EFFECT OF DIFFUSION SEPARATION WHEN HYPERSONIC FLOWS OF A RAREFIED GAS MIXTURE COLLIDE

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The results are described of an experimental investigation using an electron beam of colliding hypersonic flows of an argon–helium mixture. The region of the flow near the frontal point indicates an increase in the concentration of the heavy component of the mixture. We consider the collision of two axisymmetric counter flows and the collision of two-dimensional supersonic flows at a concave plate.

When supersonic flows collide, a region of the flow with a pressure gradient in the direction of its center may be formed. This case is of interest in the study of barodiffusion processes, as a result of which the above-mentioned region is enriched with the heavy component of the mixture. A flow pattern with significant enrichment is fundamental to the creation of devices for separating gaseous mixtures. We note that [1] is devoted to the separation of gases into like streams.

1. The experiments were made in a low-density wind tunnel fitted with apparatus for the electron beam diagnosis of rarefied flows similar to that described in [2].

The gas in the region of the flow under investigation is excited by a beam of electrons with energy 10 kV and current 1-5 mA (the diameter of the beam was ≈ 1.5 mm). An ISP-51 spectrograph, used as a monochromator and fitted with an FÉU-27 photomultiplier, was used to analyze the radiation. To ensure that the measurements were made locally, part of the light spot, corresponding to a beam height of 1.5 mm, was cut off at the input slit.

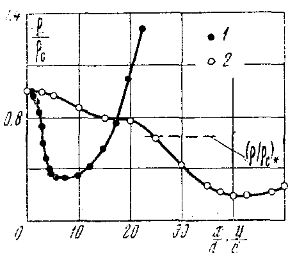

Fig. 1

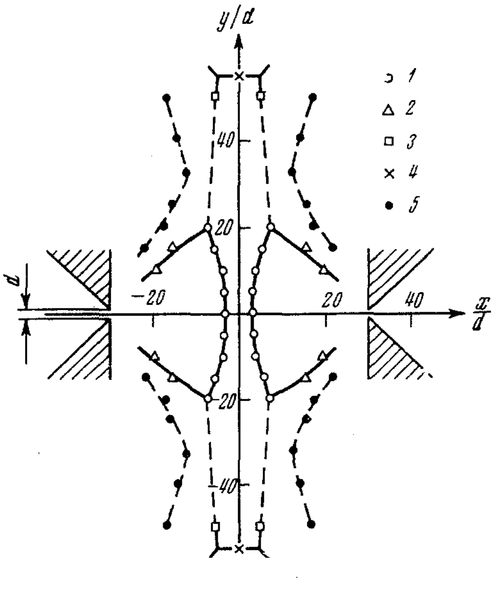

Fig. 2

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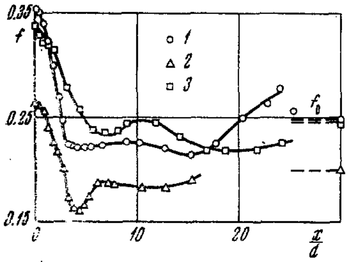

Fig. 3

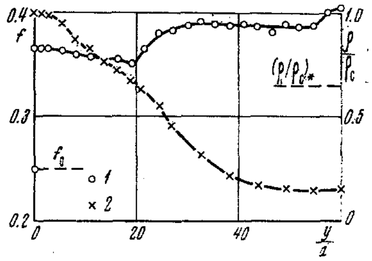

Fig. 4

To measure the partial densities the following were used: the 5016 Å line for helium, the nitrogen band at 4278 Å for air, and the region 4200 ± 50 Å for argon. Before the measurements were made the densities were calibrated in static conditions. All the measurements were made in conditions in which the excitation and radiation processes were not perturbed by molecular collisions.

2. The experiments used two sonic pipes of diameter d = 2 mm arranged coaxially at a distance of 121 mm from each other on a common stand.

The prechambers of both pipes had a common gas supply and common takeoffs for measuring the braking pressure. The whole system was placed in the reference framework of the working section in such a way that the electron beam intersected the flow in a direction perpendicular to the axis of the pipe, and the whole region of the flow between the pipes is scanned by the travelling reference framework.

To determine the general pattern of the flow an experiment was made using air as the working gas with braking parameters p_0 = 286 mm Hg, T_0 = 300°K and vacuum chamber pressure $p_k = 3.6 \cdot 10^{-2}$ mm Hg.

