects of the nonhomogeneity of the flow of the mixture (in the region of two-phase flow the gas velocity is considerably lower than near the nozzle boundary and the particle velocity is also lower than in the case of $\varepsilon \ll 1$; see Fig. 3) and the nonequilibrium (the particle velocity is considerably lower than the gas velocity) are seen. Consequently, the expansion angle $\theta_1 = 5°$ is too large and does not assure the optimum acceleration, since gas leaves the region of two-phase flow. A decrease in the aperture angle (dash–double-dot lines for $\theta_1 = 3°$ and dashed lines for $\theta_1 = 1°$ in Fig. 4) creates more favorable conditions for acceleration, since with the same nozzle lengths equal particle velocities are reached in cross sections where there is still a reserve of increase in gas velocity and hence in particle velocity. Of course, this reserve can be realized only with a lengthening of the nozzle. For a fixed length there is a value of θ_1 at which the particle velocity is maximal. By curving the nozzle walls one can attain its contact with the separatrix, in which case all the gas will again participate in particle acceleration. Thus, the problem of optimization of the shape and length of an acceleration nozzle can be formulated.

In those cases when for technological reasons it is impossible to pass a given flow rate through a slot nozzle and one must use round (square) openings of the same area, it becomes necessary to use acceleration nozzles having supersonic sections with large expansion angles along one of the coordinates. Here a specific feature of multiphase flow is manifested most clearly; it consists in the appearance of clearly expressed separatrices, surfaces separating the regions of flow of pure gas and a multiphase mixture [3, 5]. Equilibrium conditions are not attained in this case, since during expansion the density of the propelling gas decreases and it goes forward without imparting significant momentum to the particles. In this case an increase in the acceleration velocity can be achieved by increasing the flow rate of the light gas while simultaneously decreasing the size of the particles being accelerated.

Similar restrictions on the shape of the critical cross section can also occur in a nozzle system which is a carrier for a vibrationally excited medium such as N_2. It is clear that with critical cross sections of the same area a slot nozzle will provide better characteristics with respect to the freezing-in of vibrational energy than a round nozzle, since the freezing-in efficiency is determined by the expansion time $\tau \sim h/a^*$, where h is the diameter of the critical cross section or the slot height and a^* is the speed of sound in this cross section. After acceleration the particles are introduced into a quasi-comoving stream through an aerodynamic sluice in which the main working gas and the particle-carrier gas interact. In the simplest sluices [7] the deflection of the light gas can be organized with the help of compression of the stream or its expansion. In the case when a mechanism of stream expansion of the type of Prandtl–Mayer flow is used the pressure decreases along the contact discontinuity separating the gases, and hence the working gas must also expand, i.e., the contact discontinuity is curved even in the case of the absence of particles. A system with stream compression can prove more practical from the point of view of minimization of disturbances in the working gas, since in this case the tangential discontinuity is close to

