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COLLISION OF SUPERSONIC FLOWS IN VACUUM AND AMBIENT SPACE

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Based on numerical Monte Carlo simulation, the collision of plane–parallel supersonic flows in vacuum and ambient space is studied. The study of the transonic zone of a plane source instantaneously switched on in vacuum made it possible to establish the regular features of the flow parameters in the critical cross section and the validity of using gas-dynamic dependences obtained in the continuum approach for simulating gas exhaustion. Evolution of the structure of a compressed shock layer arising in the region of flow collision is studied. It is found that a collision of flows in the ambient space leads to a more significant increase in temperature in the compressed layer than in the case of a collision in vacuum.

The problem of collision of supersonic flows at low pressure arises in solving astrophysical problems (collision of gas clouds of cosmic scale), problems of spacecraft gas-dynamics (interaction of thruster jets with the atmosphere of the Earth and other planets), and problems of creation or modeling of light sources obtained as a result of interaction of flows from pulse sources of gas. The initial stage of flow collision, namely, the formation of shock structures, has not been studied systematically. The most similar problems related to the problem of kinetic processes during flow collisions were considered by Bird [1] and Diewert [2] who used the direct statistical simulation of compression of a rarefied gas by a piston in a one-dimensional case. Numerous monographs, for example, [3–6], contain necessary information on calculation of the formation and behavior of shock waves and compressed layers during flow interaction with obstacles. The results obtained in these works refer to continuum flow conditions.

The objective of the present paper is to study the process of collision of plane–parallel supersonic flows at the molecular level, i.e., to study the field of the gas parameters from the beginning of the collision process to the formation of localized shock waves and compressed layers during the transition to continuum or near-continuum flow. At the first stage, a collision of identical monatomic gases was simulated, the hard sphere model being used as the interatomic potential. The symmetry of the problem allowed us to pass to the problem of flow collision with a rigid mirror wall. The problem was solved by the direct simulation Monte Carlo (DSMC) method [7], which is an effective tool for studying the processes of an arbitrary level of nonequilibrium. In a particular formulation of a one-dimensional problem of flow collision with an obstacle, we used a plane–parallel source, which was instantaneously switched on. Plane I was placed at the point $x = 0$, and the half-space to the left of this plane is filled by a quiescent gas with particle density n_0 and temperature T_0. A mirror surface, which is the collision plane, is located to the right of the plane I at some distance L. At the time $t = 0$, the plane I is instantaneously removed and the motion of previously quiescent gas begins. Two cases were considered: (a) the region between the plane I and the collision plane is vacuum (initial density $n_b = 0$); (b) this region serves as a buffer and is filled by the same gas with density n_b and temperature T_b.

The solution of the problem of unsteady spreading of particles from the surface I involves a great number of particles to the left of this plane, which significantly increases the computational cost. At the same time, analytical functions for continuum flow are known [4], which describe the entire flow field in time. The

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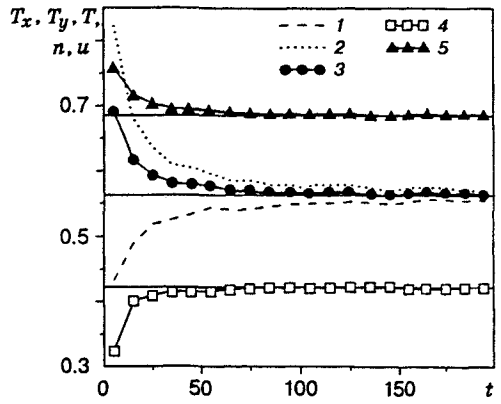

Fig. 1. Dimensionless temperature, density, and velocity versus time on the sonic surface in the case of one-dimensional plane–parallel exhaustion of a quiescent gas into vacuum: T_x (1), T_y (2), T (3), n (4), and u (5); the solid curves refer to the results of [4].

gas parameters in the plane I are constant in time. It is convenient to use these functions to prescribe the parameters of the source in the plane I in order to avoid the necessity of calculating the collision processes to the left of this plane. Justification of this procedure required an analysis of the effect of rarefaction on the distribution of parameters in the flow, in fact, an analysis of the difference between the model and inviscid gas. According to Stanyukovich [4], the flow velocity u, the speed of sound c, and the density n in an inviscid flow are described by the following formulas:

$$u = \frac{2}{\gamma+1} c_0 \left(1 + \frac{x}{c_0 t}\right), \qquad c = \frac{2}{\gamma+1} c_0 \left(1 - \frac{\gamma-1}{2}\frac{x}{c_0 t}\right),$$
$$n = n_0 \left[\frac{2}{\gamma+1}\left(1 - \frac{\gamma-1}{2}\frac{x}{c_0 t}\right)\right]^{2/(\gamma-1)}. \tag{1}$$

Here c_0 is the speed of sound in the gas at rest, γ is the ratio of specific heats, x is the distance from the plane I, and t is the time. We have M = 1 at the point $x = 0$.

