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BODY DRAG CONTROL IN SUPERSONIC GAS FLOWS BY INJECTION OF LIQUID JETS

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There are different approaches that enable one to change the structure of the flow field in the near-field zone of supersonic flow around bodies. One of the active techniques of body drag control in supersonic flows is the use of a thin spike jutting upstream of a blunted body [1]. This results in such a flow rearrangement that a so-called separated flow forms and the drag of the body in the flow is significantly decreased. The main investigations on flow separation control are presented in [2, 3]. Further generalization of works on body drag control involves the injection of different inert and reacting gases through the spike. This enables control of the flow fluctuations in separated zones near the spike, which significantly affects the aerodynamic characteristics of the bodies [4].

A supersonic flow is actively rearranged if small solid particles are present in the flow especially when rebounds of particles from the body surface occur [5–9], or if a special injection of a two-phase jet is performed [10–11]. Such a flow rearrangment leads to significant drag reduction of the blunted bodies.

An analogous effect is expected if liquid jets are locally injected out of blunt bodies counter to a supersonic flow. The physical picture of the interaction of a liquid jet with a freestream gas is described in [12]. The decrease in the drag of different bodies in the local injection of a liquid jet has been established in [13, 14]. In the present work, this phenomenon has been studied extensively and the optimal modes of liquid jet injection providing maximal drag reduction have been found.

1. Experimental Facility and Measurements. The flow structure and the consequences of the interaction of liquid jets injected upwind from the front stagnation points of different axisymmetric bodies with a supersonic freestream gas were studied. The experiments were performed in a T-313 (ITPM SO RAN) supersonic wind tunnel with working volume 0.6×0.6 m at freestream Mach numbers M = 1.75, 2, 3, 4 of flows and Reynolds numbers determined by the freestream parameters and normalized to a length of 1 m [$\mathrm{Re} = (2.5\text{–}5.5) \cdot 10^7$].

As supersonic bodies, we used NV-1 and NV-2 test models and a cylinder 60 mm in diameter and 300 mm in length with the following forebodies: pop-up head (model T) and cones with apex angles of 20, 30, 38, 52, and 110° (N20, N30, N38, N52, and N110 models, respectively). The models were supported in the flow by an axial stand. The liquid was supplied upwind of the front stagnation point through a cylindrical channel (nozzle) with the diameter varied from 0.6 to 3 mm by the channel replacements and with length equal to five times its diameters. Furthermore, in some of the experiments on the N110 model swirl jet injectors with spraying angles of 15 or 25° were mounted instead the cylindrical nozzle. Ethanol, kerosene, and ethylene glycol–water mixtures, nonfreezing at low temperatures, were used as injection liquids. The design of the models enabled a rod 6 mm diameter to be mounted instead of the nozzles for injecting liquids. Its length of extension out of the model head could be varied from zero up to three model diameters. Depending on the forepart, the rod could be used as a spike type or as a stand for mounting a leader body. Blunted arrow type heads or flat discs of 8, 12, and 16 mm diameter were used as a leader body. All the experiments were performed at a zero angle of attack. The models and the accessory head parts are shown in Fig. 1.

In the experiments, the initial parameters of the incoming flow and the weight characteristics were measured, and the flow shadowgraphs were taken with exposure times of 1/30 and $4 \cdot 10^{-6}$ sec. The liquid

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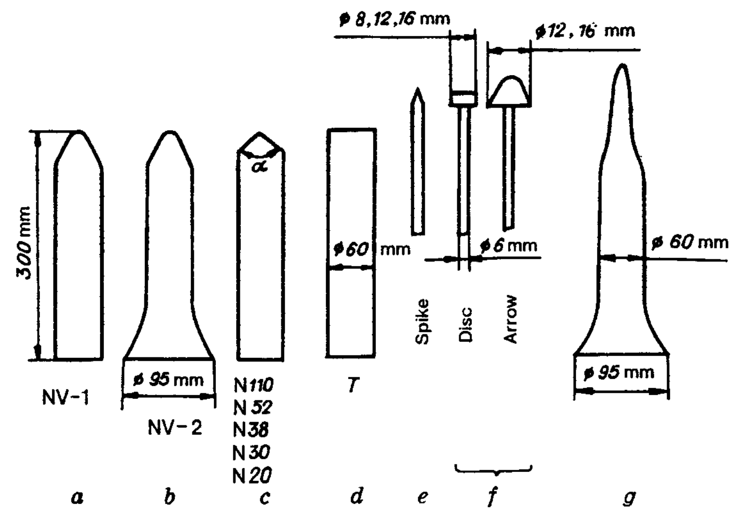


