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Interaction of a Solid Body with the Multiphase Supersonic Flow: Physico-Mathematical Models and Numerical Investigations

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Abstract

A brief description of the equation system of the multiphase flow is done, taking into account a multitude of the physical processes accompanying the impingement of particles upon solid obstacles. On the basis of derived physico-mathematical models and corresponding numerical codes, characteristic parameters of carrying gas, impinging , rebounded and chaotical particulates are found. Surface distribution densities of heat and electric current upon the body are found, as well as spatial distribution of the particles concentration in the impinging two-phase flow and shock layer, and also of electric charge and scattered sounding radiation. Some illustrations of the numerical results are presented which may be useful for numerous practical applications in hydro-thermodynamics of high-speed vehicles and powder technologies.

Keywords: *non-equilibrium polidisperse flow, partially elastic and non-elastic particle/body collisions.*

Nomenclature

a – radius of a spherical particulate, m

ε^0 – mass fraction of the dispersed material in the mixing chamber

$\mathbf{V}_1$, $\mathbf{V}_2$, $\mathbf{V}_3$ – velocity vector of the carrying gas, impinging and rebounded particulates, m/s

T_1, T_2, T_3 –their temperature, correspondingly, K

ρ, p –density, pressure

q_T – heat flux density from impinging particulates to the body surface, J/m^{2}s

ρ_e – electric charge density C/m^3

I, electric current, A

j, electric current density A/m^2

r_* – nozzle critical radius, m

Indexes

a – nozzle exit

$*$ – the nozzle critical section

0 – stagnation conditions

1 – carrying gas

2, 3 – impinging and rebound particles

n, τ –normal and tangential component of a vector

s –jet «boundary»

w – body surface

In this 100-year jubilee of TsAGI, it is reasonable to review our own twenty-year experience of the investigations devoted to multiphase flows [1, 2], which are of interest due to the following circumstances. Firstly, flyers often meet the non-homogeneous atmospheres, volcanic eruption and ice crystal clouds; in the technological practice, the high-speed air-dusty jets are being used to change the surface properties of details [3-5]. Secondly, the ground-based gas-dynamics tunnels, accompanied with the theoretical models and numerical investigations, may be used to obtain the information which could not be predicted immediately, – for example, concerning angular velocities and temperature of the rebounded microparticles. For this reason, the list of the species of particles under investigation was essentially enlarged.

