INFLUENCE OF THE ENTROPY LAYER ON THE STABILITY OF A SUPERSONIC SHOCK LAYER AND TRANSITION OF THE LAMINAR BOUNDARY LAYER TO TURBULENCE

V. I. Lysenko

UDC 532.526

The use of pointed bodies, designed for high Mach number flight, is limited by the excessive heating and by ablation of the sharp nose of a body or of the leading edge of a wing. Therefore bodies with slight blunting of the nose (or of the leading edge) are more suitable for such flight. In that case there is a new effect, in comparison with sharp bodies, the blunting effect connected with the distribution of entropy along the stream lines. The stream lines near the body surface, after passing through a detached shock wave, in the vicinity of the nose form the so-called entropy (high-entropy) layer, which exists theoretically in an inviscid gas at any distance from the nose. In the entropy layer the gas flow has high temperature, low density, practically zero pressure gradient across the layer, and an appreciable velocity gradient. The intensity of the entropy layer increases with increased nose blunting.

The present paper describes an experimental investigation of the influence of leading edge blunting of a plate on the stability of the outer flow (relative to the boundary layer) in the shock layer (in fact on the stability of the entropy layer itself), on the stability of the laminar boundary layer, and on transition of the latter to turbulence.

Literature Review. The theory of the entropy layer arising with blunting of the nose of a body in hypersonic flow, has been described quite well in [1-3]. The influence of the entropy layer (including also its absorption by the boundary layer) on the different parameters of the mean flow, heat transfer, surface friction and other phenomena for bodies of different shapes was described in [4-14]. The asymptotic theory was used in [15] to study the downstream propagation of perturbations introduced by nose blunting in hypersonic flow of a perfect gas over a body of step form. They investigated the perturbed flow in the outer region (between the entropy layer and the shock wave) and here the perturbations propagating along characteristics are formed in the process of subsequent reflection from the shock wave and the wedge surface. They obtained the result that in axisymmetric flows the perturbations attenuate considerably faster than in plane-parallel flows.

The influence of the entropy layer on the propagation of unsteady perturbations into the boundary layer in hypersonic flow over a body was focused on in [16, 17]. This influence was investigated in [16] for the case when the frequency and wave number take purely real values. As the blunting increases the wave number increases. Here to achieve penetration of the perturbations upstream required increasing growth of the excess pressure along the longitudinal axis. Complex wave number and frequency were examined in [17]. It was shown that for blunting tending to zero there was stable free interaction of internal waves propagating into the boundary layer. For blunting tending to infinity, of all the roots with a purely imaginary value of wave number there are modes for which the real part of the complex frequency can take both negative and positive values. Then the real part of the frequency is zero and traveling waves of Tollmien—Schlichting type arise in which there are neutral oscillations of the fluid with amplitude constant with time. Increasing blunting of the leading edge first leads to loss of stability of the longer wave perturbations and, then, to loss of stability of the shorter wave perturbations.

The stability of the laminar boundary layer of a blunted flat plate in supersonic flow were investigated in [18] and the computations were done mainly for Mach number $M_\infty = 4$. The nonuniformity in the general flow behind the shock wave was described with the aid of two length scales — the boundary layer and the entropy layer thicknesses, the latter being on the order of the leading edge blunting radius. Waves of Tollmien—Schlichting type with

---

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 74-80, November-December, 1990. Original article submitted May 18, 1989.