Fig. 1

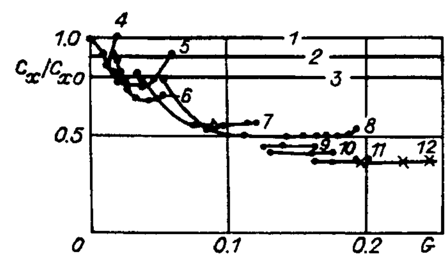


Fig. 2

flow rate was determined from pressure measurements in the collector in front of the nozzle, and also by an IR-61 electromagnetic flow meter. Prior calibration of each nozzle was performed therewith.

2. Experimental Results and Discussion. By analogy with flow around cylindrical bodies with a spike [1], it was reasonable to expect a reduction in the aerodynamic drag of the models in supersonic flows with liquid jet injection from the head part of the model. A reduction in the aerodynamic drag was found for flow around the NV-2 test model. Its absolute value exceeds the drag reduction caused by mounting a spike of optimal length on the model [1–3]. As in the case of the model with a spike, the liquid jet injection led to a change in the wave structure of the flow in front of the body. The physical picture of the interaction of liquid jets with a supersonic flow, as recorded by shadowgraphs, qualitatively coincides with the results of [12]; therefore the peculiarities arising from the geometrical differences of the models will be considered below.

The studies of the efficiency of the effect of liquid jets of different diameters on the incident flow were perfomed on the NV-2 model at M = 2, 3, 4. They showed that the value of the aerodynamic drag reduction of the model is determined not only by the liquid flow rate but also by the jet diameter.

Figure 2 shows the normalized variations of the aerodynamic drag coefficient C_x of the test model NV-2 in M = 4 supersonic flow under different conditions. Line 2 shows the C_x reduction due to the mounting of a spike $1.5D$ in length (D is the diameter of the cylindrical part of the model). Curves 4–12 correspond to the values of the coefficient C_x versus the liquid mass flow rate at different diameters d of the nozzle outlet for liquid supply. Curve 4 corresponds to $d/D = 0.006$, 5 to 0.009, 6 to 0.013, 7 to 0.025, 8 to 0.03, 9 to 0.033. 10 to 0.0366, 11 to 0.04, and 12 to 0.05. It is seen that for each of the nozzle outlet diameter there is a value of the normalized flow rate such that the coefficient C_x is minimal. Further increase in the liquid flow rate leads to an increase in C_x. This effect suggest that there is some critical value of the normalized liquid

