Fluid Dynamics, Vol. 31, No. 2, 1996

EXPERIMENTAL STUDY OF THE POSSIBILITY OF REDUCING SUPERSONIC DRAG BY EMPLOYING PLASMA TECHNOLOGY

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UDC 533.6.011.72

The possibility of reducing the aerodynamic drag of a body by injecting plasma into the oncoming supersonic flow is confirmed experimentally.

As is known, supersonic aerodynamic drag can be reduced either by mounting a needle or by injecting a gas jet at the tip of the aircraft nose [1]. Regulation of the needle position or the injected gas pressure permits both a considerable surface pressure redistribution and a reduction in the drag coefficient.

The effect is attained as a result of the formation of flow separation zones ahead of the body, where the pressure is lower than behind the separated shocks ahead of analogous bodies without a needle or gas injection.

In [2] it was shown that model drag can be reduced as a result of the formation of a narrow rarefied channel ahead of the body. The numerical calculations carried out in [3] for supersonic flow past a sphere in the presence of external heat release sources showed that the wave drag can be reduced by approx. 50% to 60%.

The effect of an electric discharge in front of an axisymmetric body on the supersonic flow was studied in [4, 5].

This paper describes an experimental study of the possibility of reducing aerodynamic drag by injecting plasma from the body surface.

The tests were conducted in a supersonic vessel-type V-I wind tunnel with Mach number $M_\infty = 2.0$–4.5, a prechamber pressure of 2.5–18.5 atm, a Reynolds number of $(3.2$–$8.4)\cdot 10^7$ (for $l = 1$ m), and a working section measuring 0.4 m by 0.4 m.

In order to conduct the studies we designed and manufactured a cone-cylinder model with in-built plasma generator and strain gauges.

In Fig. 1 the plasma generator is shown schematically. The bar-like uncooled copper electrodes are embedded in a fluoroplastic insulator. The latter is inserted into a ferromagnetic-steel housing and fastened by three set screws. The clearance between the housing and the insulator is sealed with a rubber ring. The plasma generator nozzle is connected with the housing by a ferromagnetic-steel adapter. The adapter–nozzle and adapter–housing connections are threaded and sealed with rubber rings. The nozzle is made of copper. The inner surfaces of the housing and adapter are coated with electrical insulation.

A tap is introduced into the insulator to measure the pressure in the plasma generator chamber. An arc discharge is initiated by short-circuiting the electrodes with a thin copper wire. The electrodes are connected to the three-phase AC 380 V mains via an automatic circuit breaker.

The plasma generator was mounted on a sting installed in the wind tunnel working section, and the model–tubular strain gauge assembly was fitted on it. The strain gauges were fixed to the plasma generator housing with set screws.

When voltage is fed to the electrodes, an electric (three-phase, AC) arc is started. Driven by the electrodynamic forces, it moves towards the electrode ends, heats the gas in the plasma generator housing, is blown out of the inter-electrode gaps, and breaks up.

The plasma generator has the following major characteristics: the working section is up to 120 mm long, the inter-electrode gaps are 10 mm wide, the electrode diameter is 4.5 mm, the short circuiting wire diameter is 0.4 mm, the inner diameter of the arc chamber is 30 mm, the nozzle throat diameter is 2 mm or 4 mm, the exit diameter is 5.65 mm and 7.61 mm respectively, and the discharge current and time are approx. 300 A and 0.05 s respectively.

The model, made in the form of a thin-walled cylinder-cone shell with a front vertex angle of 40°, is mounted on six-component aerodynamic strain gauges which, in turn, are fastened to the tubular plasma generator housing, Fig. 1.

There are small clearances between the front of the model and the plasma generator nozzle housing as well as between the rear portion of the model and the afterbody fairing. The effect of gas penetration into the model interior on the measured drag was considerably reduced by making the front clearance much smaller than the rear one.

Moscow. Translated from Izvestiya Rossiiskoi Akademii Nauk, Mekhanika Zhidkosti i Gaza, No. 2, pp. 177-182, March-April, 1996. Original article submitted February 6, 1995.

