

HYPERSONIC FLOW AROUND A BLUNTED BODY WITH COUNTERFLOW PLASMA JET

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Flow non-uniformity may have a pronounced impact on aerodynamic characteristics of flying bodies. This non-uniformity can be organized in different ways: using other bodies, counter-jets, artificially produced energy-income regions, etc. [1-7].

In the present paper, results of experimental and numerical studies of the impact of counterflow plasma jets on integral and distributed aerodynamic characteristics of blunted bodies in hypersonic flows are described. These studies, performed in ITAM SB RAS were a continuation of our previous studies of supersonic flows around blunted bodies with counterflow plasma jets [7-12] to hypersonic regime with Mach number $M_\infty=6.0$.

The experimental studies were performed in a hypersonic blow-down wind-tunnel T-326 of ITAM SB RAS. The model was a cylinder with replaceable forbodies. The forbodies were truncated cones with cone angles 30° or 60° (Fig. 1). The diameter of the cylindrical part of the model was 60 mm. The cone-bluntness diameter, whose value was chosen so that to match the nozzle diameter of the plasma generator used to inject the jet into the flow, was 15 mm. The model was installed in the flow on a one-component strain-gage balance at zero incidence. The plasma generator was housed in the thin-walled forbody of the model; in all cases it was mounted on a strut in order to avoid its influence on balance measurements. In the present study, a direct-current plasma generator with non-fixed arc length in the anode region and gasdynamic vortex arc stabilization at the cathode was used. The mean-mass temperature of the generated nitrogen-plasma jet was 5 000 K, and the rate of the jet flow was 0.8-1.2 g/s. The plasma jet with the Mach number $M_a=2.5$ emanated from a supersonic nozzle with an outlet diameter of 3.5 mm. To measure the surface pressure, 14 drainage orifices 0.7 mm in diameter were provided on the forbody: ten in the conical part and four in the cylindrical part of the model (see Fig. 1).

In the experiments, the aerodynamic drag, the forbody surface static pressure and the pressure inside the model were measured. To gain data on the flow pattern around the body, Schlieren visualization and video shooting were used.

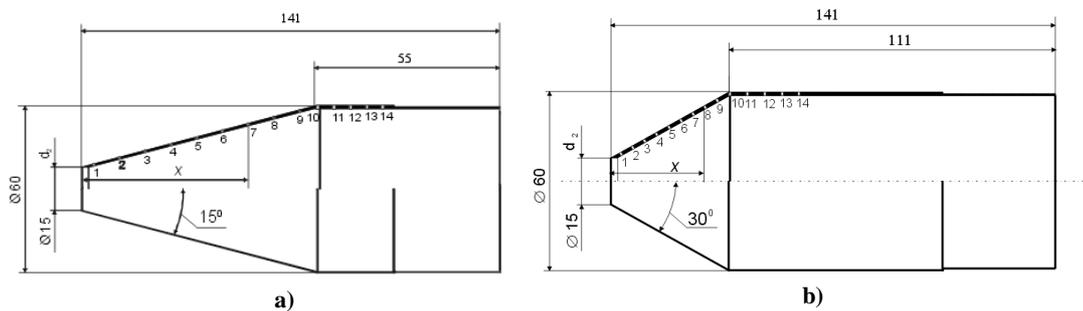
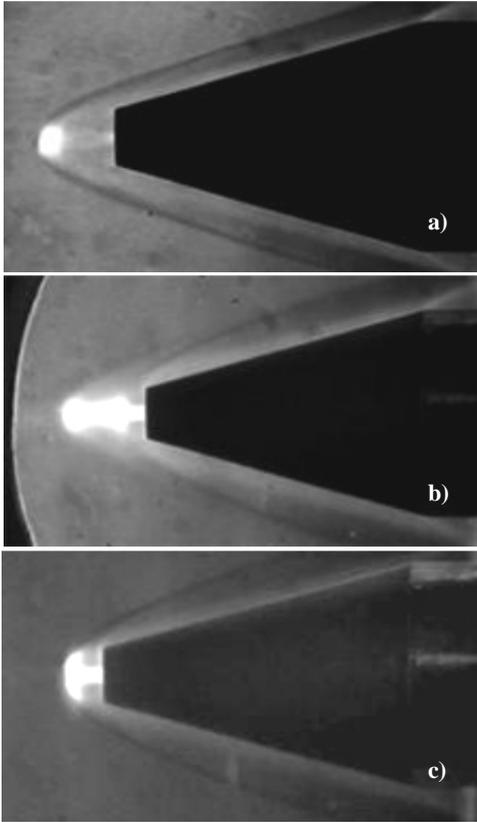