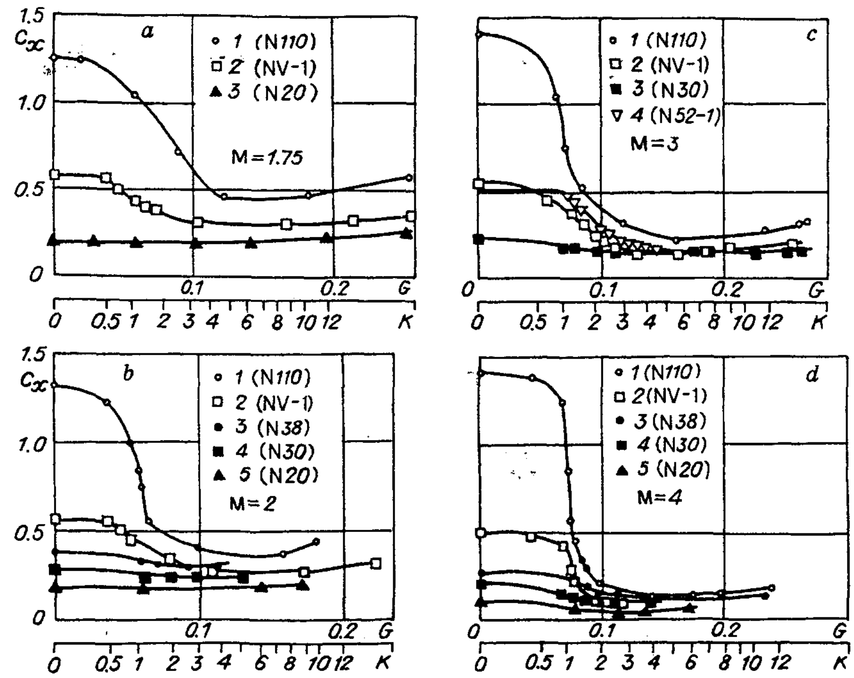


Fig. 3

flow rate for each jet diameter. We believe that the critical liquid flow rate can be described by the Reynolds number of a jet $\mathrm{Re_j} = V_\mathrm{n} d_\mathrm{n}/\nu_\mathrm{l}$ (V_n is the velocity of the liquid mass flow at the nozzle outlet, d_n is the nozzle diameter, and ν_l is the liquid kinematic viscosity). The values of $\mathrm{Re_j}$ determined from the experimental data for curves 5–12 are within the $(1.2\text{–}1.4) \cdot 10^5$ range, and only in the case of a very thin jet (curve 4) is $\mathrm{Re_j}$ equal to $0.63 \cdot 10^5$.

Also, from Fig. 2, it is evident that an increase in the jet diameter by more than $0.04D$ causes no decrease in the aerodynamic drag. Therefore, further investigation of the decrease in the aerodynamic drag of different blunted bodies with liquid jet injection from the front stagnation point was conducted with a jet diameter of $0.04D$. In this experiment, the jet diameter was 2.4 mm. The study of the flow around cylindrical bodies with different head parts was peformed under identical liquid jet injection conditions, close to the optimal ones.

Figure 3 gives the measure aerodynamic drag coefficient C_x for different models against the normalized flow rate of the liquid G:

$$G = \frac{\rho_\mathrm{n} V_\mathrm{n} d^2}{\rho_\infty V_\infty D^2},$$

where ρ_n and V_n are the density and velocity of the liquid at the nozzle outlet, and ρ_∞ and V_∞ are the density and velocity of the freestream gas.

The scale of the normalized dynamic pressure $K = \rho_\mathrm{n} V_\mathrm{n}^2/\rho_\infty {V_\infty}^2$ is drawn parallel to the abscissa axis. For all the investigated models at the Mach number range from 1.75 up to 4 the increase in the normalized dynamic pressure K from 1 up to ≈ 5 leads to drag reduction, which may be several times for the NV-1 or N110 type blunted models.At further flow rate enhancement the drag of the models begin to increase. And only in the case of the sharp-nosed H20 model at M = 1.75 and 2 does the liquid jet injection not lead to drag reduction. With increase in M the drag reduction effect increases, and in the optimal regimes of liquid jet injection ($1 \lesssim K \lesssim 5$) the drag dependence of the models on the shape of its forepart becomes progressively weaker.

A sequence of shadowgraphs of the flow field structure at different flow rates of the liquid injected out

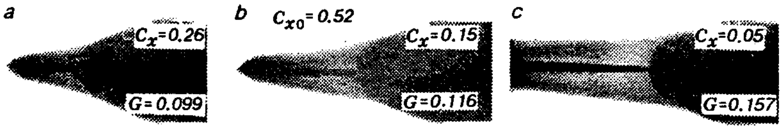


Fig. 4

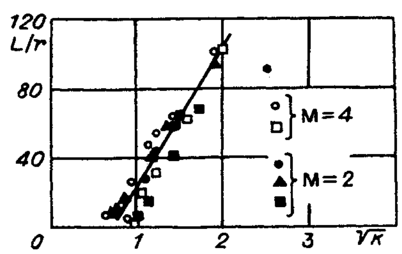


Fig. 5

of the NV-1 model through a nozzle with orifice diameter $d = 2.4$ mm at M = 4 is presented in Fig. 4. The exposure time was 1/30 sec. The values of the flow rate of the liquid injected through the nozzle are given at the bottom corners and the values of the coefficient C_x and also of the coefficient C_{x0} at $G = 0$ are given at the top corners. On the basis of the shadowgraphs the dependence of the normalized depth of penetration of the jet L/r on the normalized dynamic pressure $\sqrt{K}$ was obtained. This dependence for M = 2 and M = 4 is given in Fig. 5.