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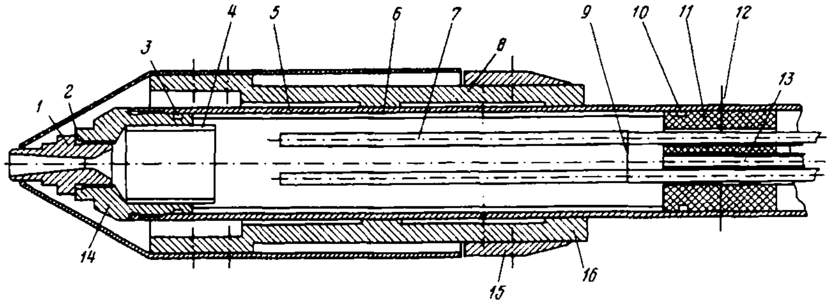

Fig. 1. Diagram of the plasma generator: *1* nozzle; *2*, *3*, and *10* rubber rings, *4* and *6* electrical insulators, *5* housing, *7* electrodes, *8* and *12* set screws, *9* thin copper wire, *11* fluoroplastic insulator, *13* pressure tap, *14* adapter, *15* afterbody fairing, and *16* strain gauges.

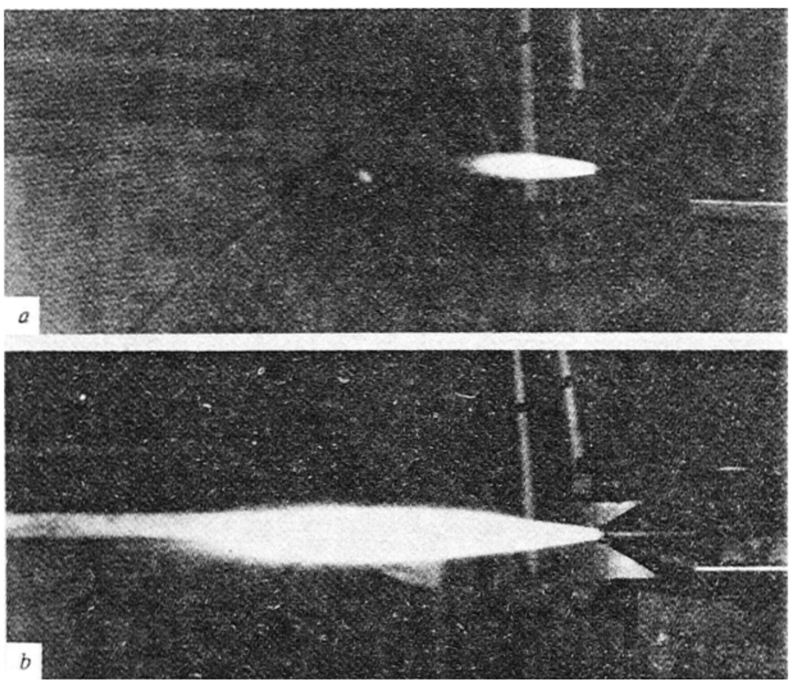

Fig. 2. Photographs of plasma generator jets in the atmosphere: (*a*) $d=2$ mm, (*b*) $d=4$ mm.

In choosing the strain gauges, preference was given to tubular multicomponent dynamometers with short, and hence stiff, elastic elements whose aspect ratio was less than unity.

Figure 2 shows photographs of plasma generator jets flowing into the atmosphere (in the absence of an oncoming flow) for various nozzle throat diameters *d*. Clearly, an increase in the nozzle diameter results in a considerable increase in the plasma jet range.

The pressure in the plasma generator chamber was measured using a DMI inductive transducer. The oscillograms show that an increase in the nozzle throat diameter results in the maximum pressure decreasing by a factor of 1.5; the plasma efflux time also decreases.

The experiments were carried out at $M_\infty=4$ and prechamber pressure $p_0=12$ atm.