Fig. 1. Forbody: a) 30° -cone, b) 60° -cone.



As in previous experiments with supersonic flows with $M_\infty = 2.0 - 4.0$ [8, 9, 12], two steady-state flow modes, short penetration mode (SPM) and long penetration one (LPM), were observed. In addition, within one test, we could also observe a transition between the regimes. Figures 2 a, b, and c show Schlieren photographs that illustrate the LPM, SPM \rightarrow LPM, and LPM regimes for a 30° -cone, respectively. Under LPM conditions, one barrel is clearly seen in the plasma jet.

Typical distributions of pressure coefficients, $C_p = p / \rho_\infty V_\infty^2$, along the dimensionless coordinate x/d_2 are shown in Fig. 3 for the stagnation pressure $P_{0f} \approx 40$ bar. These distributions were calculated from measured surface-pressure data. The interface between the conical and cylindrical parts of the model is shown as a vertical line. In the forbody, a substantial change in the pressure distributions under the action of the counterflow plasma jet is observed.

The drag coefficients were calculated from measured surface-pressure distributions by the formula $C_d = \sum_{i=1}^{10} C_{p_i} \frac{S_i}{S_m}$, where S_m is the cross-sectional area of the model. i is the number of the

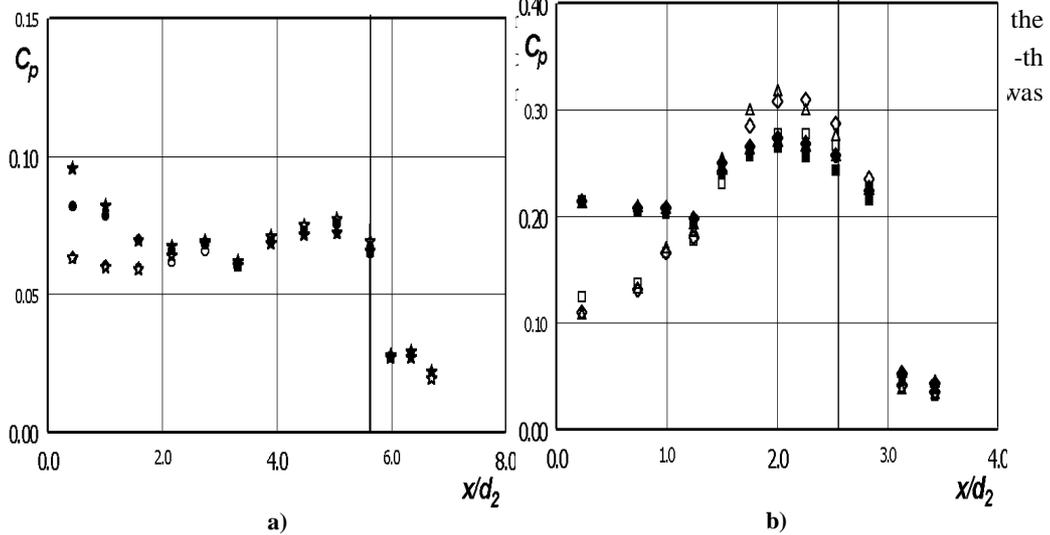


Fig. 3. Surface-pressure distributions over the model surface taken in a series of tests. Full symbols - without plasma jet; open symbols - with the plasma jet. a) 30° -cone, b) 60° -cone.

