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SUPERSONIC FLOW PAST A CYLINDRICAL BODY WITH TRANSVERSE JETS AT LARGE ANGLES OF ATTACK

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Supersonic flow past a cylindrical body with a system of transverse jets ejected from its surface at angles of attack $\alpha = 60$–$120°$ is characterized by a complicated gasdynamic flow pattern [1]. The body surface is affected by both the oncoming flow and the ejected jets which shield a portion of the surface from the external flow. This results in considerable transverse and longitudinal pressure gradients appearing on the body surface. The experimental pressure distributions over a cylindrical model with four transverse jets at a Mach number M=4 and $\alpha = 60°$, $90°$, and $120°$ make it possible to study the specific features of the flowfield and derive correlations for the "jet obstacle" dimensions.

The pattern of flow past a body with a system of ejected transverse jets depends on the ratio of the total jet momentum $J_j = mf_jk_jP_jM_j^2(\lambda_j^\circ/\lambda_j)$ and the oncoming flow momentum $J_1 = f_1kP_1M_1^2$, where m is the number of nozzles in the system of transverse jets, f_j and f_1 are the nozzle exit section area and the body cross-sectional area respectively, k_j and k_1 are the adiabatic exponents of the jet gas and the oncoming flow respectively, P_j and P_1 are the static pressures at the nozzle exit and in the freestream respectively, and λ_j° and λ_j are the velocity coefficients of the jet for $P = P_1$ and at the nozzle exit respectively.

Since the body surface may be fully shielded from the external flow at corresponding values of $J^\circ = J_j/J_1$ and the body aspect ratio L/d_M, its pressure levels may vary widely. For large values of J°, the interaction between the system of jets and the oncoming flow is analogous to the effect of a single strongly underexpanded jet opposing a supersonic flow [2–4].

Supersonic flow past a cylindrical body with a system of transverse jets at large angles of attack results in the formation of a single complex shock wave ahead of the body and the system of jets (Fig. 1). The distance between the wave and the body is determined by the value of J°, the oncoming flow Mach number, and the angle β between the jet axis and the oncoming flow direction.

In what follows, the interaction between a supersonic (M=4) flow past a cylinder with a conical nose and a system of four oblique jets ($\beta = 60°$, $90°$, and $120°$) located in the same cross-section of the body is considered. Two of the iets lie in the flow symmetry plane.

The total aspect ratio of the body $L^\circ = L/d_M = 8.62$, the conic nose radius $r^\circ = r/d_M = 0.28$, and the cone half-angle $\theta_k = 10°$. The four sonic nozzles were uniformly distributed in the cross-section at a distance $L^\circ = 4.95$ from the forward stagnation point.

Pressure taps for measuring pressure were located in five cross-sections at distances $L^\circ = 3.3$, 4.5, 5.6, 6.45, and 7.3 from the forward stagnation point. In the azimuthal direction the coordinates of the pressure taps varied from $\varphi = 0°$ to $\varphi = 180°$ with a step of 22.5°.

The dynamic pressure profiles in the jet–oncoming flow mixing layer were measured using a rake of Pitot tubes which could travel along the cylindrical part of the model and rotate though an angle $\varphi = \pm 45°$ in the azimuthal direction. Moreover, the accuracy of orientation of the tubes with respect to the flow velocity vector in the jet–oncoming flow mixing layer was improved by varying the angle δ between the rake and the model axis ($\delta = 30°$, $75°$, and $90°$).

An analysis of the results of the experimental studies makes it possible to propose the following scheme of interaction between the system of transverse jets and the oncoming flow at large angles of attack (Fig. 1). The strongly underexpanded jet ($J^\circ \geq 1$) opposing the oncoming flow first makes an angle β with the longitudinal axis until the formation of the closing shock *2* and the discontinuity surface *4* that separates the jet gas from that of the oncoming flow.

Shock *2* falls within the bounds of the first jet "barrel" at a distance from the nozzle exit at which the pressure behind it is equal to that behind the shock wave *1*. The interface separating the two gases (fictitious "fluid body") is actually the compressed layer between the two supersonic flows which first collide and are then deflected towards the mainstream. The impingement of the compressed layer on the cylindrical body surface results in the formation of shocks *3*.