Here and in what follows, the reference length in the DSMC calculations is the mean free path $l_0 = 1/(n_0\sigma\sqrt{2})$ (σ is the collision cross section of the molecules), and the reference velocity and temperature are the most probable thermal velocity $u_0 = \sqrt{2kT_0/m}$ and temperature T_0. In calculating the macroparameters of the gas, we averaged 50 to 470 dimensionless time units $(1/(2n_0\sigma))\sqrt{m/(kT_0)}$ on time intervals.

It was found in the course of calculations that the coordinate with M = 1 at $t > 50$ remains unchanged but shifted relative to the plane I by approximately five mean free paths of the molecules in the gas at rest. Variation of the temperatures T_x and T_y was also studied, T_x and T_y being determined using the velocity components parallel and perpendicular to the flow direction, respectively. The temperature anisotropy, which reflects nonequilibrium and is quite considerable at the initial stage, decreases with time. Because of temperature anisotropy, the Mach number determined from the DSMC data is rather conventional and can be used only as a qualitative characteristic.

Figure 1 shows the variation of the flow parameters at the point where M = 1 is established (all quantities in the figures are presented in the dimensionless form). The values of density, velocity, and mean temperature $T = (T_x + 2T_y)/3$ are in good agreement with those calculated using the formulas derived in [4] after 60–70 time units. By this time the gradients of the parameters drastically decrease and thermodynamic equilibrium is rapidly reached in the vicinity of the point with M = 1.

Introducing the local Knudsen number as the ratio $\mathrm{Kn}_l = (l/n)dx/dn$ and using relation (1), we can

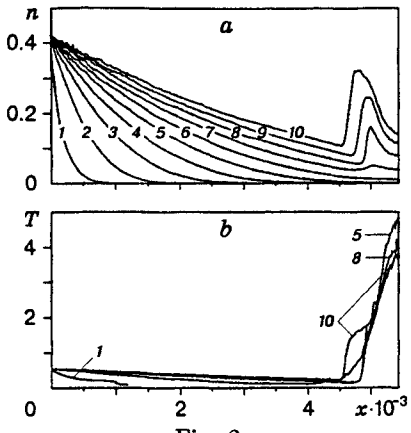

Fig. 2

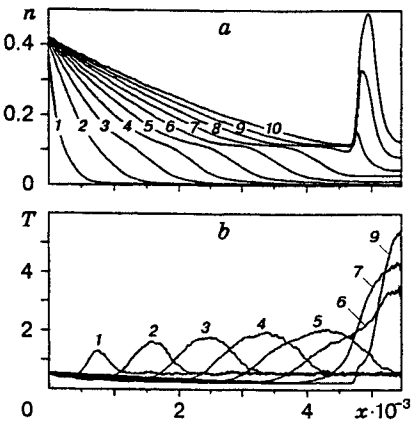

Fig. 3

Fig. 2. Density (a) and temperature (b) profiles at different times during gas exhaustion into vacuum: curves 1–10 refer to $t = 240$, 710, 1190, 1660, 2130, 2610, 3080, 3560, 4030, and 4500, respectively.

Fig. 3. Profiles of the total density (a) and total temperature (b) at different times during gas exhaustion into a space filled by a buffer gas with $n_b = (1/230)n_0$ (notation is the same as in Fig. 2).

conclude that the equilibrium at the critical point is reached at $\mathrm{Kn}_l < 0.02$. According to the theory [4], determination of the time of flow formation at the critical point is important as such. Note that the fore front of the gas flow, which is determined by the density $0.1n_0$, shifts during this time by approximately $(60–70)l_0$. Concerning the solution of the problem posed in the present paper, it is important to understand the specific features of molecular processes during the collision of gas flows by the simplest example with account of rarefaction effects including the processes of the initial formation of the flow.

At rather large distances L (thousands of mean free paths of the molecules of the quiescent gas), the effect of the initial shift of the surface with M = 1 can be ignored. We can use the parameters in the plane with M = 1 as the boundary conditions, in accordance with the theory [4], i.e., prescribe a locally Maxwellian distribution function of molecular velocities in this plane.

