THE FLOW OF A FLUID FILM ENTRAINED BY A SUPERSONIC FLOW OF GAS

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We have conducted an experimental study into the flow of a high-viscosity fluid directed through an orifice of small diameter onto the surface of a body contained within a supersonic flow of air

The jet flow of a low-viscosity fluid injected at high speed (perpendicular to the surface of a body) contained within a supersonic flow of gas has been studied in a number of papers (see, for example, [1, 2]). The jet penetrates through a considerable distance into the gas and breaks down into fine droplets. We have studied the depth of fluid penetration and the fineness of its atomization.

In this particular study, we examine yet another extreme case: a high-viscosity fluid, injected at low pressure, penetrates the gas through a small distance and forms a thin liquid film at the surface of the streamlined body. We study the conditions under which such a flow is achieved, as well as the extent to which the liquid film expands beyond the orifice.

The experiments were conducted in a supersonic wind tunnel whose operational section was formed by an Eifel chamber. We utilized conic nozzles with a critical cross-sectional diameter of 22 mm and outlet diameters of 30 and 80 mm, with Mach numbers at the outlet sections of the nozzle $M_\infty = 2.2$ and 4, respectively. In the following we present only those results obtained for a Mach number of $M_\infty = 2.2$. The deceleration temperature in all of these experiments was identical: $T_0 = 280$ K. The total pressure in the pressure chamber of the wind tunnel varied from $8 \cdot 10^5$ to $31 \cdot 10^5$ Pa. The Reynolds number $Re_{\infty D}$, calculated in this case from the parameters of the unperturbed gas flow and the diameter of the entering edge (blunting) of the model, varied from $0.45 \cdot 10^6$ to $2.65 \cdot 10^6$. With such a range of Reynolds number values, in the presence of a negative pressure gradient, we usually have a laminar flow regime.

We must take into consideration that owing to losses in total pressure in the bow shock wave the pressure P_0' at the point of complete deceleration on the model is significantly lower than the total pressure P_0 in the pressure chamber of the wind tunnel. In particular, with $M_\infty = 2.2$, $P_0' \simeq 0.54\ P_0$.

The models were made in the shape of a blunted cone, with a half-flare angle of about 5° and a spherical blunting radius of 10 mm, or in the shape of a blunted wedge with half-flare angles of 0 and 4°. The leading edge of the wedge was fashioned in the shape of a cylinder with a radius of 8 mm and was directed perpendicularly to the incident stream ($\chi = 0$) or it was inclined to it ($\chi = 45°$). We examined the flow of the fluid against the blunted edges of the cone and wedge.

For the high-viscosity fluid we used primarily glycerin with a kinematic viscosity $\nu = 500$ cSt at normal temperature.

Fluorescence excited by a defocused laser light source in the form of a beam or plane ("a laser cutting edge") [3], was used to visualize the fluid flow.

1. Penetration of the Fluid into the Gas Flow. The nature of the fluid flow injected through the orifice into the gas stream about the body significantly depends on the positioning of the orifices relative to the critical point (or critical line) at which total deceleration of the gas occurs.

In the immediate vicinity of the deceleration point (or line) the velocity of the gas is small. The conditions for fluid flow are here analogous to the conditions of flow in a gas at rest. With a limited fluid flow rate the fluid does not separate and spreads out over the surface of the body. With a relatively large fluid flow rate it separates from the surface over the entire perimeter of the orifice. Figure 1a shows a diagram of the fluid flow in the gas deceleration zone in the case of a large flow rate. The glycerin is injected through an orifice with a diameter of 0.38 mm, situated at the surface of the cylindrical rounded edge of the wedge, near the line of symmetry (on a generatrix with a center angle of $\omega = 4°$). The Reynolds number calculated for the average velocity of the fluid in the orifice, from the viscosity of the fluid, and