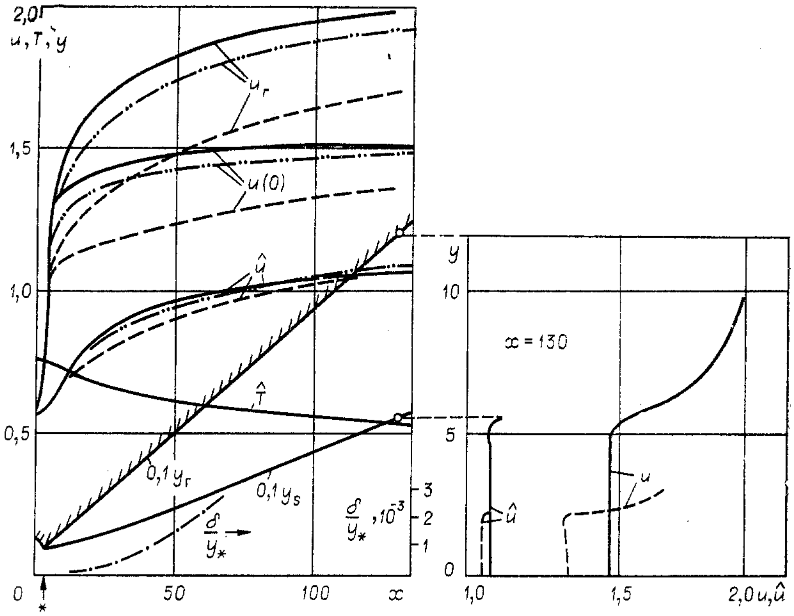

Fig. 4

a plane surface, the pressure at which is constant.* As shown in [3], however, such a system requires rather precise regulation and works in a narrower range of initial pressures and flow rates of the light gas than a system based on expansion. Therefore, at considerable flow rates of the light gas a system based on expansion can prove to be more practical. In principle, in either system the exhausted light gas can be reused in another aerodynamic sluice designed for the extraction of radiation [7].

In an exact formulation the problem of the interaction of a two-phase stream with a hypersonic stream in which internal degrees of freedom are excited is complex and as yet unsolved. A numerical solution of this problem without allowance for vibrational relaxation but with allowance for vaporization can be obtained on the basis of a program permitting the calculation of particle acceleration [3] (Figs. 2 and 4), although this is a very laborious task, especially in connection with the necessity of optimizing the solution with respect to several parameters. Therefore, even after an exact solution is obtained it will make sense to simplify the formulation as follows. Suppose that the flow in the interaction region is plane and inviscid and a counterinfluence of particles on the gas is absent. We designate the parameters of the light carrier gas by the index 1 and those of the working gas into which the particles are introduced by the index 2. In the present report the investigated gases were hydrogen and nitrogen, respectively, and the same program for calculating plane supersonic flows as in [3] was used. From the basic requirement of minimizing disturbances in stream 2 it follows that the shock wave must lie in the light gas, while a contact discontinuity must be located at the contact boundary between the streams. Let us determine the range of flow parameters in which this condition is satisfied. In doing this we take into account the results of the solution of the particle-acceleration problem presented in Fig. 4. For this purpose it is convenient to introduce two dimensionless parameters, $W_1 = \hat{u}/u_1$ and $W_2 = \hat{u}\cos\alpha/u_2$, characterizing the relative lag of the particles in the accelerating gas 1 and the working gas 2 (α is the angle of encounter of the two streams). Isochors of ρ_1/ρ_2 are shown in Fig. 5 for given values of W_2, α, and the Mach number M_2; using them one can choose values of W_1 and M_1 such that the shock wave is located in hydrogen. The dependences $W_1(M_1)$ for three hydrogen acceleration nozzles with expansion angles θ = 1, 3, and 5° (see Fig. 4) are shown by dashed lines. The points in Fig. 5 correspond to different lengths x of the acceleration nozzles (in millimeters) at which the condition of minimization of disturbances in the gaseous phase is satisfied with allowance for the corresponding isochors.

*It is assumed that mutual contact of the mixing streams occurs only in the region of two-phase flow in an acceleration nozzle with a constant distribution of parameters over the cross section (right side of Fig. 4).