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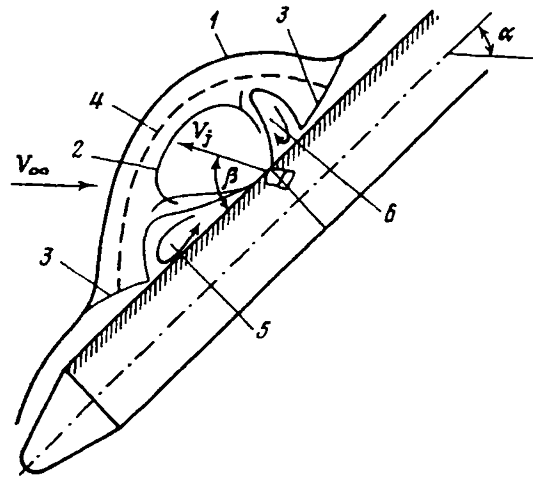

Fig. 1. Diagram of supersonic flow past a body with a system of transverse jets. *1* is the shock wave, *2* is the shock in the jet, *3* are the closing shocks, *4* is the tangential discontinuity surface, and *5* and *6* are stagnation zones *1* and *2* respectively.

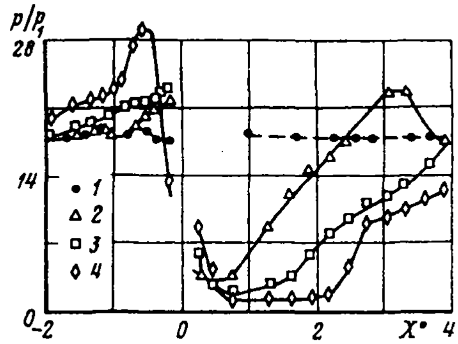

Fig. 2

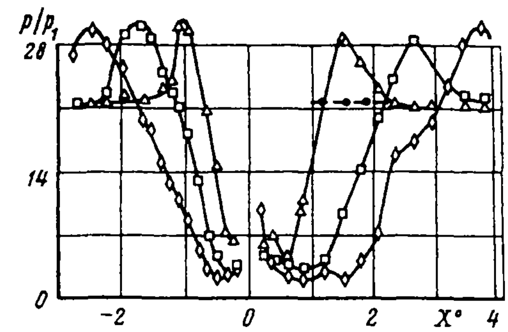

Fig. 3

Fig. 2. Pressure distributions on the windward side of the cylinder for $\alpha = 60°$. Points *1* through *4* correspond to $J° = 0$, 10, 29, and 59 respectively.

Fig. 3. Pressure distributions on the windward side of the cylinder for $\alpha = 90°$. Notation the same as in Fig. 2.

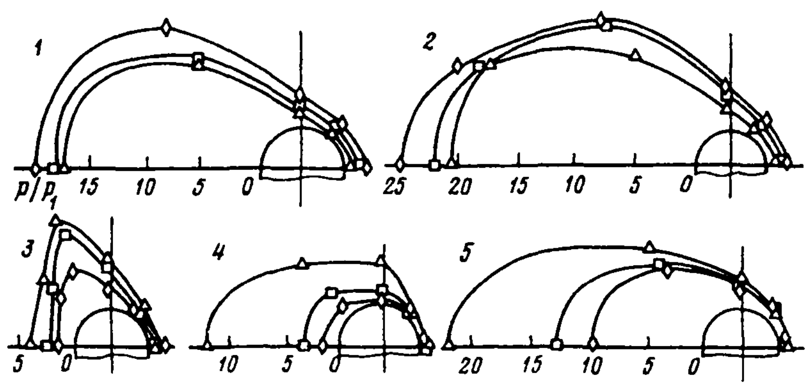

Fig. 4. Circumferential pressure distribution for $\alpha = 60°$. Notation the same as in Fig. 2.

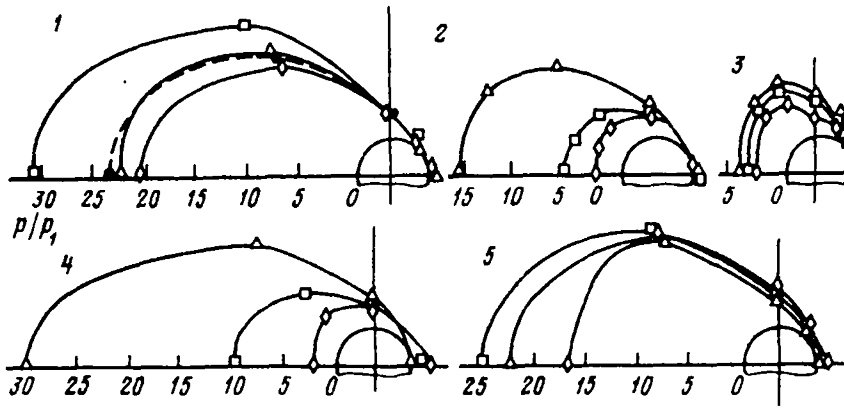

Fig. 5. Circumferential pressure distribution for $\alpha=90°$. Notation the same as in Fig. 2.

