Supersonic separated flow past a spiked body with a plane cap on the end of the spike (a flat plate or a wedge) is studied. The cases of both symmetric and nonsymmetric flow, with a rotating or nonrotating spike, are considered. The flow pattern, visualized by means of a Toepfer instrument and a laser knife, and the limiting streamline patterns are analyzed. The reasons for the initiation of self-oscillations in the flow between the cap and the body are determined. The flow patterns for a rotating and nonrotating spike are compared.

Investigation of the supersonic flow past spiked bodies is a classical problem of aerodynamics, so that the class of separated flows in question has been studied quite well [1]. If a plane cap is mounted on the end of the spike, the flow in the forward separation zone becomes three-dimensional and nonstationary. Flow past spiked spheres with a wedge or a flat plate on the end of the spike was investigated in [2]. The effect of disturbances, due to the rotation of a spike with a plane cap on its end, on the flow in the forward separation zone was studied in [3]. As distinct from previous studies [2, 3], our main concern in present research was with the flows past spiked flat-end cylinders and cones, with a wedge on the end of the spike. The diameter of the models was D=60 mm and that of the spike was d=3 mm. The cone vertex half-angle was $\theta=45^\circ$. The streamwise dimension of the wedge was $a=10$ mm, while the cross-stream dimensions were $b=10$ mm and $c=3$ mm. The length of the spike took the following values: $L_0=21, 41, 61, 81,$ and $101$ mm, $L_0$ being the distance from the nose of the cap to the model.

The experiments were carried out in a supersonic wind tunnel with an axisymmetric test section at $M=3$ and $Re=(0.8\sim 1.4) \times 10^6$. The Reynolds number was based on the freestream parameters and the model diameter. The flow stagnation temperature and pressure were $T_0=300\sim 410^\circ K$ and $p_0=(2.7\sim 5) \times 10^9$ N/m$^2$, respectively. Both symmetric (with the spike axis coinciding with the freestream direction) and nonsymmetric (when the spike axis makes an angle $\alpha$ with the freestream direction) flows past the model were considered.

1. It was found in [1] that the flow past a spiked sphere with a plane cap on the end of the spike possesses two planes of symmetry. These planes pass through the spike axis parallel to the longer $b$ (plane I) and shorter $c$ (plane II) bases of the cap. Accordingly, the flow around the model and the pressure distribution over its surface were investigated precisely in these planes.

2. As distinct from the flow past a sphere [2], the flow past a spiked cylinder or cone turns out to be nonstationary for certain values of the spike length $l=L_0/D$ which exceeded the bow shock stand-off distance in the case of undisturbed flow past a cylinder (cone) but were less than a certain value $l_1$ [4-6].

In Fig. 1 the photographs show such nonstationary flow patterns for $l=0.5$ at various times, the freestream conditions being stationary. If a plane cap is mounted on the end of the spike, the flow past the cylinder remains nonstationary. This is confirmed by flow pictures obtained in plane I (Fig. 1b, $l=0.7$). The onset of a nonstationary flow regime (flow self-oscillation) is due to the violation of the Chapman-Korst relations in the region of flow reattachment on the cylinder (cone).

Figure 2a presents the pressure distributions on a spiked flat-end cylinder, with and without a wedge-shaped cap on the end of the spike, in planes I and II ($l=0.7$, curves 1-3, respectively). Here, $p=p_1/p_0'$ and $r=r_1/r_0$, where $p_1$ is the pressure at a point on the flat end with the coordinate $r_1$, $p_0'$ is the stagnation pressure behind the shock in the undisturbed stream, and $r_0$ is the flat-end radius.

A comparison of these distributions shows that the integral pressure profiles in planes I and II are different; hence, the gas must flow from the high-pressure into the low-pressure region. This is confirmed by the limiting streamline pattern on the flat end of a spiked cylinder with a wedge-shaped cap (Fig. 3a, $l=0.7$). A sink line can be observed in plane I. A minimum of the heat flux on the flat end is to be expected along this line.

With increase in the length $l$ of the spike, starting from a certain value $l_0$, the flow past a spiked flat-end cylinder (irrespective of whether a plane cap is mounted or not) turns out to be separated. This flow is characterized by
separation from the tip of the spike (or from the cap) and reattachment in the vicinity of the flat-end edge. In the case considered, separated flow appeared at \( l = 1, l_1 < l < l_1^* \), \( l_1 \) being the spike length at which the separation shifts onto the spike itself. As an example, the photograph in Fig. 1c presents the flow pattern for a spiked flat-end cylinder with a wedge-shaped cap in planes I \((l = 1.37)\) and II \((l = 1)\), respectively.

As distinct from axisymmetric flow past a spiked flat-end cylinder, in the case of 3D flow the pressures in the reattachment region can differ considerably in planes I and II (Fig. 2b, curves 1-3, respectively, \( l = 1 \)). As in the case of flow past a wedge-sphere model [2], the pressure difference between planes I and II in the reattachment region on the cylinder (cone) causes gas to flow from the high-pressure into the low-pressure region and to "splash" out of the separation zone, thus causing it to oscillate. This is confirmed by the limiting streamline pattern on the surface of the wedge-cylinder model presented in Fig. 3b \((l = 1.37)\).

The line I-I in Fig. 3 is a sink line, while the line II-II is a spreading line. The minimum and maximum values of the heat flux to the flat end are to be expected along lines I-I and II-II, respectively. For comparison with the case of 3D flow, Fig. 3c also shows (for \( l = 1 \)) the limiting streamline pattern on the surface of a spiked flat-end cylinder.

Moreover, this is also confirmed by pictures of the flow past a wedge-cone model in planes I and II taken at various moments of time under stationary wind tunnel operating conditions (Fig. 4a, \( l = 0.7 \)). An analysis of the photographs shows that in the reattachment region the shock wave in plane II (snapshots 3 and 4) is observed continuously in the course of the experiment, while the shock wave in plane I (snapshots 1 and 2) now appears, now vanishes, thus confirming the suggestion that gas "splashes" out of the separation zone.