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Technical Notes

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Use of Vortex Generators to Control Internal Supersonic Flow Separation

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Introduction

FLOWS in the boundary layer are retarded due to skin friction at the body surface. This, in the case when an adverse pressure gradient is present, can lead to boundary-layer separation. To prevent this phenomenon, the streamwise momentum of decelerated air particles in the boundary layer should be continuously supplemented by momentum coming from the external flow. This can be achieved by increasing turbulence in the flow at the surface, which enhances mixing of the retarded and freestream airflows. To this end, various vortex generators, such as small plates or airfoils, small jets normal or oblique to the surface, acoustic actuators etc., were used to manipulate the flow at the body surface.[1–5] As a result, it is possible for the flow to overcome a larger pressure increase along the boundary layer before it separates. In other words, the separation can be delayed. This manipulation can become more efficient when it is performed by oscillating rigid elements or jets at a certain suitable frequency.[6]

Numerous investigations of the effect of the boundary-layer excitation on the delay of flow separation were carried out in case of low-velocity subsonic flows for a wide variety of configurations. In subsonic flow, the pressure in a decelerated flow region increases gradually. In contrast, in supersonic flow the pressure increase occurs at a short distance in the proximity of a shock wave, which usually induces separation.

The present experiment is an investigation of the capability of various boundary-layer manipulations to delay separation in a supersonic internal flow (Laval nozzle). Because, in this case, separation is accompanied by a shock wave, the shock should move downstream when the upstream boundary layer is excited.

Brief Description of Experiment

An asymmetric two-dimensional convergent-divergent channel with a planar surface at one side and a bump having a cylindrical contour with a diameter of 500 mm (half Laval nozzle; Fig. 1a) was used in the present experiments.

This contour was chosen to obtain a separated flow for any pressure difference along the channel. Obstacles and swirling jets were used to disturb the boundary layer at the nozzle surface in the divergent section. In the first case, a row of oblique (V-shaped) half-cylinders were mounted flush on the nozzle wall (Fig. 1b).

It was noted in preceding experiments conducted by the present authors (unpublished) with a V-shaped generator located on a flat plate that at the tip of the downstream directed obstacle two stable counter-rotating vortices are present. In the second case, three twin jets from orifices (Fig. 1c) in the nozzle wall were injected into the boundary layer. They were strongly swirled to induce the vortex breakdown phenomenon. As a result, the air of the jets spread around the orifices and disturbed only the flow region close to the nozzle wall.

The experiments were conducted in the transonic wind tunnel discharging into a downstream container (150 m^3) evacuated before the test. Air was sucked from another container made of impregnated fabric in which the air humidity was constant and equal to 12%. The air pressure and temperature in the container (stagnation conditions) were 0.1 MPa and 293 K, respectively. The air from this container was also used to produce the swirling jets. The pressure distributions along the symmetry plane of the nozzle contour were measured by means of a Pressure Systems 16-channel electronic pressure scanner ESP16HD. Flow patterns corresponding to measured pressure distributions were visualized using the schlieren system.

Results

Figure 2 shows the normalized (with respect to the stagnation pressure in the fabric container) pressure distributions along the nozzle surface (vs the angular coordinate Φ; Fig. 1a) for four settings of the adjusting valve of the tunnel. Figure 3 shows schlieren

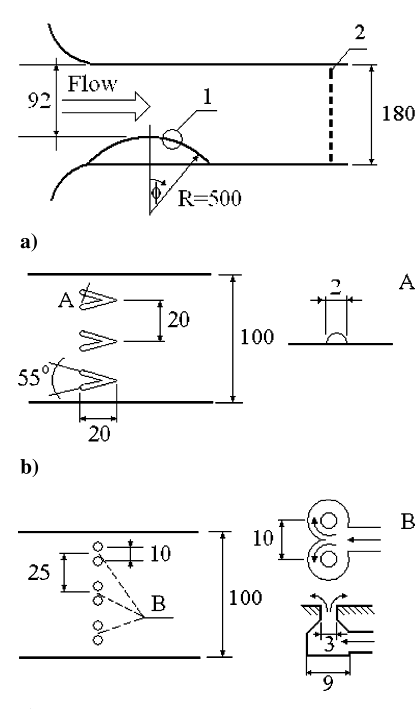

Fig. 1 Experiment: 1, generator location; and 2, adjusting valve; dimension in millimeters: a) test section of wind tunnel, b) obstacle generator, and c) swirling jet generator.