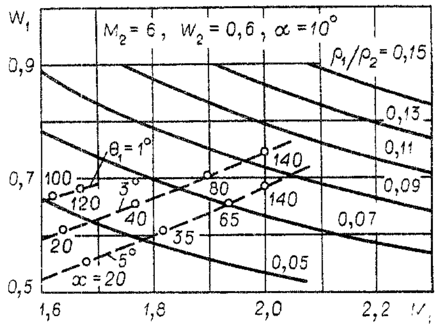

Fig. 5

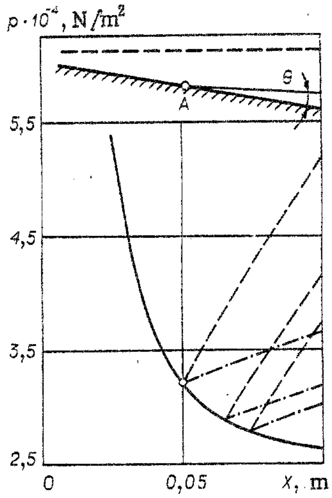

Fig. 6

The introduction of particles into a comoving supersonic stream raises the problem of the uniformity of mixing of the multiphase streams. One must have a uniform gas-dynamic field in the working part of the wind tunnel and in the zone of action of the resonator. However, shock waves can develop in the mixing zone, both due to the interaction of the gas streams and ahead of the collection of entering particles if their velocity is supersonic relative to the gas. Moreover, wave disturbances develop in the mixing zone owing to the fact that the particles carry mass, momentum, and energy and they can vaporize and thereby alter the macroscopic parameters of the original flow. Some problems connected with the investigation of the conditions under which multiphase hypersonic mixing can be uniform are discussed in [3, 4]. The influence of vibrational relaxation on the process of particle vaporization is also investigated in these reports and final equations are obtained for the depth of penetration of different particles into a comoving supersonic stream in the modes of a continuous medium and of transitional and free-molecule streamline flow.

All these investigations were conducted for ideal flow without allowance for boundary layers, separation zones, etc. In hypersonic modes of mixing, however, the relative role of viscous phenomena grows in comparison with flows of moderate supersonic velocity. Moreover, with the introduction and vaporization of particles the pressure can vary [3, 4], which leads to the propagation of disturbances upstream and to separation of the boundary layer. This in turn disturbs the uniformity of the inviscid core of the stream, as well as the degree of inversion and amplification of the medium. Therefore, let us dwell in more detail on phenomena connected with the presence of boundary layers. For this purpose we use the results obtained in [8]. The flow into which the particles are introduced is hypersonic, expanding in a nozzle of special shape to Mach numbers $M_2 = 6$–8. The distribution of the displacement thickness of the boundary layer in such a nozzle is characterized by a positive second derivative, and yet the ratio of the displacement thickness to the size of the inviscid core in the exit cross section of the nozzle is small, as the calculations show (see Fig. 4). In a nonseparation mode of flow the influence of viscous forces is concentrated near the nozzle walls, but sharp changes in the nozzle profile or pressure increases in the working section can lead to separation of the boundary layer and to variation of the flow parameters in a region comparable in thickness with the nozzle radius. The pressure change occurring during the introduction of particles and the degree of this change in one direction or the other as a function of the number of particles, their velocity relative to the gas, the degree of vaporization, etc., can be determined from the equations obtained in [4]. Thus, it remains to establish those critical drops for which separation of the boundary layer occurs upstream from the section of particle introduction. In the present work we used the equations obtained in [8, 9] to estimate these drops in the cases of laminar and turbulent modes of flow in the boundary layer. In Fig. 6 the solid line shows the pressure variation during discharge from a wedge-shaped nozzle with an aperture half-angle $\theta_* = 10°$ at $p_0 = 6$ MPa and $T_0 = 3000°K$, while the dashed lines (turbulent boundary layer) and dash-dot lines (laminar boundary layer) emerging from different points of this curve give the pressures at which stream separation occurs in the corresponding nozzle cross section. It is seen that the turbulent mode is more stable against separation. The angle θ at which separation and the development of a viscous mixing zone occur is also shown in Fig. 6. Although this angle is less than the half-angle of expansion of the wedge ($\theta \approx 4°$), separation flow can occupy a quite considerable part of the area in the nozzle exit cross section. The calculations show that the separation point moves upstream with an increase in p_0 and with a constant value of Δp connected with the introduction of particles. This is explained by an increase in the Reynolds number and a decrease in the critical pressure drop caused by separation in the given nozzle cross section. We note that suction of the boundary layer in a nozzle system of this type should lead to a decrease in the undesirable effects connected with viscosity. Refinement of the results obtained also requires further analysis allowing for the three-dimensional character of the flow and the reverse influence of the boundary layer and separation on the external inviscid flow. Allowance for these phenomena requires changes in the approach to the formulation of the problem of flow in nozzles for the circle of problems under consideration. In the general case the geometrical configurations of these nozzles require the solution of the three-dimensional problem. The corresponding calculation programs are presently in the development stage, so that the question of how correct are two-dimensional calculations in the presence of a boundary layer is important. One of the possible courses of solution consists in the use of the method of successive approximations, when the profile of the boundary layer is first estimated for a given geometry, then the multiphase flow or the flow of a vibrationally excited gas is calculated for the "effective" shape of the resulting nozzle, then the boundary layer is again refined, etc. Just this course was used in the present work. Here, of course, the results of the calculation of an inviscid stream [3] can be taken as the zeroth approximation. It is feasible to do this in those cases when the initial configuration of the nozzle system does not raise doubts as to the two-dimensionality of the flow. But in those cases when the "three-dimensionality" is relatively minor (such as in pyramidal nozzles having a small expansion angle along one of the coordinates) there is reason to be confident that it will actually be eliminated due to the boundary layer, in which case it is better to take the "effective" profile, obtained with allowance for the displacement thickness, as the zeroth approximation.