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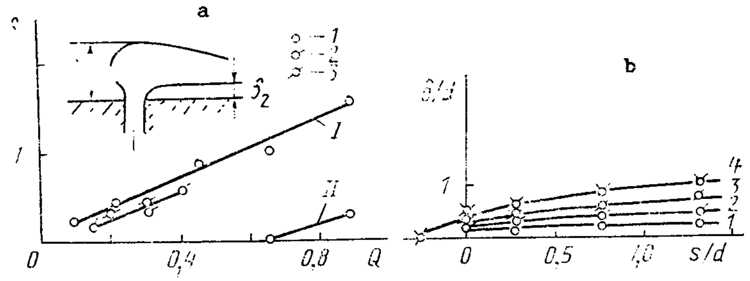

Fig. 1. Penetration of the fluid into the gas stream: a) on streamlining of a cylinder ($\chi = 0$), an orifice with d = 0.38 mm is situated on the generatrix $\omega = 4°$; I) δ_1; II) δ_2; 1) $P_0 = 7.9 \cdot 10^5$ Pa; 2) $19 \cdot 10^5$; 3) $30.4 \cdot 10^5$. b) In the streamlining of a sphere, an orifice with d = 0.53 mm is situated at the point $\omega = 45°$, $P_0 = 25 \cdot 10^5$ Pa, 1) Q = 0.015 cm^3/sec; 2) 0.05; 3) 0.26; 4) 0.85.

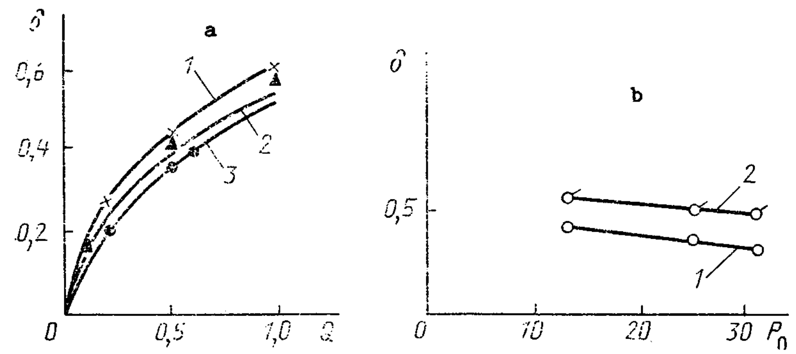

Fig. 2. Thickness of the fluid film as a function of the fluid flow rate and gas pressure (s/d = 1): a. 1) $P_0 = 13 \cdot 10^5$ Pa; 2) $25 \cdot 10^5$; 3) $31 \cdot 10^5$. b. 1) Q = 0.4 cm^3/sec; 2) 0.8. The lines represent theory.

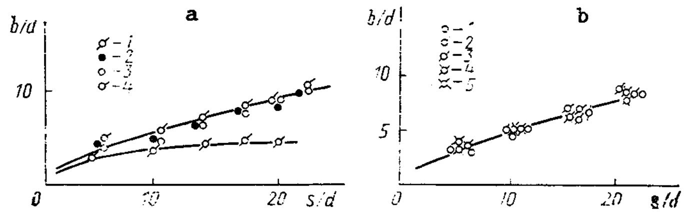

Fig. 3. Effect of fluid flow rate and gas pressure on the width of the fluid film: a) $P_0 = 31 \cdot 10^5$ Pa; 1) Q = 0.055 cm^3/sec; 2) 0.07; 3) 0.25; 4) 0.40; b) Q = 0.3 cm^3/sec; 1) $P_0 = 8.2 \cdot 10^5$ Pa; 2) $13 \cdot 10^5$; 3) $19 \cdot 10^5$; 4) $25 \cdot 10^5$; 5) $31 \cdot 10^5$.

from the diameter of the orifice, varied from $Re_\ell \simeq 0.017$ in the case of a flow rate of Q = 0.2 cm^3/sec to $Re_\ell \simeq 0.07$ for Q = 0.8 cm^3/sec. Measurements of the depth of fluid penetration, carried out by means of photography, demonstrated (Fig. 1a) that the separation of the fluid from the surface of the body over the entire perimeter of the orifice began with a glycerin flow rate of Q = 0.6 cm^3/sec. This flow rate corresponds to a Reynolds number of $Re_\ell \approx 0.05$ and a ratio of the fluid velocity head to the local velocity head of the gas, such that $q_\ell/q_g \approx 10$.