The density profiles were measured at cross sections parallel to the axis of the pipe at various distances from the axis. From the density profiles the configuration of the shock waves and the boundaries of the stream, shown in Fig. 1, were determined. The positions of the shock waves (curves 1, 2, 3, 4) were determined at the point of maximum density gradient and the boundary of the stream (curve 5) was defined at the point where the density begins to rise above that of the surrounding space.

Figure 2 shows the profile of the relative density along the axis of the pipe (curve 1) and at a section perpendicular to the axis at an equal distance from the pipe (curve 2).

We note the following features of the flow.

1. There is symmetry not only with respect to the axis but also with respect to the plane passing through the nominal frontal point of the collision of the streams and perpendicular to the axis of the pipe. This makes it possible to draw an analogy between the case under consideration and the pattern of interaction between a free stream and a two-dimensional unbounded obstacle perpendicular to the axis of the stream under the condition that no boundary layer is formed at the surface of the obstacle (the velocity of shear is equal to that of the flow). An inviscid flow of this kind was discussed in [3].

Under the conditions of the experiment the flow in the neighborhood of the plane separating the streams cannot be assumed to be a potential flow in view of the viscous effects in the flow gradient at small Reynolds numbers.

2. The form of the shock waves (curve 1, Fig. 1) due to the collision of the streams is approximately spherical with radius greater than the distance to the corresponding pipe. These shock waves cannot be identified with the Mach disc. Estimates according to [4] give the natural position of the Mach disc for the flow conditions under discussion at a distance of 189 mm from the section of the pipe.

3. A secondary system of compression discontinuities is formed (at the sides and ends) in the gas extending beyond the collision of the streams (Fig. 1, curves 3, 4). The estimate

$$(\rho'/\rho_c)_* = [2/(k+1)]^{-1/(k-1)}$$

of the critical density in this flow, assuming isentropic expansion (Fig. 2) gives the position of the sonic section y/d = 25, which is slightly greater than the position of the point of intersection of the shock waves 1, 2, and 3 (Fig. 1).

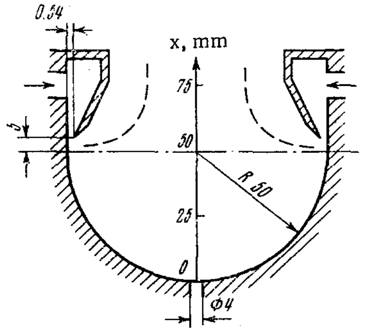

Fig. 5

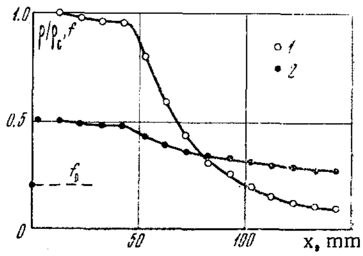

Fig. 6

The density profiles (Fig. 2) and the formation of a secondary system of discontinuities prove that in the region of the frontal point the pressure and density gradients are directed inwards and it is here that we must expect the greatest barodiffusion effect separating the gaseous mixture. Figure 3 gives the results of measuring the molar concentration of argon

$$f = n\,(\mathrm{Ar})\,/\,[n\,(\mathrm{Ar}) + n\,(\mathrm{He})]$$

along the axis of the pipe for the flow of an argon–helium mixture.

Curves 1, 2, 3 correspond to the values $p_0 = 135, 289, 63$, mm Hg, $p_k = 8.5 \cdot 10^{-3}, 2 \cdot 10^{-2}, 6 \cdot 10^{-3}$ mm Hg, $f_0 = 0.249, 0.173, 0.246$.

On the right of the ordinate axis is measured the concentration of the mixture supplied to the prechamber of the pipe. A typical feature of all the conditions is the significant enriching of the region near the frontal point with argon. When the pressure is greatest (curve 2) the leading edge of the shock waves is clearly enriched by helium, which corresponds to the structure of the shock wave in a gaseous mixture. Curves 1 and 3 were obtained when the pressure in the flow was reduced. The enriching of the leading edge of the shock wave with helium is not observed in this case, because the effect is compensated by the diffusion of argon from the central region.

When $x/d > 10$ the change in the concentration in all flow conditions is determined by diffusion processes in the stream.