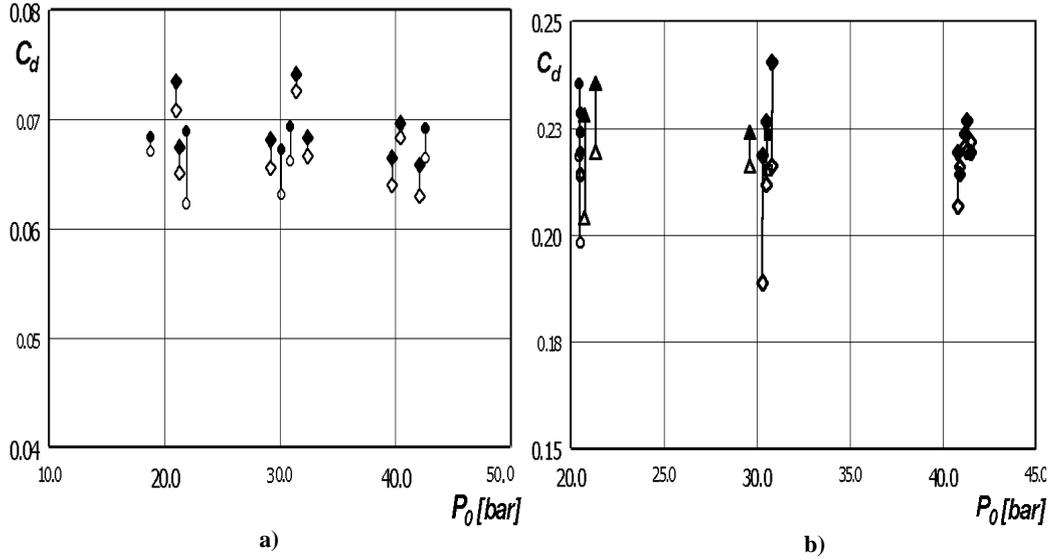


Fig. 4. Drag coefficient versus stagnation pressure.
 Full symbols – without plasma jet, open symbols – with the plasma jet. \diamond – LPM, \circ – SPM.
 a) 30°- cone; b) 60°- cone, \square – SPM \rightarrow LPM, Δ – LPM \rightarrow SPM.

assumed uniform over the whole S_i area. Figure 4 shows the calculated values of C_d for the cases with and without the plasma jet and for various stagnation pressures. As is seen from the graphs, the best drag reduction is 25% for the LPM regime and 5% for the SPM one. It should be noted that previously for $M_\infty = 2.0$ we had 45% and 15%, respectively [8, 9, and 12].

The largest decrease in the drag was observed for the LPM and SPM \rightarrow LPM regimes, and the greatest decrease was displayed by the 60°-cone. With the plasma jet, the flow pattern (see Fig. 2) was found to change dramatically, and the drag at some regimes was substantially reduced. Farther penetration of the jet into the flow permits a substantial reduction in the effective cone angle of the model.

Numerical calculations of the various jet formation scenarios and those of the impact of corresponding regimes on the aerodynamic characteristics of cone-cylinder bodies were carried out. The calculations were performed in the framework of a 3D inviscid model by the method of finite volumes. A central-difference, second-order approximation scheme was used, explicit in time and implicit in coordinate [10, 11].

The numerical studies were performed for 30°- and 60°-cones; the forbody geometry and the geometry of the plasma-jet exit diameter were the same as in the experiments. The flow Mach number was $M_\infty = 6.0$, and the plasma-jet Mach number was $M_a = 2.5$. The range of relative pressure was $1.3 < P_{0j}/P_{0f} < 21.5$, where P_{0j} is the jet stagnation pressure; and the temperature ratio was $T_{0j}/T_{0f} = 15.0$, where T_{0j} is the jet stagnation temperature and $T_{0f} = 283$ K is the flow stagnation temperature. The calculation results for flow around the 30°-cone are shown in Fig.5. The calculations displayed that the LPM regime is indeed possible, with all specific features inherent to supersonic flows with $M_\infty = 2.0 - 4.0$ [8, 10, 11]. The results have shown that the laws of forming of SPM and LPM regimes and their influence on total drag are the same as for cold jets at smaller Mach numbers of free flow. The cone drag was calculated in respect of reactive force of the jet. The drag of the truncated cone decreases at LPM-regimes. However in LPM-regime the length of jet penetration into counterflow does not exceed the face diameter and its influence on drag is less at $M_\infty = 6.0$ than at supersonic Mach numbers [10].