The jet behavior in the interaction with the freestream depends on the jet penetration depth and on the normalized dynamic pressure. At $K < 1$, the liquid jet does not come out of the shock layer range near the body, and the shock wave position is stationary. An increase in K leads to displacement of the shock wave upstream. The liquid jet expands to $(1.6–1.8)d$ and then shapes into a cylindrical section whose length increases with increasing K. On reaching a certain limiting depth of penetration for the given flow rate, the jet spreads, becomes mushroom- or droplet-shaped, stops, and disintegrates into drops entrained by the flow. These phenomena are particularly well pronounced in the shadowgraphs in Fig. 4, where the supersonic (M = 4) flows past the NV-1 model at liquid flow rates of 69, 81, and 110 g/sec and $K = 1.92$, 2.65, 4.89, respectively, are shown. In the case where the liquid jet interacts with the shock wave, a flow rearrangement occurs which has a substantially nonsteady-state character. The pulsation frequency was determined from the number of the shock wave positions registered in the shadographs during an exposure of $3.3 \cdot 10^{-2}$ sec.

In Fig. 6, one can see 5–10 positions of the shock wave taken during one exposure time, which correspond to a pulsation frequency of 0.15–0.3 kHz. The pulsations also manifest themselves in the shape of the "liquid cone" boundary formed by the gas–droplet mixture after jet disruption. This is evident in Fig. 7, which gives a set of photographs of M = 2 flows (model N110) with an exposure of $4 \cdot 10^{-6}$ sec. The normalized flow rates and the aerodynamic drag coefficients are given at the bottom and top right corners of the photographs, respectively. The values of the drag coefficient versus the jet penetration depth or versus the extension length of a spike (arrow) are shown in Fig. 8 for different models at M = 2 and M = 4.

As is shown by the experiments performed, the physical picture of the interaction of the liquid jet with the freestream gas coincides qualitatively with flow past blunted bodies with a spike. If the regimes of flow around bodies with a jet, with a spike, and around a leader body of the type of an arrow are compared via the reduction in the drag coefficient of the models, then the regimes with a liquid jet correlates better with flow around a model with an arrow (Fig. 1f), as can be seen in Fig. 8a (model N110). In this case, there is a good coincidence of the flow field structures in front of the bodies (in particular, the boundary shapes of separated flow and of the "liquid cone," Fig. 7c,e). However, for sharp-nosed bodies, where in accordance with [1] the mounting of a spike does not affect the drag and the shock remains attached, the liquid jet injection leads to

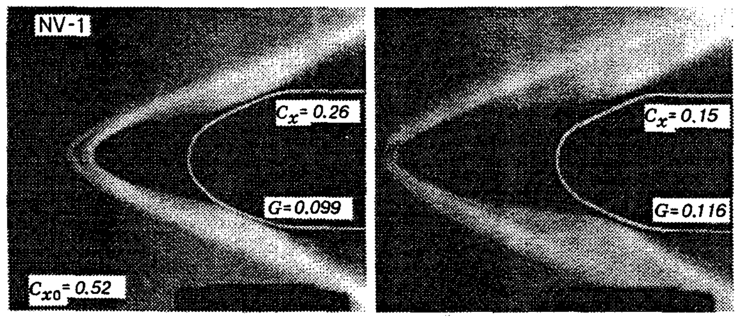
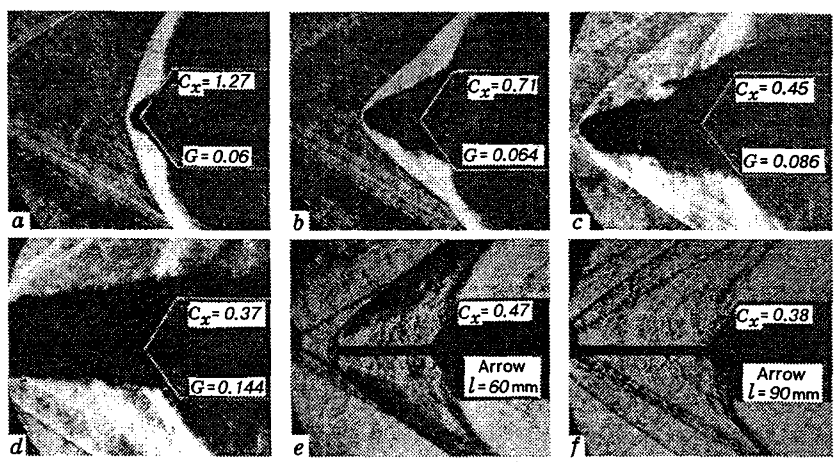


