NUMERICAL INVESTIGATION OF NONEQUILIBRIUM FLOWS OF MIXTURES OF FUSIBLE METAL PARTICLES AND GASES IN A LAVAL NOZZLE

N. N. Ivanov and R. A. Ivanova

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There are numerous papers [1-11] on the determination of the parameters of condensed oxide particles which are formed during combustion of metallized fuels. The ambiguity, and sometimes the contradictoriness, of the test results obtained [3-5, 9-11] indicate the difficulties in conducting correct experimental investigations. In this connection, numerical studies using mixtures of calibrated liquid-metal particles and different gases are of practical interest. Different probes can be calibrated by using "calibrated" two-phase flows, the two-phase flow around models and probes can be studied, as can the interaction between liquid-metal particles and the front of an aerodynamic compression shock, their intrusion in different entraining media, the interaction between fine particles (particle-projectiles) and large size particles (particle-targets), etc. In many cases, the prehistory of the flow and the parameters of the gas mixture with the particles in the area of the nozzle exit section must be known to investigate the above-mentioned phenomena. The parameters of different nonequilibrium flows of mixtures of gallium particles and gases in a Laval nozzle are investigated numerically in this paper; the maximum diameter (upper boundary of the spectrum) of the particles (d_s = 30 μ) which are not destroyed in the nozzle under the effect of the aerodynamic forces and are suitable for use in a "calibrated" two-phase stream is determined. The computations were carried out in a one-dimensional approximation according to [12-14].

Gallium (Ga) is a metal from which calibrated fluid particles can be obtained.

Some thermophysical properties of gallium [15] are presented in Table 1 (γ_s is the specific gravity of the particles, λ is the coefficient of thermal conductivity, c_v is the specific heat, σ is the coefficient of surface tension, and η is the coefficient of viscosity). Besides the gallium, its eutectic alloys (Table 2) which melt at low temperature (T_m = 276-290 K) are also of great interest for experimental investigations.

Nonequilibrium one-dimensional flows of mixtures of gallium particles with inert gases, He, CO_2, N_2, as well as with air, taking account of coagulation and aerodynamic crushing, were investigated numerically for a Laval nozzle of the following geometry (Fig. 1): diameter of the minimal nozzle section $d_* = 20$ mm; relative round-off radii of the nozzle throat in the contracting and expanding parts of the nozzle $\bar{R}_1 = R_1/d_* = 1$ and $\bar{R}_2 = R_2/d_* = 1$, respectively; the half-angle at the entrance to the contracting conical part of the nozzle $\theta_1 = 15°$; the half-angle at the entrance to the expanding conical part of the nozzle, as well as the exit from the nozzle, $\theta_2 = \theta_3 = 2°$; the geometric degree of nozzle expansion is $f_c = F_a/F_* = 3.76$.

The gas pressure in the chamber was taken as p_0 = 10 bars = const and the temperature as T_0 = 600°K in all the computations (in some cases the gas parameters were taken at T_0 = 573°K).

Preliminary computations in which the critical Weber number W_* was taken equal to W_* = 17-22 [2] showed that liquid polydispersed gallium particles of $d_s \geq 35$ μ diameter were crushed during passage of the minimal nozzle section. For this reason, a spectrum which is not deformed during acceleration of a two-phase stream in a nozzle (in which the gallium particle diameters were in the d_s = 0.5-30 μ range and the particle concentration was assumed insignificant) was taken as initial spectrum; parameters of just particles of the maximum diameter $(d_s)_{max}$ = 30 μ were later tracked, since it is expedient to conduct the experiments on particles of the greatest size.

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TABLE 1

Thermophysical properties of gallium		Ga
T_m, °K		302,8
T_b, °K		2503±283
$\gamma_s \cdot 10^{-3}$, kg/m³	solid	5,904 (at T=293°K)
	liquid	6,095 (at T=302,8°K)
σ, N/m		0,698 (at T=573°K)
$\eta \cdot 10^3$, Nsec/m²		1,097 (at T=573°K)
λ, W/m·deg		27 (at T=373°K)
c_v, J/kg·deg		345 (at T=573°K)

TABLE 2

Eutectic alloy composition, %	T_m, °K
88 Ga, 12 Sn	290
76 Ga, 24 Sn	288,7
30 Ga, 60 In, 10 Sn	285
62 Ga, 25 In, 13 Sn	278
61 Ga, 25 In, 13 Sn, 1Zn	276

The results of computations are represented in Figs. 1 and 2. The dependences $w = f(x/d_*)$ and $w_s = f(x/d_*)$, as well as $\Delta w_s = f(x/d_*)$, are shown here for nonequilibrium flows of mixtures of gallium particles and inert gases (He, N_2, CO_2) or air. It can be seen that the magnitudes of the absolute w_s and relative velocities $\Delta w_s = |w - w_s|$ of the gallium particles in a Laval nozzle depend radically on the thermophysical properties of the transporting gas and reach comparatively high values: upon acceleration of gallium particles by a low-molecular-weight gas (He, $\mu = 4.002$) they acquire the greatest values of the absolute and relative velocities ($w_s \approx 1300$ m/sec, $\Delta \omega_s = 870$ m/sec); among the variants considered at the nozzle exit; when a high-molecular-weight gas (CO_2, $\mu = 44$) flows around them, they acquire the least values of the absolute and relative velocities. It is interesting that the curves ($w_s = 450$ m/sec, $\Delta w_s = 250$ m/sec) for gallium particles around which the above-mentioned gases flow become parallel to each other and to the abscissa axis starting with $x/d_* \approx 3$.