A different picture arises when the fluid is injected into the high-speed gas flow through an orifice situated at some distance from the critical point. The glycerin is injected through an orifice situated on the surface of a sphere at a point with a central angle $\omega = 45°$. With a large ratio of velocity heads $q_\ell/q_g \geq 4$ (the Reynolds number in this case does not exceed values of $Re_\ell \approx 0.1$) the fluid is separated from the surface of the sphere over the entire perimeter of the orifice. With smaller values for this ratio, the fluid also separates from the surface, but only in a portion of the orifice perimeter, i.e., from the side of the incident gas flow. The fluid does not separate on the remaining portion of the orifice perimeter (on the opposite side), spreading out over the surface of the sphere. This can be seen from Fig. 1b, which shows the profile outlines of the fluid film, determined by means of large-scale photography.

Such "separation-free" flow was observed in the above-described series of experiments with a change over a broad range of both the total gas pressure ($P_0 = 8 \cdot 10^5$–$31 \cdot 10^5$ Pa) and the rate of fluid flow ($Q = 0.02$–1.6 cm^3/sec) through the orifice. Here the ratio of the fluid velocity head to the local velocity head of the gas attained values of $q_\ell/q_g \approx 1.7$, while the Reynolds number $Re_\ell = 0.15$. In other experiments, conducted at even higher values of q_ℓ/q_g, we noted separation of the fluid over the entire perimeter of the orifice (with $q_\ell/q_g \approx 4$). When the velocity-head ratio attained values of $q_\ell/q_g \approx 10$, the fluid jet penetrated into the gas to a greater depth (on the order of 80d).

We devoted our attention mainly to a study of the separation-free flow of the fluid film. Experiments have demonstrated that the thickness of the film increases with increasing distance from the orifice, and within the indicated range of parameters it is smaller by an order of magnitude or equal to the diameter of the orifice. The film thickens as the fluid flow rate increases (Fig. 1b) and it becomes thinner as the velocity head of the gas increases (i.e., the total pressure of the gas).

The thickness δ of the liquid film can be evaluated by calculation if we assume a linear profile for the changes in velocity with increasing distance from the surface. We have come up with the following results: $\delta = \sqrt{2\mu[(Q/b)/\tau]}$ (μ is the viscosity of the fluid). If we assume that the boundary layer of the gas is in the laminar state (i.e., $\tau \sim \sqrt{P_0}$) and if we neglect the change in the width of the film as a function of the rate of flow and pressure, as is confirmed by the data presented below, we arrive at the conclusion that $\delta \sim (\mu^{1/2}Q^{1/2})/P_0^{1/4}$. This conclusion is in agreement with the experimental data (Fig. 2). However, the theoretical data presented here have been obtained by recalculation of the experimental value for the film thickness at a flow rate of $Q = 0.5$ cm^3/sec and a total pressure of $P_0 = 13 \cdot 10^5$ Pa, based on the above-cited relationship. When the boundary layer is in the turbulent state, i.e., when $\tau \sim P_0^{0.8}$, the influence exerted by the pressure of the gas on the thickness of the fluid film is even more significant: $\delta \sim (\mu^{1/2}Q^{1/2})/P_0^{2/5}$.

2. Spreading of the Fluid Film Beyond the Orifice. When subjected to the forces which arise in the interaction of the fluid with a solid surface the fluid spreads out in a direction perpendicular to the streamline on the boundary of the film (i.e., during wetting). This spread of the fluid is enhanced by a transverse gradient of additional pressure which creates a convex surface in the fluid film within the gas flow: the gas flow "crushes" the film. The surface tension of the film serves to block this lateral spreading out of the fluid. In addition to the above-enumerated forces emanating out of the gas flow, the fluid is affected by the force of friction which moves the fluid in the longitudinal direction, i.e., along the streamlines. As a result of the combined effect of all of these forces, the film is made to expand beyond the orifice. Figure 3 shows the change in the relative width of the fluid film formed on the cylindrical surface of an unswept rounded wedge ($\chi = 0$), as a function of increasing distance from the orifice. Glycerin was injected through an orifice 0.38 mm in diameter, this orifice situated on a generatrix with a center angles of $\omega = 45°$.