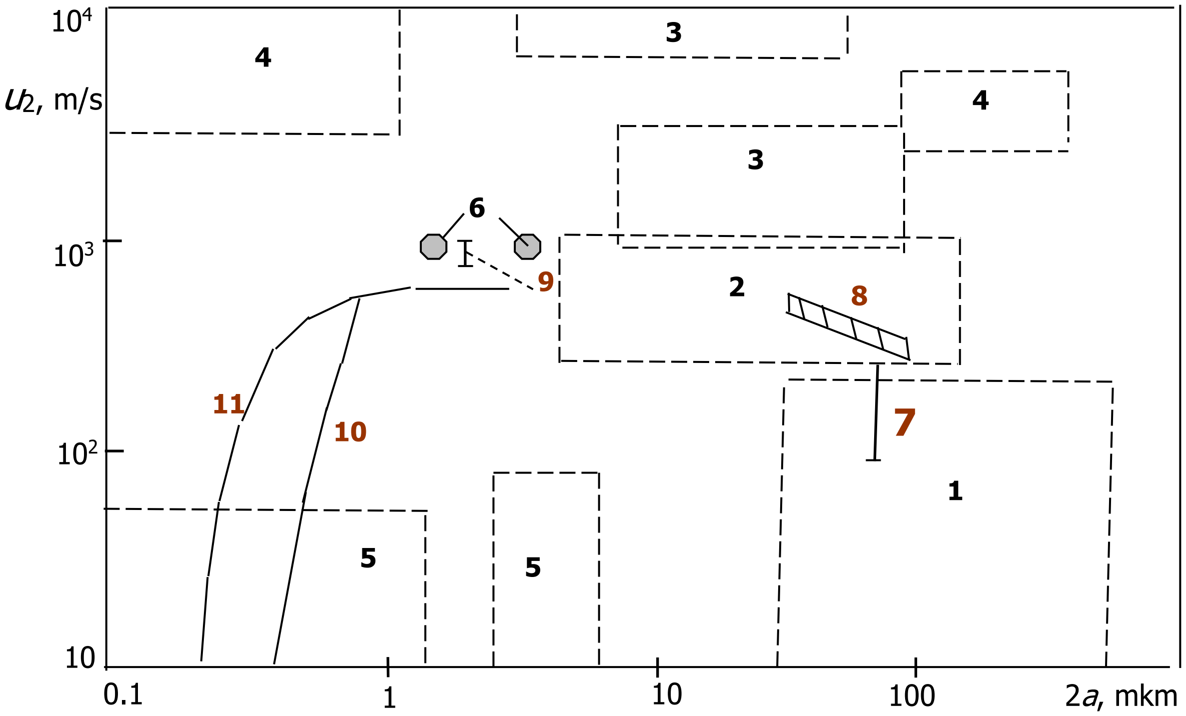


Fig 1.

To show the domain of our investigations, in Fig.1 are presented numerous regions of particle/surface body interaction, investigated by other researchers in the coordinates: impingement velocity u_2 – particle diameter 2a. One may see the following domains: 1 – erosion; 2 – cold dust imbedding; 3 – superdeep imbedding; 4 – supersonic collision; 5 – sticking,6 –acceleration in Van de Graaf generator [6] ; 7 – «cold » mixture chamber, T_0= 294 K [7]; 8 – the «hot» one, T_0=1650 K [7]; 9 – average temperature regime T_0= 570 – 800 K [8]; 10,11 – analytical estimation for Fe_2O_3 and Fe particles, correspondingly. Numbers 7–11 correspond to our investigations.

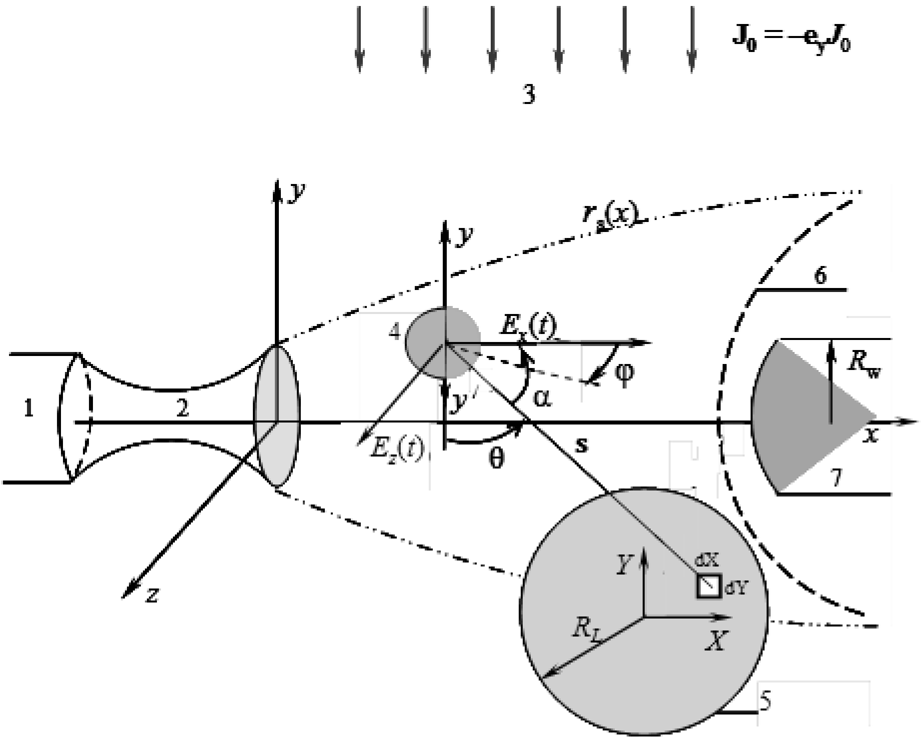


Fig 2.