Figure 4 shows the flow patterns prior to and at the instant of plasma discharge from the internal plasma generator. The photographs were taken using an IAB-451 shadowgraph (by the circular knife-edge method) and an AKS-2 movie

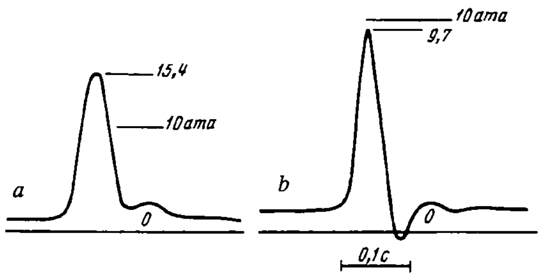

Fig. 3. Oscillograms of the pressure in the plasma generator chamber: (*a*) $d=2$ mm, (*b*) $d=4$ mm.

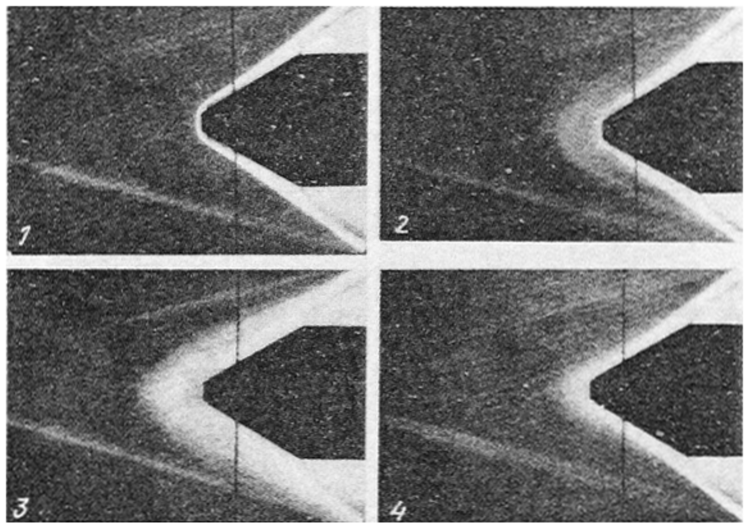

Fig. 4. Shadowgraphs of the plasma flowing from the intra-model plasma generator for $d=4$ mm.

camera shooting 48 frames per second with an exposure of about 0.01 s. The time between successive frames was approx. 0.02 s.

The first frame shows the flow past the model prior to plasma discharge. The bow shock wave and the rarefaction fan centered on the junction of the conical and cylindrical portions of the model are clearly seen. The second frame shows a conical, slightly luminescent halo ahead of the model and the shock wave. This is evidently the instant when the plasma starts flowing from the nozzle. The third frame demonstrates the decomposition of the original bow shock wave and the formation of a distinct luminescent conical plasma cloud whose distance from the nosetip is of the order of the cylinder radius. Moreover, the frame shows the plasma flow from the nozzle and the formation of a plasma spot of enhanced luminescence at a certain distance from the model nosetip. In the fourth frame the conical luminescent cloud contracts and the initial flow pattern is restored. In the next frame (not shown here) the flow pattern is fully restored and is identical to that in the first frame. Thus, in the case under consideration the interaction between the plasma jet and the oncoming flow lasted for about 0.08 s.

Figure 5 presents a sequence of flow pattern shadowgraphs made with the AKS-2 movie camera at the same shooting speed and exposure for plasma flowing from the intra-model generator through a nozzle with a throat diameter of 2 mm. In this case the effect of the plasma jet on the flow pattern is stronger. The plasma cloud penetrates the oncoming flow nearly twice as far as in the preceding experiment. The plasma spot is more elongated, and the frames exhibit conical shocks induced by the plasma cloud. The discharge time increases by a factor of approx. 2.5.

Figure 6 presents the experimental time dependence of the drag coefficient c_x for plasma flowing from a nozzle with a throat diameter of 4 mm. The drag coefficient was calculated using the measured drag, supersonic flow parameters, and bottom pressure and the geometrical characteristics of the model.