Stagnation flow zones form near the boundaries of each of the four jets. On the leeward side they are open towards the environment.

For convenience, in what follows the stagnation flow zones that form ahead of the jet and behind it are denoted by subscripts *1* and *2* respectively. According to Figs. 2-5, the pressures in the zones are significantly different only for an angle of attack $\alpha=60°$ (Fig. 2); for $\alpha=90°$ and 120° they nearly coincide. Although the dimensions of the zones are quite different, it was found that their total extent is the same for all three values of α. In particular, this conclusion is verified by the pressure distributions along the windward generator of the body (see Figs. 2 and 3, where the coordinate $X^\circ = X/d_M$ is reckoned from the jet ejection point).

Figures 4 and 5 present the azimuthal pressure distributions in cross-sections *1* through *5* for the above-indicated flow modes and $\alpha=60°$ and 90° respectively. The distributions are plotted in the polar coordinate system centered on the body axis. The pressure is reckoned from the body surface, and the flow comes from the left. Each curve corresponds to a fixed nondimensional momentum J°.

The pressure distributions indicate that the pressure in zone *2* downstream of the jets is much lower than in the separated-flow zone *1*. This is especially so for $\alpha=60°$ (Fig. 2) when the pressures differ by a factor of 5 to 6. For $\alpha=90°$ the pressure distribution in zones *1* and *2* is smoother, and for $\alpha=120°$ zones *1* and *2* as it were change places.

On the portion of the body surface on which the compressed layer impinges the maximum pressure p_{01}, registered for $J^\circ=29$—59, exceeds the stagnation pressure p_0' downstream of the shock wave *1* approximately by a factor of 1.2—1.6 (Figs. 2 and 3). If the positions of the maxima on the body surface are assumed to correspond to the boundaries of the disturbed region on the windward side of the cylinder, then its total length may be described by the dependence

$$l/d_M = 0.8\sqrt{J^\circ}$$

Above it was indicated that this quantity is nearly independent of the angle of attack.

The pressure rake measurements showed that the pressure in the stagnation zone *2* is nearly constant and equal to $p_2=2p_1$. However, a sharp change in pressure is observed in the plane of interaction of neighboring jets ($\varphi=45°$) along the normal to the surface: in the case under consideration the normal pressure increases several-fold.

According to Figs. 4 and 5, the pressure in the body cross-sections decreases from $\varphi=0°$ to $\varphi=90°$ by nearly an order of magnitude and may be approximated everywhere, except for cross-section *3*, by the law $(p - p_1)/p_1 \sim \cos\varphi$. The pressure on the leeward side of the body is nearly constant and equal to $(0.5—1.0)p_1$.

The dependence of the pressure on φ in cross-sections downstream of the jet ejection site indicates that neighboring jets interact leading to an increase in the pressure in the space between the jets, i.e. for $\varphi=45°$ (see cross-section *3* in Figs. 2 and 3). The interaction determines the dimensions of the "window" through which the gas flows from zone *1* to zone *2*. The larger the parameter J° the smaller the "window" through which the gas flows into zone *2*.

The experimental dependences of the distances from the jet nozzle to the interface between the two flows (radius R) and to the shock in the jet (radius r) on the windward surface of the body on the parameter J° show that for $120° \le \alpha + \beta \le 210°$ the following relations are valid:

$$r/d_M = -0.035J^\circ \cos(\alpha + \beta), \qquad R/d_M = -0.055J^\circ \cos(\alpha + \beta)$$

These dependences agree with the results calculated using the modified technique [2] for large pressure drops: $p_{0j}/p_1 > 10^3$.

Summary. When a system of transverse jets interacts with an oncoming supersonic flow at large angles of attack $\alpha = 60° - 120°$ the character of the pressure variation in the longitudinal and transverse directions on the surface of a cylindrical body is almost the same. There are, however, certain differences: an increase in the angle between the jet and the external flow results in an extension of the forward separated-flow zone and a contraction of zone *2*, though the total extent of the zones is independent of the angle of attack and may be approximated by the dependence

$$l/d_M = 0.8\sqrt{J^\circ}$$

For large values of the parameter J° the geometric characteristics of a jet on the windward side of the body which forms part of a system of four jets nearly coincide with those of a single jet.

Editorial note: In view of the author's death this paper was prepared for print by V. N. Shmanenkov.

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