Particularly noteworthy is the result of our experiments which demonstrated that the width of the film at the cylindrically rounded wedge ($\chi = 0$) and at the spherically rounded cone depend little on either the fluid flow rate, nor on the pressure of the air (Fig. 3). Only with minimum values for the fluid flow rate (below $Q \approx 0.1$ cm^3/sec in the case of an orifice diameter of $d = 0.38$ mm) does the width of the film increase significantly as the flow rate is increased. With any further increase in the rate of flow the film expands only slightly (Fig. 3a). The change in the air pressure in the range under consideration ($P_0 = 8.2 \cdot 10^5$–$31 \cdot 10^5$ Pa) also has only a slight effect on the width of the film (Fig. 3b, the pressures on the cylinder at the locations of the orifices correspond to the indicated range of total-pressure values from $2.2 \cdot 10^5$ to $8.8 \cdot 10^5$ Pa). The film expansion angle γ on an unswept leading edge of a wedge fashioned out of an acrylic-like plastic goes from 19° to 17° as the pressure rises from $8 \cdot 10^5$ to $31 \cdot 10^5$ Pa. The change in the angle γ is somewhat greater when glycerin flows over a sphere fabricated out of Kh18N10T stainless steel: from 42° to 36°, in the same pressure range. Were the spreading of the film to be determined exclusively by the forces of air friction and by the wetting of the solid surface, then in the case of laminar gas flow the quantity tan γ would change in proportion to $P_0^{-0.5}$, i.e., it would become smaller by a factor of virtually 2 in the range of pressures under consideration. The actual change in the angle γ was significantly smaller and this is probably associated with the influence exerted by the pressure induced by the film, with this pressure intensifying the lateral spreading out of the fluid, thus offsetting the narrowing of the film, owing to an increase in the force of friction as the pressure rises.

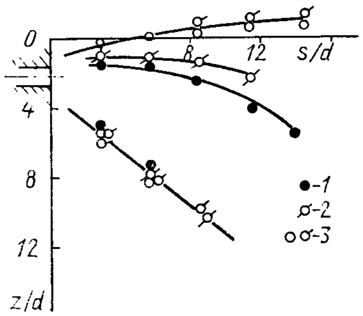

Fig. 4. Fluid flow over a cylindrical surface ($\chi = 45°$) with air blown through the orifice (d = 0.47 mm), situated near the plane of symmetry ($\omega = 8°$): $P_9 = 31 \cdot 10^5$ Pa. 1) Q = 0.001 cm^3/sec; 2) 0.23; 3) 0.63; the axis of abscissas represents the wedge symmetry line.

No significant influence on the part of fluid viscosity and the composition of the fluid was noted in the experiments with respect to the width of the film. This may possibly be associated with the fact that in these experiments the fluid did not spread out over a dry surface of the model, but rather over a surface that had been wetted just moments earlier.

The spreading out of the film was also studied on a rounded wedge with a sweptback leading edge. The orifice was either situated at some distance from the line of symmetry (on the generatrix of a cylinder with a center angle ω = 45°) or in the vicinity of the symmetry line (ω = 4 and 8°).

In the first case (ω = 45°) the width of the film as a function of the fluid flow rate and of the air pressure is qualitatively the same as for an unswept wedge. However, stabilization of film width on a swept wedge occurs with considerably greater rates of flow (with Q ≈ 0.25 cm^3/sec) than in the case of an unswept wedge. With an increase in pressure on the sweptback wedge, the film becomes constricted to a greater extent than in the case of an unswept wedge. These differences are brought about by the fact that the sweepback involves a velocity component that is parallel to the generatrix of the cylinder. As a result of this, the total velocity at the cylindrical grounded edge when $\chi \neq 0$ is considerably greater, and the film is subjected to a greater velocity head, which deforms the film as the rate of flow and pressure are increased, than is the case when $\chi = 0$.