It is necessary to note that the counterflow jet may not reduce the body drag. Calculations for a 60°-cone and jet Mach number $M_a = 6.0$, i.e., for a jet Mach number identical to the flow

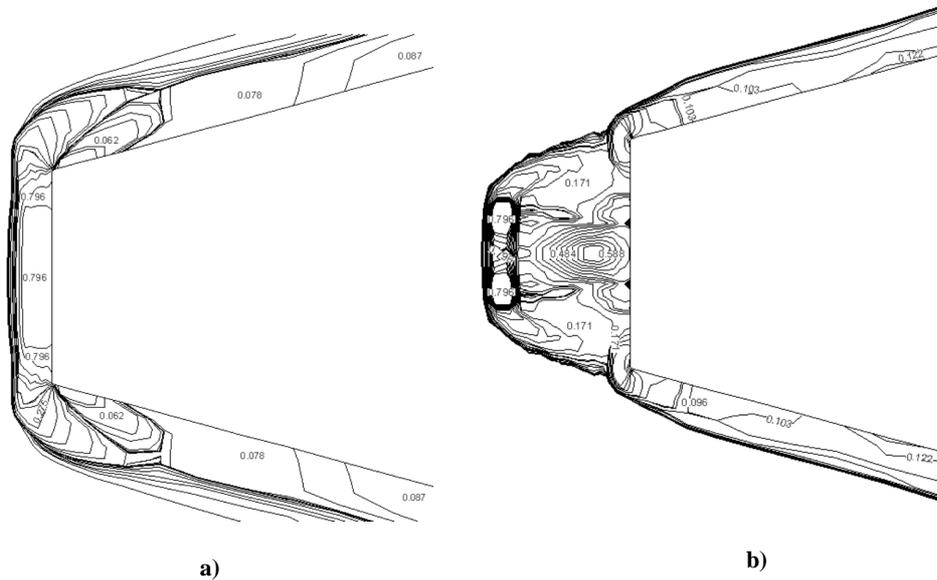


Fig.5. Isobars for truncated 30°-cone flow, $M_\infty=6.0$.
 a) without counterflow jet; b) with jet: $M_a=2.5$, $P_{0j}/P_{0f}=10$.

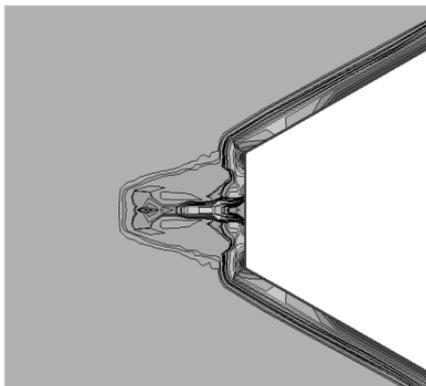


Fig. 6. Isobars field of the 60°-cone.
 $M_\infty=6.0$, $M_a=6.0$.

Mach number, were also performed. Figure 6 shows the isobars field for this case. As is seen, inspite of the LPM jet regime the shock wave is situated very close to the surface of the cone, thereby increasing the pressure on it and, hence, the total drag.

Thus, we showed, both experimentally and numerically, that two flow modes of a hypersonic flow with $M_\infty = 6.0$ around blunted bodies, SPM and LPM, are possible. The jet changes strongly a flow pattern around the body. The largest decrease in the drag is achieved with LPM and with the SPM \rightarrow LPM transition mode. With a counterflow plasma jet, a decrease in the total-drag coefficient for a 60°-cone up to 25% at the LPM regime was observed. A value of penetration length obtained in the experiments is much more than obtained one in

the calculations. It may be because viscosity and plasma effects have not been taken into account at the numerical research.

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