Collision of Flows in Vacuum. The fore front of an inviscid gas flow expanding in vacuum has the Mach number $\mathrm{M} = \infty$. A shock wave is formed at the moment of collision of these flows with a fivefold increase in temperature behind the shock wave. Nevertheless, the temperature and density of the gas in front of this shock wave are infinitely small; hence, the gas-state parameters behind the shock wave are also infinitely small. After the collision, the shock wave moves upstream and meets the gas flow whose density increases and Mach number decreases with time. In an inviscid gas, previous portions of the gas are adiabatically compressed in the initial period near the collision surface by the gas flow passing through the shock wave. In a real heat-conducting gas, heat transfer from the previously compressed gas to new portions of the gas occurs; therefore, the behavior of the temperature near the surface cannot be predicted *a priori*. The DSMC calculations allow one to trace the details of evolution of the temperature profile in the compressed layer.

The initial distance in the calculations was $L = 5450\,l_0$. The calculation was terminated when the shock wave started its upstream motion from the mirror surface (collision surface of the flows). The evolution of the density and temperature profiles is shown in Fig. 2.

The calculation allows us to consider the evolution of the shock-wave precursor, a sudden increase in temperature in the collision region, which is induced by superposition of molecular flows in an almost collision-free regime, where fast molecules from a high-energy tail of the distribution function meet. Theoretically, the temperature at this short-time period can reach infinitely large values. In our case, the statistics revealed a level of translational energy that can be determined by the mean temperature $T \approx 4.8T_0$.

It follows from the comparison of the temperature and density distributions that the reflected shock wave starts to form in a strongly rarefied high-velocity flow and the temperature increase occurs in a space that does not have a sufficient amount of gas to form a shock-wave structure satisfying the shock-adiabat laws. We watch the evolution of the shock-wave structure from the time $t = 2130$ when the maximum temperature near the collision surface is reached. Only at the time $t = 3080$ is a weak increase in density in the shock wave observed, which corresponds to a lower temperature near the surface. At the time $t = 3560$, we observe a 2.9-fold increase in density on the shock wave as compared with the free-stream density ahead of the shock wave and a 9.8-fold increase in temperature on the shock wave. The free-stream Mach number is M = 4.5. This Mach number corresponds to a 3.7-fold increase in density in the reflected shock wave and a 12.7-fold increase in temperature as compared with the corresponding free-stream parameters ahead of the shock wave. Obviously, it is impossible to locate the shock-wave front near the collision surface. The complex character of formation of the reflected shock wave is explained by superposition of the phenomena of strong initial nonequilibrium, continued formation of the shock wave in a changing gradient flow, and the presence of an intense heat flux from the vicinity of the collision surface in the upstream direction. The calculation results give detailed knowledge of evolution of the parameters in the merged compressed layer and shock wave.

Collision of Flows through the Buffer Zone. The objective of this calculation is to establish the effect of temperature increase in the collision zone induced by shock compression of the buffer gas in the incident and reflected shock waves and possible additional compression by the main flow. The first stage of compression is similar to the process commonly observed in shock tubes. Additional compression can follow the scheme of shock processes in the case of gas compression by a piston. In this case, the piston is elastic and its "stiffness" is determined by the momentum flux of an active gas.

In our calculation, we used the previous geometry ($L = 5450l_0$), and the buffer gas had the temperature $T_b = (9/16)T_0$ equal to the temperature on the sonic surface and the density $n = (1/230)n_0$ corresponding to the number of molecules of the gas with density n_0 enclosed in a domain of length $23.7l_0$. These conditions correspond to the initial Knudsen number in the buffer gas $l/L = 0.042$.

The interaction of the source gas and the buffer gas involves mutual diffusion of the gases; hence, the contact surface can be determined only conventionally, for example, by a cross section in which both gases have equal densities.

Figure 3 shows the distribution of the total density and temperature in the buffer zone in time. The maximum value of temperature near the collision surface is reached when the density near the surface increases approximately by a factor of 19 as compared with the buffer-gas density. This increase in density is much greater than that observed at a twofold compression in the incident and reflected shock waves, which indicates an additional compression in the compressed layer. The increase in temperature is noticeably greater than the increase in temperature in the case of flow collision in vacuum. The density distribution for the source gas and buffer gas is shown in Fig. 4. The source-gas density near the surface at the moment of the maximum increase in temperature is approximately 23% of the total density, which indicates the significant role of the diffusion processes (self-diffusion and heat exchange). The role of these processes is even more important if the amount of the buffer gas is reduced.

