INTERACTION OF A SUPERSONIC FLOW WITH A TRANSVERSE JET INJECTED THROUGH A CIRCULAR APERTURE IN A PLATE

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A flow pattern created by the interaction of a supersonic flow with a transverse sonic or supersonic jet injected normally to the direction of the main flow through a circular aperture in a plate is considered. The pressure rises in front of the jet owing to the retarding action of the incident flow. The boundary layer building up on the wall in front of the injection nozzle is accordingly detached. The flow pattern in the region of interaction between the jet and the external flow is illustrated in Fig. 1. The three-dimensional zone of detachment thus formed deflects the incident flow from the wall, and in front of the jet a complicated system of sharp jumps in contraction develops. A three-dimensional system of jumps also develops in the jet itself.

The aim of this investigation was to determine the physical characteristics of the flow pattern formed by the interaction of a supersonic flow with an injected jet, and to establish the principal relationships governing the geometrical characteristics of the flow in terms of the parameters of the incident flow and the injected jet.

1. The region of interaction between the injected jet and the supersonic flow was studied experimentally under the following conditions. The Mach number of the incident flow was 2.1, 2.9, and 3.7; the Reynolds number calculated in the plane of symmetry of the flow from the length of the plane (up to the line of detachment) and the parameters of the incident flow was varied between $2 \cdot 10^6$ and $2 \cdot 10^7$, which corresponds to a turbulent boundary layer. The "degree of wastage" n of the injected gas jet, equal to the ratio of the static pressure in the injected jet to the static pressure of the incident flow, varied from 0 to 200. The Mach number of the injected jet $M_a = 1.0$, 1.96, and 2.96. The thickness of the boundary layer in front of the line of detachment $\delta = 6$ mm. The diameter of the exit cross section of the sonic injection nozzle equalled 2, 4, and 8 mm and that of the supersonic injection nozzle 8 mm.

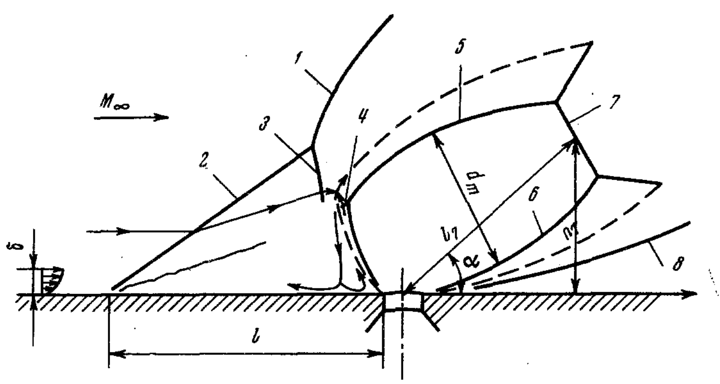

Fig. 1

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The length of the detachment zone was determined experimentally (by the oil-coating method) as a function of the parameters of the principal and injected flows. The geometry of the jumps in contradiction was examined using the shadow method. In the detachment zone, the temperature distribution was measured on the heat-insulating surface for $T_{0a} < T_{0\infty}$.

2. The system of jumps in contraction (compression) observed in the incident flow in front of the jet and in the jet itself is illustrated in Fig. 1. The system of jumps in the incident flow comprises the principal jump 1, the oblique jump 2, and the closing jump 3. Inside the jet is a barrel-shaped jump (indicated by the numbers 5 and 6 in Fig. 1) and a central jump 7 (Mach disc). The configuration of the jumps in the jet is asymmetrical. The jump 5 has a break which arises from the fact that high pressure gradients occur in the space in front of the jet. At the point of the break there is a jump 4. The figure also illustrates a jump 8, which is formed beyond the injection nozzle when the flow bent around the injected jet passes to the wall.

The flow in the region of interaction between the jet and the external flow may be characterized by the following parameters in the plane of symmetry of the flow: l is the length of the zone of detachment measured from the edge of the injection nozzle to the line of detachment, h_7 is the distance from the wall to the middle of the central jump, l_7 is the distance from the center of the cross section of the tip of the injection jet to the middle of the central jump, d_m is the greatest distance between jumps 5 and 6, and α is the angle between the barrel-shaped jump and the horizontal (Fig. 1).

3. By analyzing the interaction between the injected gas jet and the incident supersonic flow on the basis of dimensional theory, we see that the geometrical characteristics of the flow, such as d_m, should depend on the dimensions of the parameters of the main and injected flows in the form

$$d_m / d_a = f(n,\ M_\infty,\ M_a,\ R_\infty,\ \delta / d_a,\ T_{0a} / T_{0\infty},\ \varkappa_\infty,\ \varkappa_a,\ \ldots) \tag{1}$$

Here d_a is the diameter of the cross section of the injection jet at the tip.