Typical experimental situation is presented in Fig.2. Namely, the layout is presented of an experiment on visualization of a gas-disperse flow over an obstacle [8]: mixing camera (1), Laval nozzle (2), light plane z=0 (3), scattering particle (4), entrance pupil of the recorder (lens) (5), compression shock (6), and aerodynamic body (7).

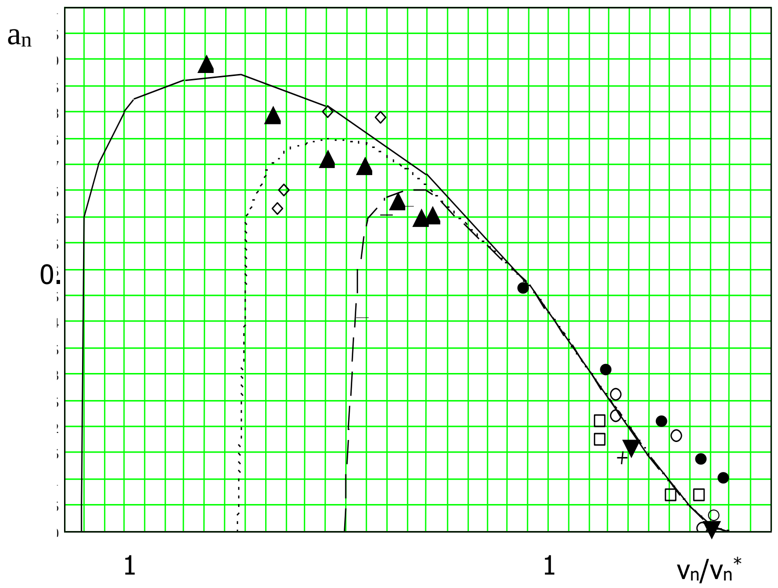
It is necessary to emphasize that multiphase flow interacting with a solid body is essentially non-equilibrium – linear and angular velocities and temperatures of the carrying gas and of the dispersed particles may be significantly different. Especially it concerns supersonic flows, in which an individual particulate may rebound (partially elastic collision) or destroyed or imbedded into a solid obstacle (thoroughly inelastic interaction); this particle may obtain an electric charge and cause the corresponding electric current in the vicinity of the body, which, in its turn, can generate the molecular glow and so on.

So, in our system of equations [9, 10], many physical phenomena are summarized – not only airhydrodynamic or Stokes forces, arisen by the phase velocity difference, but also the mutual influence of the rotation and translation velocities [11] which changes the drag force and Magnus force coefficients. In the energy equation of mixture, the following important peculiarities are taken into account: the volume non-uniformity of the temperature of an individual spherical particle [12,13], and the cut-off of its own infrared radiation [14].

No doubt, another scientific schools have influenced upon our approaches to multiphase flows description, for example [15].

The collision of a single spherical particulate with an elastic body is described in the frame of our original heuristic model [16] based on the experimental results of other investigators [17, 18]. In Fig.3, the dependence of normal recovery coefficient a_n is presented as function of the impinging

$v = v_{2n}$ velocity v_{2n} normalized with the limit value v^*_n, above which the absolute non-elastic collision occures. Our interpolations are shows as solid, pointed and dashed lines.



Ris.3

This theoretical model takes into consideration the velocity of impact, physico-mechanical properties both of the particulate and the body (densities of materials, Young and shear modulus, surface energies). Some interesting numerical results are obtained and illustrated below. For example, typical recovery coefficients obtained in our numerical research is shown in Fig. 4 in the total range of the slipping angle β, where the normal a_n and tangential $a_\tau = v_{3\tau}/v_{2\tau}$ recovery coefficients are done both.

One may see that recovery coefficients never reach unity at normal collision, so the last one may be regarded as partially elastic.

Further, it is of interest to note that in the case of large mass spectrum of particulates (we take into account 1– 50 mcm radii), the tiny and the biggest of them could obtain moderate impingement velocity. This fact is easily explained: small particulate slow down in the shock layer before the body, and the large those are too inertial to obtain a significant velocity in nozzle. As a result, the particulates from the middle part of the mass spectrum collide with the body non-elastically, so as the rebound spectrum turns to be bimodal. It must be emphasized that the mentioned phenomenon concerns the case when a dispersed phase is accelerated in jet regime.