The displacement thickness δ of the boundary layer at the upper boundary of the nozzle is shown by a dash–dot line in Fig. 4. It is seen that the quantity $\delta/y^* < 10^{-2}$ will still be an order of magnitude smaller than the local thickness δ/y in the entire calculated range of x. To calculate the flow in the boundary layer we used a scheme of second-order accuracy in the approximation of derivatives with respect to the variables x and y. It was assumed that the thickness of the boundary layer is zero in the region up to the critical cross section. Preliminary calculations confirmed the validity of this assumption. Changing the initial point of the calculation by an amount $\sim y^*$ hardly affected the distribution of displacement thickness of the boundary layer in the supersonic part of the nozzle.

In conclusion, we note that the problem of the uniformity of the flow field in a multiphase mixing zone requires the solution of the problem of the distribution of products of the vaporizing particles among the vibrationally excited molecules [3]. The particle size distribution function and the mixing mode obviously must be chosen so that the concentrations (of CO_2 and N_2, for example) are close to the equilibrium values on different streamlines. At present this problem has not been solved either experimentally or theoretically, although the methods used in the present work allow one to determine the local density of mass sources due to particle vaporization and hence to solve the problem of the distribution of vapor concentration over a cross section of a stream into which vaporizing particles are introduced. Here the possibility exists in principle of choosing that particle mass spectrum which during vaporization would provide a uniform vapor concentration over a cross section of the mixing zone.

The main results of the present work consist in the following.

1. The problem of the influence of the vaporization of solid CO_2 particles on the characteristics of the light gas H_2 accelerating the particles in a supersonic nozzle is analyzed in a two-dimensional formulation. It is found that under the stagnation conditions ($P_0 \approx 7$ MPa and $T_0 = 250°K$) in the acceleration nozzle only particles with a size of $\leqslant 1$ μm are appreciably vaporized in the process of acceleration. If the ratio ε of the mass of the particles to the mass of the light gas is close to unity and particles with a size $\geqslant 10$ μm comprise most of the spectrum, then the total amount of vapor formed in the process of acceleration insignificantly alters the characteristics of the light carrier gas.

2. Estimates are given of the maximum possible acceleration of particles by different gases (H_2, He, CH_4, air) at the low temperatures in the forechamber ($T_0 \sim 250°K$) required to reduce the influence of vaporization. It is shown that the highest velocity of particle acceleration $\hat{u}_{max} \sim 2$ km/sec (for $\varepsilon \sim 1$) can be obtained in hydrogen. A numerical solution of the two-dimensional problem of particle acceleration by hydrogen, allowing for the actually existing velocity nonequilibrium in the multiphase stream, showed that $\hat{u}_{max} \approx 1.2$ kg/sec for $\varepsilon \sim 1$, and it can hardly be increased significantly.

3. The problem of the interaction of a light gas with a hypersonic stream into which particles are introduced was solved in a simplified formulation of the "collision" of two plane, inviscid, supersonic streams directed at an angle to one another. Such an approach permits the rapid optimization with respect to various parameters of the problem with acceptable accuracy for practical work. This is necessary for the choice of those initial conditions under which strong disturbances (shock waves) developing in the interaction of the gases are absent in the working vibrationally excited gas.

4. An analysis is made in connection with the influence of viscosity on the flow field of the inversion-excited medium. The displacement thicknesses in laminar and turbulent modes of flow are obtained, as well as the possible positions of separation points and separation zones in cross sections upstream from the point of introduction of particles. It is found that the turbulent mode of flow is more stable against separation. If the increase in pressure connected with the outflow of particles is significant, which depends on ε, the particle velocity, the entry angle, and other parameters, separation flow can occupy a considerable part of the inviscid core of the stream, which also degrades the parameters of the working zone.

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