Fig. 6



$C_{x0} = 1.31$ at $G = 0$

Fig. 7

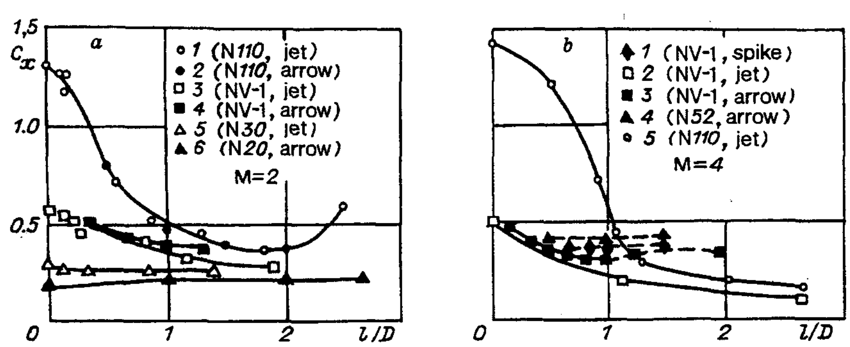


Fig. 8

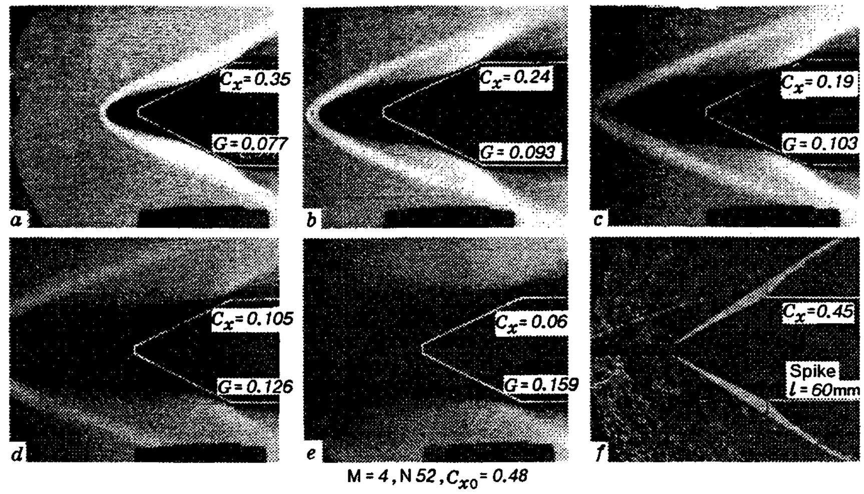


Fig. 9

a significant drag reduction. For instance, in the case of the N52 model, injection of the optimal mode jet at M = 4 reduces the drag by a factor of 8 (Fig. 9), and at M = 3 by a factor of 3. Under these conditions, a spike and an arrow do not affect the drag.

An analysis of the experimental results suggests that the jet injected generates a fictitious "liquid" body, which has an optimal drag in the given supersonic flow. To verify this hypothesis, a model with a "solid" ogival head part was made to the shape of the fictitious body generated by flow around the NV-2 model at M = 4 with liquid jet injection (Fig. 1g). Tests showed that in both cases the drag reduction was more significant than in the case of a model with a spike ($l/D = 1.5$) at M = 4. Line 2 in Fig. 2 corresponds to a model with a spike, line 3 to a model with an ogival head part, and line 7 corresponds to the NV-2 model with a liquid jet (nozzle diameter 1.5 mm). The triangle denotes the mode with a jet length equal to the length of extentión of the ogival part.

A comparison of flow around models with a jet and an ogive shows that in the case where the liquid jet affects the incoming flow a more significant drag reduction takes place. Such a reduction cannot be explained only by the friction drag reduction due to a smaller surface of the NV-2 model experiencing the flow action, as compared to the ogival head model. Probably, the drag reduction effect is due to the presence of a circulation zone inside the "liquid" body in front of the head part of the model.

In conclusion we note the following: 1) as liquid jets are injected locally from blunted bodies counter to a supersonic gas flow, flow rearrangement takes place, leading to a significant drag reduction; 2) the optimal flow regimes at which the drag reduction has optimal parameters are found.

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