Upon acceleration of the gallium particles by helium these curves $\Delta w_s = f(x/d_*)$ are characterized in the contracting part of the nozzle by high values of the derivative $\partial(\Delta w_s)/\partial(x/d_*)$, which reaches a maximum in the region of the nozzle throat, and then starts to diminish smoothly.

Presented in Fig. 2 are also the results of computations showing the change in the Mach number M_s (the gas motion relative to the particles) along the axis of the experimental nozzle for different mixtures of gases and gallium particles. Computations showed that the greatest values of the Mach number are achieved in the area of the nozzle exit section, where they hence are ~1 for mixtures of gallium particles with nitrogen, air, and carbon dioxide gas, while they are greater than 1 ($M_s = 1.34$) for a mixture of helium and gallium particles. The quantity $M_s > 1$ means that the velocity of helium flow around the gallium particles became supersonic in the area of the nozzle exit section; detached compression microshocks originated in front of the particles, while wakes extended along the stream appeared behind the particles.

It follows from results of a computation of $T = f(x/d_*)$ and $T_s = f(x/d_*)$ that when a low-molecular-weight gas (He) was blown over the gallium particles, they were cooled intensively and apparently solidified in the area of the nozzle exit section, since the particle temperature ($T_s = 280$ K) is less than the gallium melting point ($T_m = 302.8$ K). When a high-molecular-weigh gas (CO_2) as well as nitrogen and air flowed over the gallium particles, their temperature along the nozzle length varied slightly and exceeded the gallium melting point in the area of the nozzle exit section, and the particles remained fluid in these cases. According to the computations, the magnitude of the temperature lag in the gallium particles depends slightly on the thermophysical properties of the transporting gas and does not exceed $\Delta T_s = |T - T_s| = 250$ K in the area of the experimental nozzle exit in all the variants considered.

The change in Reynolds Re_s and Weber W_s numbers along the nozzle length was also investigated in the research for the mixtures of gases and gallium particles under consideration. It is seen from the computations that these curves are similar in the nozzle: their maxima are in the region of the nozzle throat (for $x/d_* \approx 3$) where the gas density is still sufficiently high and the relative velocity $|w - w_s|$ reaches the limit value. Furthermore, a rapid diminution in the numbers Re_s and W_s occurs along the nozzle axis because of the rapid diminution in the gas density. It is seen in Fig. 2 that the number Re_s has the greatest value ($Re_s = 1650$) upon acceleration of the gallium particles by carbon dioxide in the experimental nozzle, and it has the least value ($Re_s = 651$) upon acceleration by helium. The picture is the reverse for the Weber cri-

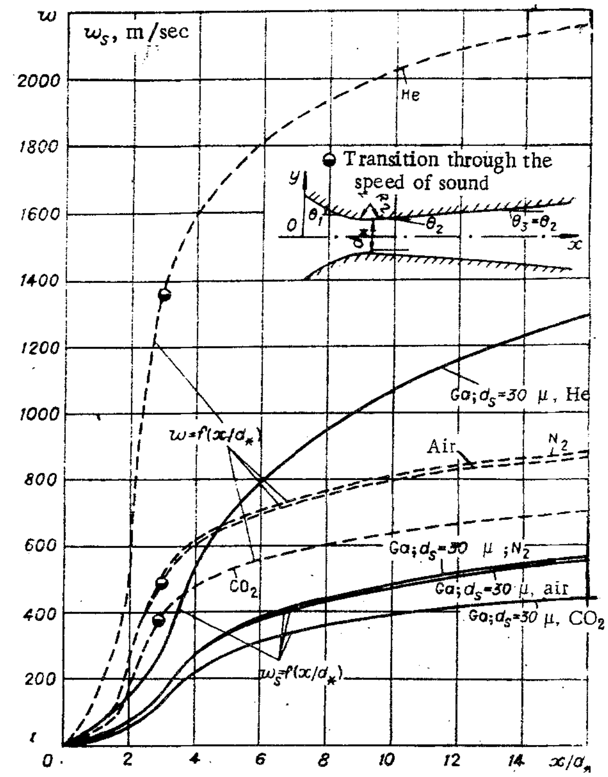

Fig. 1

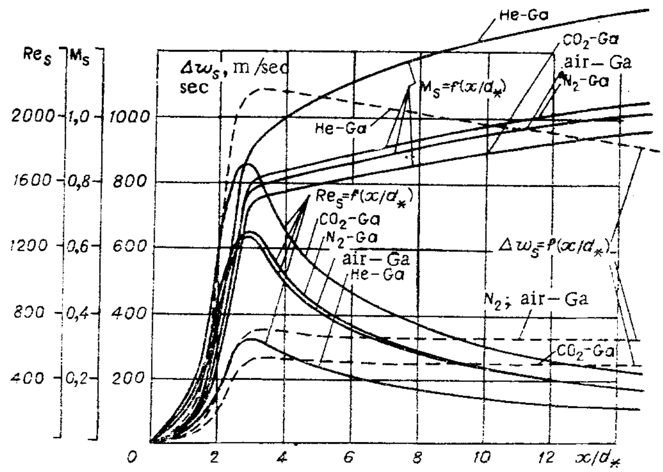

Fig. 2

terion: the greatest value (W_S = 22) is obtained when helium is blown around the gallium particles and the least (W_S = 14) when carbon dioxide is blown around the gallium particles. Obtaining calibrated liquid particles of fusible metals is possible at this time by using special drop generators. To obtain a "calibrated" two-phase gas mixture of air and gallium particles, for example, with a transporting gas discharge of $G \leq 0.7$ kg/sec and its heating to $T \approx 600$ K, it is required to deliver a W < 190 kW power to the apparatus, as computations show.

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