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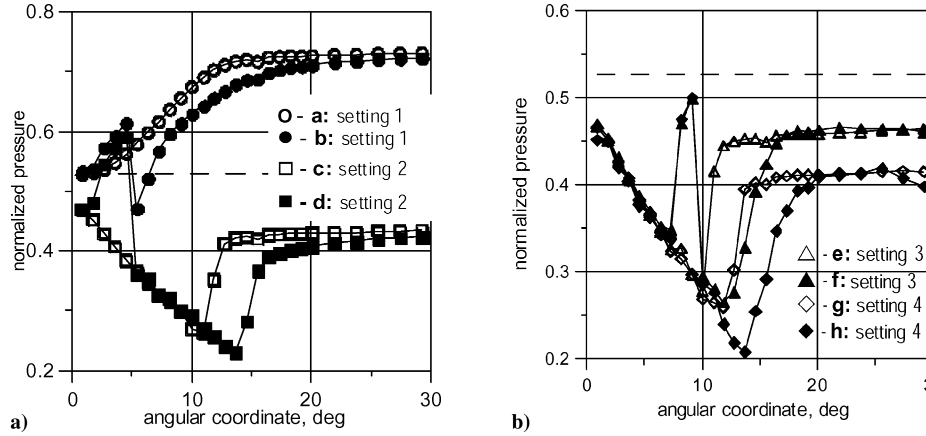

Fig. 2 Pressure distributions along the nozzle surface for four settings of adjusting valve: open symbols, without and filled symbols, with V generator; – – –, sonic flow; generator located at a) Φ = 4 deg and b) Φ = 9 deg.

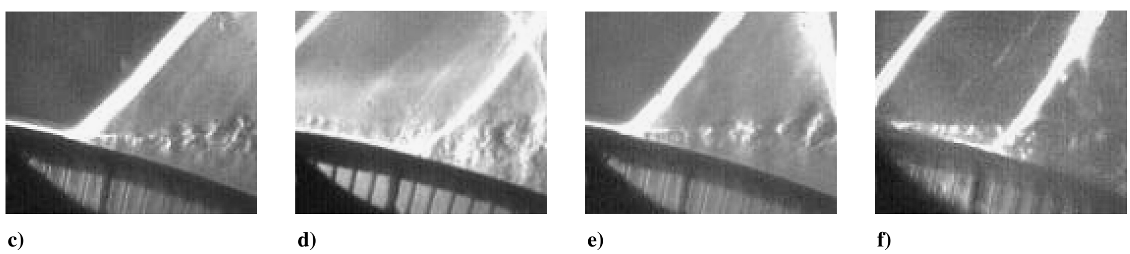

Fig. 3 Schlieren photographs of flow at the nozzle surface corresponding to pressure distributions c and d (setting 2) and e and f (setting 3) in Fig. 2.

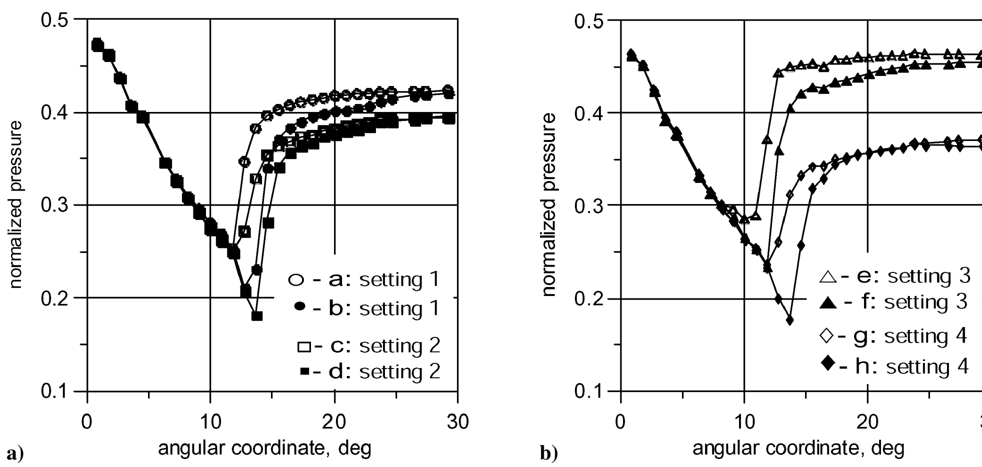

Fig. 4 Pressure distributions along nozzle surface for four adjusting valve settings; open symbols, without and filled symbols, with swirling jet generator located at Φ = 10.5 deg: a) increased and b) decreased flow velocity in symmetry plane.