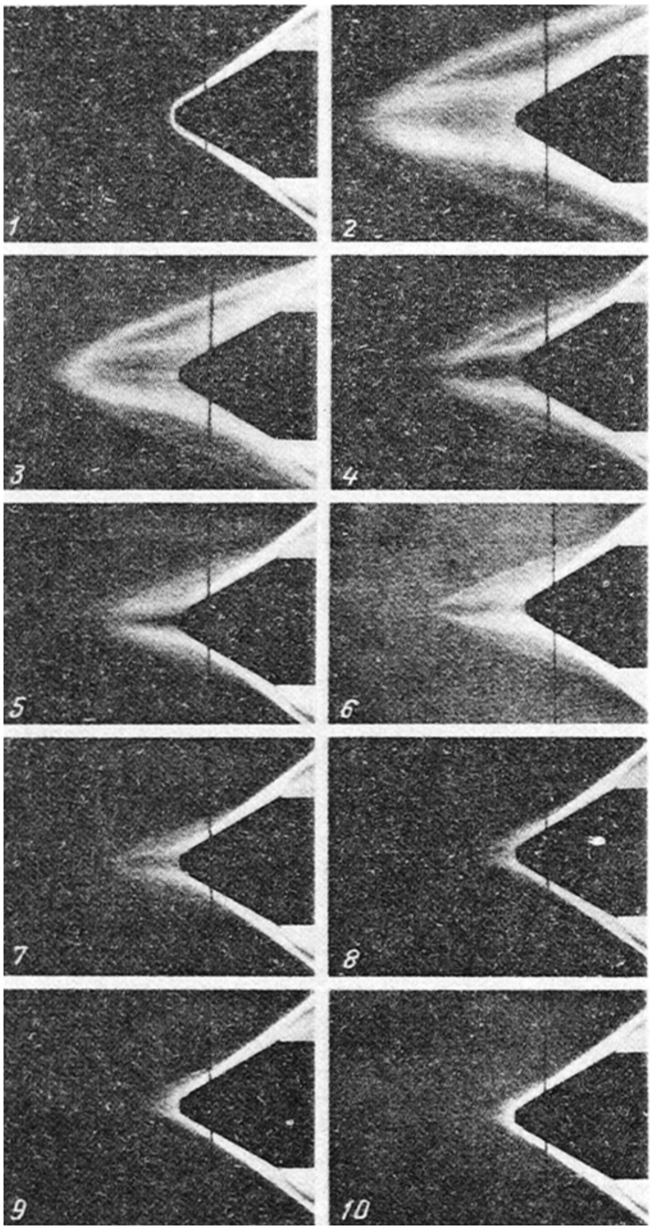

Fig. 5. Shadowgraphs of the plasma flowing from the intra-model plasma generator for $d = 2$ mm.

The data were recorded on a 386 personal computer using a RWS 3072 amplifier with 0.1 accuracy rating. The signals were received and processed with the help of the FLEYLAB program module.

Figure 6 shows that during plasma outflow the model drag decreases by more than 30%, and as it returns to the nominal value an "overshoot" of approx. 10% is observed. The values of the drag coefficient prior to and after plasma discharge practically coincide.

The plasma jet thrust, evaluated using the measured pressure in the plasma generator chamber and the geometric parameters of the nozzle, amounted to less than 7% of the total aerodynamic force.

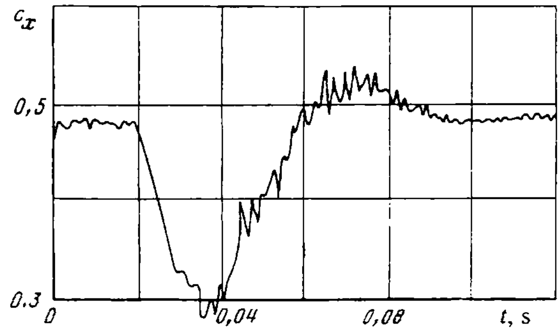

Fig. 6. Time dependence of c_x for $d = 4$ mm.

The use of a nozzle with a throat diameter of 2 mm demonstrated even greater drag reduction.

Thus, our experimental studies have shown that plasma technology can be used to reduce supersonic aircraft drag.

In conclusion, the authors wish to thank E. N. Bogacheva for her assistance in preparing this paper.

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