In the second case (for the small values for the angle ω) the flow of the fluid at the sweptback leading edge exhibits an interesting unique feature: with a large flow rate the fluid flows not only from the line of symmetry, which represents the line of gas spread, but in the opposite direction as well, i.e., to the line of symmetry. This is shown in Fig. 4: as the flow rate increases, one of the boundaries of the film shifts in the direction of the line of symmetry and at some flow rate (Q = 0.63 cm^3/sec) intersects the latter. In this case, a portion of the fluid passes through the "crossing" from the side on which the orifice is located to the opposite side.

The described phenomenon is explained by the fact that the liquid film undergoes a significant change in the shape of its "effective body" (i.e., a body coated with the film) in the vicinity of the line of symmetry. Consequently, the pressure above the film is elevated, and the pressure maximum and the spread line are displaced away from the line of symmetry of the plate in the direction of the orifice. The greater the flow rate, the greater the deformation of the effective body, and the larger the displacement of the boundary of the film situated near the line of symmetry. At the same time, another film boundary, at some distance from the line of symmetry, experiences no significant effect from the displacement of the spreading line and remains virtually unchanged with an increase in the flow rate, as is the case with an unswept wedge.

The increase in gas pressure also exerts considerable influence on the shape of the film near the line of symmetry when $\chi \neq 0$. With an increase in pressure, and correspondingly with an increase in the velocity head of the gas, the boundary of the film situated on the same side of the line of symmetry as the orifice shifts away from the line of symmetry. The other boundary, situated on the opposite side from the "crossing," in direct proportion to the increase in pressure, approaches the line of symmetry as a consequence of the increase in the pressure gradient in the main gas flow, counteracting the approaching fluid flow.

We have thus determined the conditions under which the fluid jets separate from the surface of the body in the case of low Reynolds numbers Re_ℓ. We have demonstrated that with separation-free flow a liquid film is formed beyond the orifice, and the width of this film increases with increasing distance from the orifice and depends only slightly on the fluid flow rate and the pressure of the gas. The relationship between the thickness of the film and the fluid flow rate and frictional stress (or gas pressure) can be determined by making the assumption that the velocity profiles within the film are linear. We have observed anomalous behavior in the liquid film in the vicinity of the spread line of the sliding cylinder.

NOTATION

M_∞, Mach number for the outlet cross section of the nozzle; $Re_{\infty D}$, Reynolds number calculated from the parameters of the unperturbed flow at the outlet section of the nozzle and from the diameter of model rounding; P_0, total pressure in the pressure chamber of the wind tunnel, Pa; T_0, deceleration temperature; χ, sweepback angle of leading edge of plate (between the normal to the direction of the unperturbed flow and the generatrix of the leading edge), deg; d, orifice diameter, mm; ω, angle between direction of unperturbed flow and radius vector of orifice, deg; τ, frictional stress at boundary separating fluid and gas, Pa; Q, volumetric fluid flow rate, cm^3/sec; ν, kinematic viscosity of fluid, cSt; q_ℓ/q_g, ratio of the velocity head of the fluid at the outlet from the orifice to the local velocity head of the gas; δ, thickness of fluid film, mm; b, width of fluid film, mm; γ, angle between tangents to the side boundaries of the fluid film, deg; s, coordinate calculated from the center of the orifice along the midline of the film or along the axis of wedge symmetry, mm; z, coordinate calculated along the normal to the axis, mm.

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CHARACTERISTIC AERODYNAMIC FEATURES OF NONSYMMETRIC JET FLOWS

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We present results from an experimental study of the relationship between the angle of jet rotation and the curvature radius and length of a rectangular curvilinear nozzle.

Jets flowing out of curvilinear nozzles of various geometry with R_ω = const were studied in [1-5]. The distribution of statistical dynamic characteristics of a jet flowing out of a plane curvilinear nozzle was studied in [5], where it was demonstrated that the Gertler vertices are retained downstream in a free jet, all the way to distances on the order of 10 calibers, and that they significantly affect the distribution of the averaged velocity and the mean-square values of velocity pulsations. Owing to centrifugal forces, the pressure at the nozzle outlet is not distributed uniformly, so that there exists, therefore, some angle α (Fig. 1) between the tangent to the axis of the channel and the geometric axis of the jet. The influence exerted by the curvature radius R_ω and the length L of the nozzle on the nonsymmetricity of the jet can be seen in the extent to which the deflection angle α changes.

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