The case of the three-dimensional detachment of the boundary layer in front of a solid obstacle in a supersonic flow around, for example, a cylinder set in a plate has already been fully studied [1]. One of the main features in the detachment of the boundary layer in front of a cylinder is the fact that the length of the zone of three-dimensional detachment ceases to depend on the height of the cylinder H starting from some particular value of H/d. Here d is the diameter of the cylinder.

In the case of the detachment of a turbulent boundary layer, the length of the zone of detachment varies linearly with the diameter of the cylinder. Bearing this in mind, we may reasonably consider that the length of the zone of detachment in front of a jet obstacle will also depend linearly on the cross section of the jet. It is well known that, in the efflux of a gas jet into a submerged space, the geometrical parameters of the barrel-shaped jump in compression is directly proportional to $d_a n^{0.5}$ [2]. An analogous relationship probably holds in the case of the transverse injection of a gas jet into a supersonic flow.

The effect of the Mach numbers of the main and injected flows on d_m may be estimated from the following considerations. Let us suppose that the mass of injected gas m_a is accelerated in the direction of the main flow from 0 to V_∞. Then a force $m_a V_\infty$ will act on the main flow from the direction of the injected jet (we are considering the case in which there are no chemical reactions between the injected jet and the main flow). If we equate $m_a V_\infty$ to the force of the head (frontal) resistance of a thin object, such as would exert an influence equal to that of the injected jet on the main flow, then from the equation

$$C_x A \left(\frac{\rho_\infty V_\infty^2}{2}\right) = m_a V_\infty \tag{2}$$

we may determine the characteristic size of the equivalent object. Here C is the coefficient of head resistance, A is the area of the "midship section" of the equivalent object, ρ_∞ and V_∞ the density and velocity of the main flow. It follows that the dimension d_m, proportional to the diameter of the equivalent object, should depend on the parameters of the main and injected flows in the following way:

$$\frac{d_m}{d_a} = Cn^{0.5}\left(\frac{M_a\sqrt{1+0.2M_a^2}}{M_\infty\sqrt{1+0.2M_\infty^2}}\right)^{0.5} = Cn^{0.5}K(M_a,\ M_\infty) \tag{3}$$

Here C is a constant factor. Equations (3) is derived for the case of the injection of an air jet into a supersonic air flow at $T_{0a} = T_{0\infty}$.

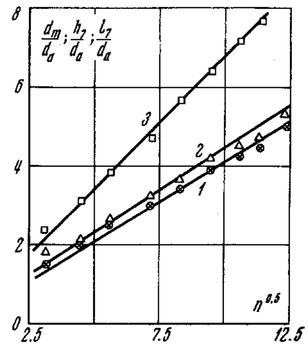

Fig. 2

4. Figure 2 shows the experimental values of the geometrical characteristics of the jumps in compression d_m/d_a (curve 1), h_7/d_a (curve 2), l_7/d_a (curve 3) observed in the jet in relation to $n^{0.5}$ for the number

$$M_\infty = 2.9, \quad M_a = 1, \quad R \approx 10^7 \text{ and } \delta / d_a = 3$$

We see from Fig. 2 that the experimental points are grouped around straight lines. Analogous results were obtained for other values of the M_∞ number. We readily see from the data here presented that the slope of the injected jet α is independent of the degree of wastage for constant values of M_∞ and M_a.

Figure 3 shows the experimental values of both the relative quantities

$$d_m{}^\circ = \frac{1}{\sqrt{n}} \frac{d_m}{d_a}, \qquad l_7{}^\circ = \frac{1}{\sqrt{n}} \frac{b_7}{d_a}$$

and the angle α for $M_a = 1$ and $R_\infty = 2 \cdot 10^6$ to $2 \cdot 10^7$ in relation to the number M_∞. The relative transverse dimension of the jet in the plane of symmetry of the flow $d_m{}^\circ$ falls with increasing M_∞. This happens because an increase in M_∞ causes a rise in the critical pressure drop. In view of this, the degree of wastage calculated from the static pressure in the region of interaction directly behind the jump 3 falls with increasing M_∞, and the angle of inclination of the jet to the main flow correspondingly diminishes.

Figure 4 shows the dependence of the same quantities on the Mach number of the injected jet for $M_\infty = 2.1$ and $R_\infty = 2 \cdot 10^6$. We see from this figure that a rise in M_a leads to an increase in both the diameter of the barrel-shaped jump in compression and also the angle of inclination of the jet. Figure 5 shows the experimental values of $d_m{}^\circ$ for values of $M_\infty = 2.1$; $M_a = 1.0, 1.96, 2.96$ (points 1) and for $M_a = 1.0$; $M_\infty = 2.1, 2.9, 3.7$ (points 2) in relation to the parameter $K(M_a = M_\infty)$. The experimental values of d_m presented in this form lies excellently on a single straight line.