Figure 4 gives the results of measuring the concentration (curve 1) and the mass density (curve 2) in the plane of the frontal point perpendicular to the axis of the pipe for $p_0 = 135$ mm Hg, $p_k = 8.5 \cdot 10^{-3}$ mm Hg, $f_0 = 0.249$. In this case the secondary system of discontinuities is essentially smeared out due to rarefaction. A feature of the concentration profile is the sharp rise at $y/d = 2.0$. As shown by an estimate of the density assuming isentropic expansion of the gas from the regions where the streams collide, the point at which the rise in concentration begins corresponds to the sonic section. From this point of view the change in the concentration when $y/d > 20$ is determined by barodiffusion processes when the supersonic flow of the gas is accelerated which are similar to the separation of the mixture of the free stream [5].

These results describe the diffusion processes leading to the enrichment of the region of symmetry of the flow. The shock wave 1 (Fig. 1) is straight only for the stream line on the axis of the pipe. For all other streamlines it is a line of discontinuity, which has a separating action leading to a deflection of the light component of the flow (helium) towards the periphery of the flow and the region of the frontal point is enriched with argon.

A second, and not less important, separating factor is the centrifugal pressure gradient as the flow passes the frontal point which gives rise to a barodiffusion flow of the heavy component towards the region where the stream line is convex.

When the flow of the mixture is accelerated in the region where the streams collide transonically, at sufficiently high rarefaction the heavy component may be left behind the light component, which also leads to an increase in the concentration of the heavy gas.

Thus, all the factors we have noted lead to an enriching of the central region, where the streams collide, with the heavy gas. Concentration diffusion and thermal diffusion smooth the inhomogeneities in the concentration.

The general pattern of the flow is a result of all the above factors.

3. We give some results of studying the collision of two-dimensional flows at a concave plate. The experimental setup is shown in Fig. 5. A mixture of gases flows from a prechamber at pressure p_0 through slotted pipes. As they flow past the concave surface the gaseous flows collide. In the collision region the counter flows form a breaking region with a subsonic flow in which we must expect an increased concentration of the heavy component. The length of the experimental setup was 100 mm. The ends were closed by impermeable walls.

To study the general flow pattern preliminary blow-through were made with visualization by means of a glow-discharge between the concave surface of the plate and the walls of the vacuum chamber. Photographs of the flow patterns showed that there were two compression discontinuities of complex shape, as shown schematically in Fig. 5 by the dotted lines. It is curious that the position and shape of the discontinuities is independent of the flow conditions when the pressure drop is large. This is evidently because the overall geometry of the flow is constructed in accordance with the hypersonic interaction of inviscid flows.

Apart from the properties described above for the gradient flow in the region where the flows collide, two further factors may be indicated which affect the enriching of this region by the heavy component. Firstly, there is a separation in the sloping compression discontinuity [6] and secondly there is an enriching by the heavy component of the region near the wall when the mixture flows past the concave surface [7].

The experiments were made with a mixture of argon and helium. The partial densities of the components and the argon concentration were measured by an electron beam along the x axis. Fig. 6 gives the profile of the mass density ρ/ρ_c (curve 1) and the argon concentration f (curve 2) for $p_0 = 6.8$ mm Hg, $p_k = 9 \cdot 10^{-3}$ mm Hg, $f_0 = 0.203$. The density profile is normalized to the value of the density at $x = 12.5$ mm.

The argon concentration in the region of the flow where $0 < x < 40$ mm is 2.5 times greater than the initial value. The nature of the density profiles permits one to conclude that the gas in the collision region is accelerated along the x axis through the speed of sound. The pressure drop when $x > 40$ mm is connected with the diffusion of helium from the region near the boundary.

We give the results of measuring the argon concentration at $x = 12.5$ mm in three different flow conditions:

TABLE 1

	p_0, mm Hg	$p_k \cdot 10^3$, mm Hg	f_0	$f_{x=12.5}$
1)	6.8	9	0.203	0.502
2)	5.0	7	0.093	0.240
3)	9.6	9	0.523	0.846

These results show that a similar setup can give a region which is considerably enriched by the heavy component of the mixture. The choice of the optimal dimensions, shape, and operating conditions is the subject of subsequent investigations. The problem of the effect of sampling the enriched mixture remains open.

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