A complex of numerical codes is derived and used to investigate thermogasdynamics, optical and electrical phenomena, realized during the interaction of polidisperse axisymmetrical jets with solid bodies in vast region of gowerning parameters: gas stagnation temperature and pressure T_0=290 – 1750 K, p_0 =0.2–2 MPa; exit nozzle Mach number 2.25 –6; their initial mass fraction (regarded to the gas mass density ε_0 =0.125 – 50 %.

The most part of numerical investigation was carried out by the Large Particle Method [19].

Using these codes, many results of practical use are obtained– heat flux densities distribution over a sphere, flat end of a cylinder, inclined plate; dependence of a screen formed by the rejected particulates on the turbulent pulsation generated by the disperse phase; space distribution of the concentration and electric charge of the rejected particulate of the molecular glow excited by free electrons; influence of the optical properties of particle material (complex refraction index) [20] on the scattering of a sounding laser radiation.

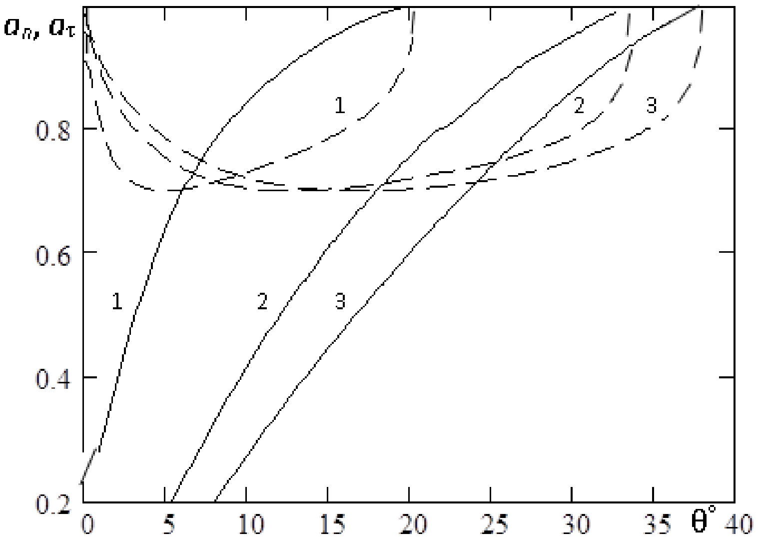

a_n, a_τ
0.8
0.6
0.4
0.2
0
5
10
15
20
25
30
35
θ°
40
1
2
3
1
2
3

Fig.4

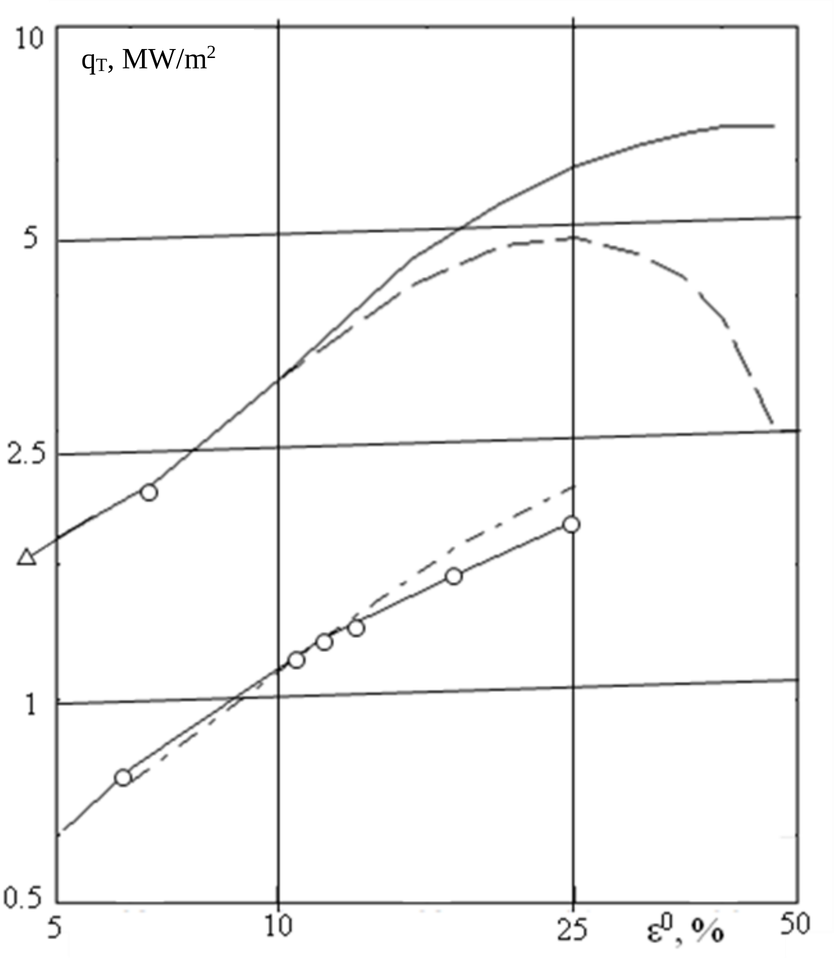

10
q_T, MW/m^2
5
2.5
1
0.5
5
10
25
ε^0, %
50

Fig.5

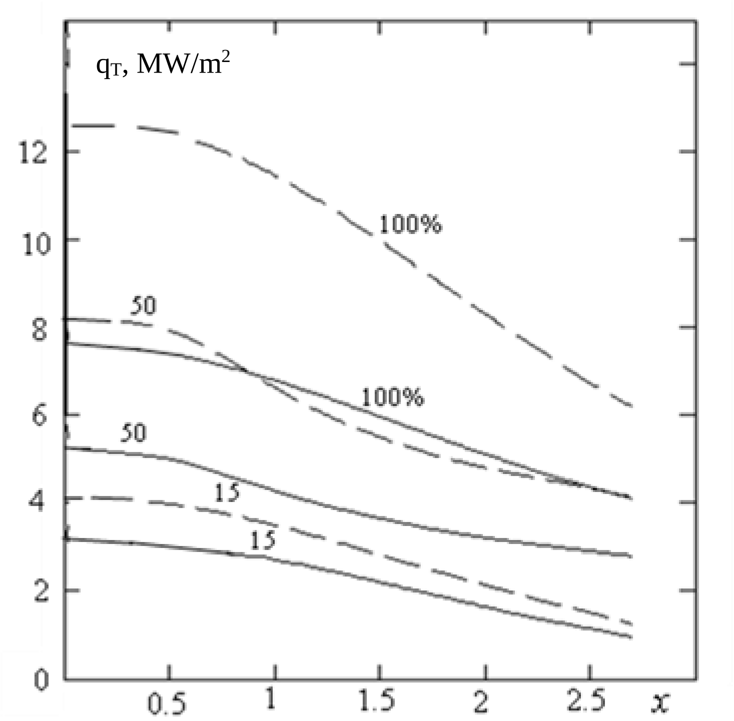


Fig.6

In particular, in Fig.5 one may see the dependence of heat flux density (vertical scale, MW/m2) in the critical point upon the surface of sphere (upper curves, T =290 K) and on the cylinder flat end (lower ones, 1650K) on the value of particulates mass fraction in the mixing chamber. The circles and triangle mark experimental data of another researchers [7], and curves correspond to our numerical investigations. The dash line illustrates a pronounced screen effect of rebounded particles on the heat flux density carried by disperse phase to the body.