5. To a first approximation, the effective solid obstacle equivalent to the jet as regards its action on the main flow may be taken as a cylinder with diameter d_m and height h_7 set in a plate at an angle α. Figure 6 shows the dependence of the ratio l/d_m on the degree of wastage of the injected gas jet n for the case $M_a = 1$ and $\delta/d_0 = 1.5$, and also for the case $M_a = 1$ and $M_\infty = 2.1$, where the points 1', 2', 3' correspond to the values $\delta/d_a = 0.75, 1.5, 3.0$.

It follows from Fig. 6 that the number M_∞ has no effect on the relative length of the zone of detachment as the wastage factor varies. The vertical line in this figure indicates the characteristic value of the degree of wastage n_*. For values of n less than n_*, the relative length of the zone of detachment l/d_m depends on the parameter δ/d_a. This is because, for $n < n_*$, the length of the zone of detachment depends both on the diameter of the effective object and also on the depth of the penetration of the jet into the main flow in the same way as in the case of the flow around a cylinder set in a plate. When $n > n_*$, the depth of

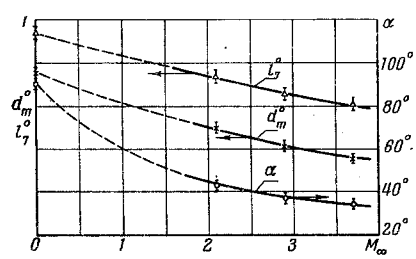

Fig. 3

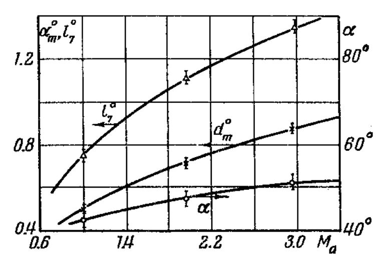

Fig. 4

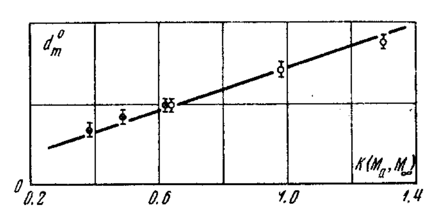

Fig. 5

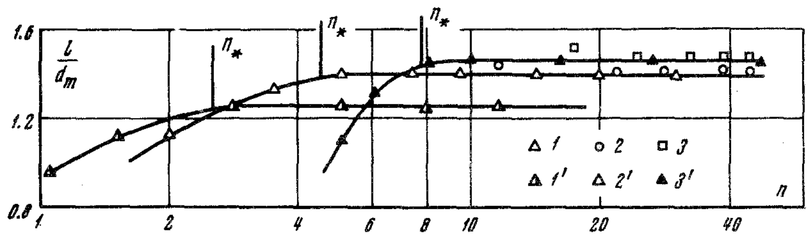

Fig. 6

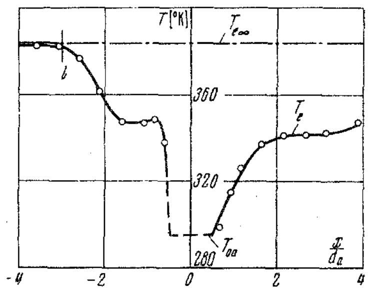

Fig. 7

penetration has no effect on the value of l/d_m, and the length of detachment zone only depends linearly on the diameter of the effective obstacle. We see from Fig. 6 that the value of n_* increases with increasing parameter δ/d_a. This is because the "piercing" of a thicker boundary layer takes place for a greater degree of wastage. No effect of the M_∞ number on n_* was observed in the range of M_∞ values studied.

6. As a result of the mixing of the main and injected flows, some of the injected gas is thrown right up to the line of detachment, whereas most of the injected air is carried down the flow from the point of injection. This is confirmed by measuring the temperature of the heat-insulated wall in the neighborhood of the injection aperture. Figure 7 illustrates the measured temperature distribution of the heat-insulated surface in the plane of symmetry of the three-dimensional region of interaction between the injected and main flows. Injection was carried out perpendicularly to the direction of the main flow, with numbers $M_\infty = 2.9$, $M_a = 1$, $R_\infty = 6 \cdot 10^6$, $n = 15.5$, $\delta/d_a = 0.75$. The temperature of the main flow $T_{0\infty} = 395°$ K, the temperature corresponding to the retardation of the injected jet $T_{0a} = 295°$ K. The vertical line indicates the position of the line of detachment.

As a result of the foregoing investigations, which confirmed the similarity between the detachment phenomena respectively taking place in front of solid obstacles and jets, we may expect to find regions of high pressure and thermal flux in the front of the detachment region.

LITERATURE CITED

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