photographs of the nozzle flow corresponding to undisturbed and disturbed (by the V generators) boundary layer. The generators were located alternatively close to the throat of the nozzle at $\Phi = 4$ deg and at some larger distance from it, $\Phi = 9$ deg. One can observe that in both the subsonic and the supersonic flow the V generators induce a distinct pressure bump. In the latter case, it is accompanied by a shock wave followed by an expansion wave. The waves, which are very close to one another, are visible in the photographs in Figs. 3d and 3f as a preceding light strip (in the upper-left-hand corner) originating beyond the field of observation. In the supersonic flow, the V generator, independent of its location, causes a distinct delay of the flow separation and thereby a downstream displacement of the accompanying shock wave. The location of the vortex generator in respect to the separation point (shock wave location) in the undisturbed boundary layer is not, however, distinctly noticeable as in the case of low-velocity subsonic flow investigated by Greenblatt and Wygnanski[6] with other generators. In the present experiment, the vortex generator acted just at the point of separation of the turbulent subsonic boundary layer (Fig. 2a, curves a and b).

Therefore, in this case it does not affect the separation. (The subsonic flow separation was not a subject of the present investigations.) Figures 4 and 5 show the results obtained in the case of the boundary layer disturbed by swirling jets. The swirl generator could be turned by 180 deg. Thus, the swirl direction was changed to have an increased or decreased flow velocity in the symmetry plane (the plane in which the pressure distribution were measured). Note that the swirling jets generator, like the V generator, disturbs the boundary layer sufficiently to cause a noticeable delay of the supersonic flow separation. The swirl direction, however, shows negligible effect on the pressure distribution. This means that the change of the flow velocity distribution caused by the jets themselves do not affect the separation. Delay of separation occurs due to the secondary flow that appears when a swirling jet issues into the nonuniform flow in the boundary layer. In each schlieren photograph (except Fig. 5e) two

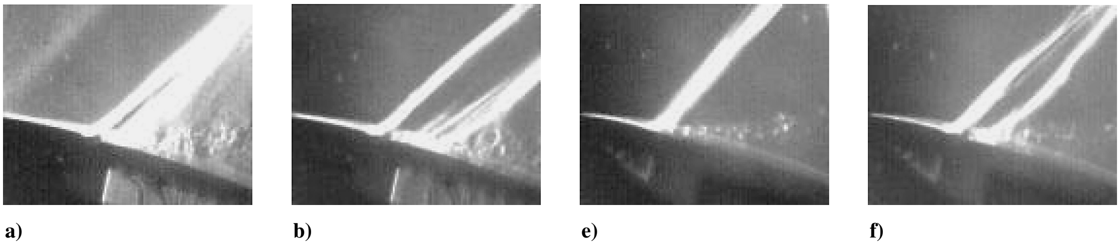

Fig. 5 Schlieren photographs of flow at the nozzle surface corresponding to pressure distributions a and b (setting 1) and e and f (setting 3) in Fig. 4: left column, without swirling jet generator and right column, with generator.

distinct strips are visible. The first strip shows the disturbance caused by the orifices (used to generate swirling jets) at the Laval nozzle wall and the following one shows the shock wave accompanying separation. The former is weak and does not leave any trace in the pressure distributions. (The orifices were located on the sides of the symmetry plane, Fig. 1c.) In Fig. 5e, the shock wave originates just at the orifices; therefore, in this case only one strip can be observed.

Conclusions

The flow separation in the supersonic flow of a Laval nozzle can be delayed when the turbulence of the flow close to the wall is increased. This was achieved in the present investigations by means of an array of obstacles composed of V-shaped half-cylinders and by means of swirling jets issuing normally to the nozzle wall. The obstacles induce a shock wave and a following expansion wave, which form wavy lines in the spanwise direction. Because various changes of flow properties along streamlines crossing these waves, the secondary flow appears downstream of the obstacles in the plane normal to the wall. This enhances mixing of air particles in the boundary layer and external flow. This effect seems to dominate the effect of the streamwise vortices observed downstream the V-shaped obstacle in the low-velocity subsonic flow.

The swirling jets injected through the nozzle wall provide results analogous to wavy shock-expansion waves. In this case, the secondary flow appears because of stationary vortices due to swirling jets superimposed on the uniform flow (in the spanwise direction). It seems that the swirling jets-type generator, in contrast to the obstacle generator, does not increase the drag on the wall. Moreover, the delay of separation can be controlled, to some degree, by control of the strength of the jets.

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