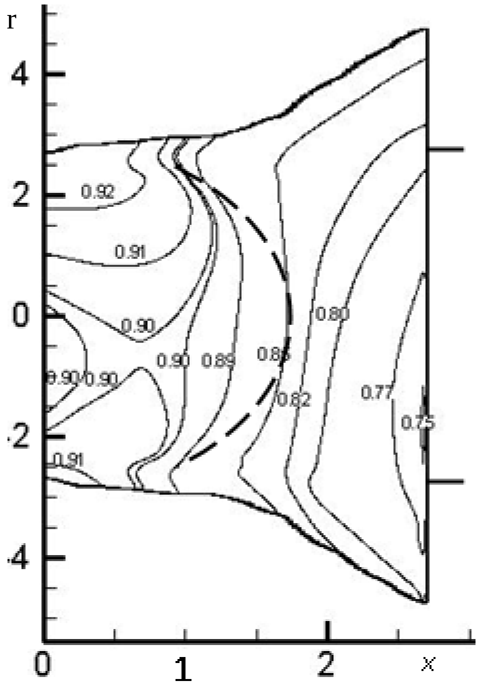


Fig.7

The remarkable influence of this effect is also clearly seen in Fig.6 for the case of one value of temperature (T_0 = 290 K). In this figure, the radial distribution of heat flux density is presented on the cylinder flat cut-off. The curves are marked with the value of initial mass fraction of particles.

In Fig. 7, one may se the distribution of the extinction coefficient over a jet axial section in the laser sounding «knife». The nozzle cross-section corresponds to $x = 0$, the flat cylinder cut-off – to x=3; $y = 0$ marks the jet axis. The laser light falls down from above (see Fig. 2) and gradually scatters on the spherical corundum (Al_2O_3) particles; their radius equals to a= 0.185 mcm, and initial mass fraction 1%. The Figure shows the extinction of light scattered perpendicularly to the sounding radiation. It is seen, that the scattered radiation diminishes gradually from above to the bottom of the jet.

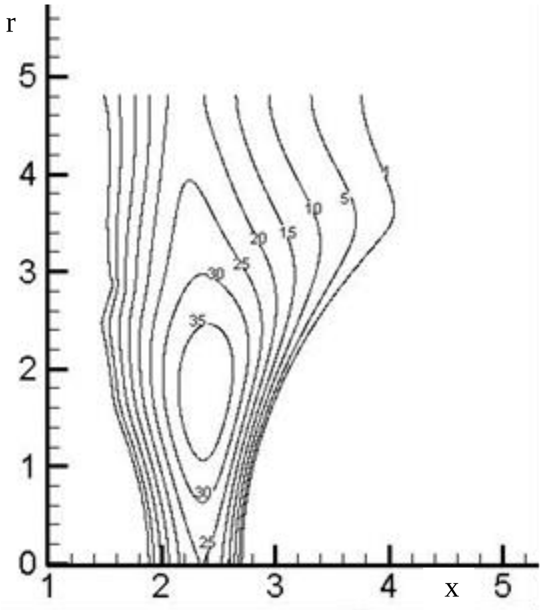


Fig.8

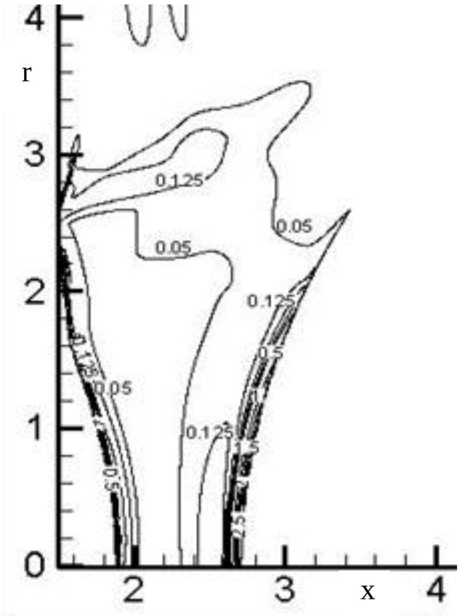


Fig.9

In Fig.8, distribution of the electrical potential (Volts) is shown in the axial cross section of the jet carrying corundum particles (radius *a*=2,5mcm, particle initial mass fraction 2.6%). Axial and radial coordinates are scaled by critical nozzle radius r_*=5 mm. The two-phase mixture flows from left to right. The electric field is generated by the particles rebounded from the sphere and gained the maximal electric charged.

At last, in fig. 9, one may see the corresponding distribution of the electric charge density (C/m^3).

Conclusions

As a result of physico-mathematical modeling and numerical investigations of gas flows, carrying solid particulates, in a nozzle, in shock layer and upon solid body, regions of partially elastic and absolute inelastic particle-body collisions are determined; heat fluxes to the body are found and verified by comparison with experimental results; optical and electrical characteristics of multiphase currents are estimated.

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