To illustrate the temperature effects induced by collision of flows, Fig. 5 shows the temperature as a function of density near the collision surface for the cases of collision in vacuum and through a buffer zone whose length is $10{,}900l_0$, $5450l_0$, and $2725l_0$, the density in the buffer zone being 230 times as low as the source-gas density. As the buffer zone filled by the gas increases, the maximum temperature increases. The increase in temperature is related to the process of compression in shock waves and adiabatic compression. The decrease in temperature with time is caused by thermal conductivity and mixing of the gases. If the compressed layer and the shock wave occupy less than 5–10 mean free paths, the definition of the thermal energy of the gas in terms of temperature is rather conventional, as it is in the case of flow collision in vacuum at times when a sharp rise in temperature occurs near the surface (Fig. 5). Based on the data in Fig. 5, we can conclude that, for the initial data used in calculations, the temperature reaches the maximum value $T \approx 4.2T_0$ in the case of flow collision in vacuum; after that, the temperature decreases as the density near the mirror surface increases.

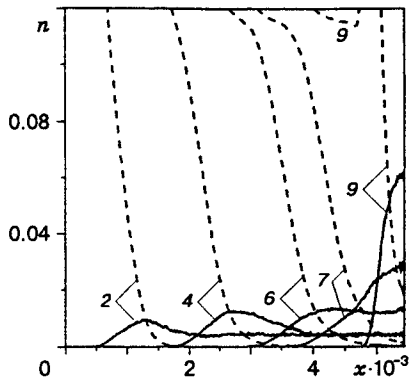

Fig. 4

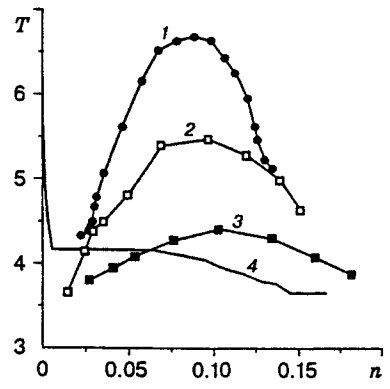

Fig. 5

Fig. 4. Density profiles for the buffer gas (solid curves) and source gas (dashed curves) at different times during gas exhaustion into a space filled by a buffer gas with $n_b = (1/230)n_0$ (notation is the same as in Fig. 2).

Fig. 5. Temperature versus density near the collision surface at a fixed ratio of densities: $n_b = (1/230)n_0$ and $L = 10.900l_0$, $5450l_0$, and $2725l_0$ (curves 1–3); $n_b = 0$ and $L = 5450\,l_0$ (curve 4).

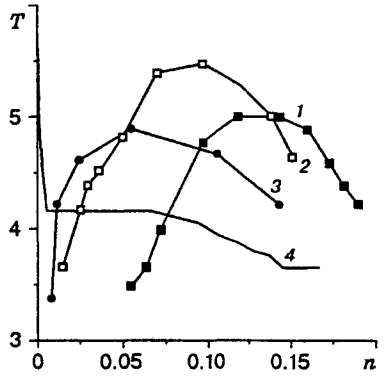

Fig. 6. Temperature versus density near the collision surface at a fixed distance between the plane of the source and the collision surface $L = 5450l_0$: $n_b = (1/115)n_0$ (curve 1), $n_b = (1/230)n_0$ (curve 2), $n_b = (1/460)n_0$ (curve 3), and $n_b = 0$ (curve 4).

The DSMC calculation allows one to determine the conditions of reaching the maximum temperature as a result of flow collision depending on the initial density of the gas in the buffer zone n_b and the buffer-zone length L. Figure 6 shows the relationship between the temperature and density at a fixed distance $L = 5450l_0$ for different densities of the buffer gas. The maximum temperature ($T \approx 5.5T_0$) is reached in our calculations for the Knudsen number determined from the initial density n_b of the buffer gas and equal to 0.042.

Conclusion. The results obtained reveal the kinetics of the formation of shock-wave structures during the collision of supersonic flows in the case of free one-dimensional expansion into vacuum and in the presence of a buffer gas. Owing to superposition of shock and adiabatic compression, flow collisions through the buffer gas allow one to obtain temperatures in the compressed layer that cannot be reached in the case of collision in vacuum. The possibility of obtaining high temperatures in an initially quiescent rarefied gas in the case of gas compression without contacting the walls is proved.

The study of the evolution of the transonic region of a plane source suddenly switched on during gas exhaustion into vacuum allowed us to find the formation conditions of a continuum flow in the critical cross section and confirmed the validity of the functions [4] for a flow with molecular spreading of the front.

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