0021-8944/90/3106-0868$12.50

wavelengths corresponding to these scales were analyzed individually in [18]. In the absorption zone of the entropy layer the interaction of the boundary layer with the vorticity of the outer inviscid flow becomes strong and the mean flow profiles exhibit complex variations when absorption effects are accounted for. They obtained the result that the viscous–inviscid interaction causes boundary layer growth due to the gradients of the two kinds of pressure induced by the outer flow — the self induced pressure and pressure induced by vorticity from blunting of the plate leading edge (actually the action of the former is small). The absorption of the entropy layer considerably stabilizes the outer inviscid flow (outer relative to the boundary layer), due to absorption by the boundary layer of the comparatively unstable internal part of the external flow. An increase in leading edge blunting through the mechanism of self induction destabilizes both the first and the second modes of perturbation in the boundary layer and through the mechanism of induction due to vorticity destabilizes the first mode (beginning at some degree of blunting) and stabilizes the second mode (the second mechanism is the main one). Here in the dependence of distance (from the leading edge to the stagnation point) on the blunting one observes a reversal, a successive increase and decrease in this distance. Increased blunting of the leading edge destabilizes the outer flow (from the unstable part of the entropy layer). A generation mechanism (similar to that of [18]) is depicted schematically in [19] for entropy perturbations and vorticity perturbations into which some of these perturbations are transformed upon reflection from the shock wave (due to the occurrence of pressure perturbations in the boundary layer on the body).

In fact, the only experimental investigation of the influence of the entropy layer on the stability of the shock layer (boundary layer and entropy separately) is [20], which described results of tests on a blunted cone at $M_\infty = 8$ using a thermal anemometer. Perturbations of the second mode were investigated in the boundary layer. It was determined that comparatively small blunting of the cone nose (to radius 3.75 and 6.25 mm, which corresponded to 3 and 5% of the base radius) attenuated the perturbations of all frequencies for large local Reynolds number values. For 3% blunting the critical Reynolds number was $\mathrm{Re}_* = 5.1\cdot 10^6$ and, for 5%, it was $10\cdot 10^6$. The region on the cone where the entropy layer is absorbed by the boundary layer proved to be stable and the location of the critical point coincided approximately with the location where the entropy layer is absorbed. When Re_* was exceeded the degree of growth of the perturbations increased constantly and quickly became larger than the degree of amplification in the boundary layer on a sharp cone. A large amplitude of perturbations was observed outside the boundary layer, in the entropy layer, and the existence of an inviscid instability was also observed. The data obtained showed that the perturbations of the entropy layer first increase weakly and, then, strongly after it impinges into the boundary layer. It should be noted that the boundary layer is most stable at a blunting radius of 6.25 mm (here it is stable over the whole model surface); for larger blunting the stability of the boundary layer was not measured.

In constrast with [20] in this paper the investigations were conducted on a flat plate at $M_\infty = 4$, and we determined the stability of both the entropy layer and the boundary for perturbations of the first mode for large values of blunting of the model leading edge (from the viewpoint of the plate experiments).

Equipment and Experimental Method. The basic experiments were conducted in the T-325 wind tunnel of the Institute of Theoretical and Applied Mechanics, Siberian Branch, Academy of Sciences of the USSR, with a working section area of 200 × 200 mm [21, 22].

The test model was a flat steel plate of length 450 mm, width 200 mm, and thickness 5 mm. The nose taper angle was 20°. The plate was rigidly attached to the side walls of the tunnel working section and set at zero angle of attack. The leading edge blunting was varied widely over the range: b = 0.1; 1; 1.5; 2; 3; 5 and 10 mm, and the leading edge was tapered in the direction perpendicular to the working surface of the model. The flow stagnation temperature was about 290 K and the plate surface temperature was equal to the recovery temperature. The stability characteristics (and the monitor measurements of transition location) were measured with a constant current type TPT-4 thermal anemometer and sensors with tungsten wire of diameter 6 μ and length 1.5 mm. In the experiments we also used a type U2-8 selective amplifier, a selective type V6-9 microvoltmeter, and a type G3-112/1 signal generator.

The basic pressure measurements were taken with the aid of a total head tube and a type GRM-2 recording manometer. The total head tube had outside dimensions of 0.22 × 1.0 mm

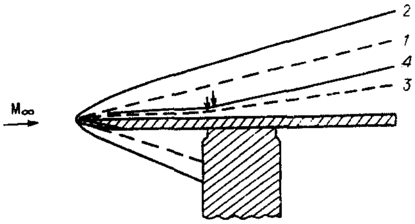

Fig. 1

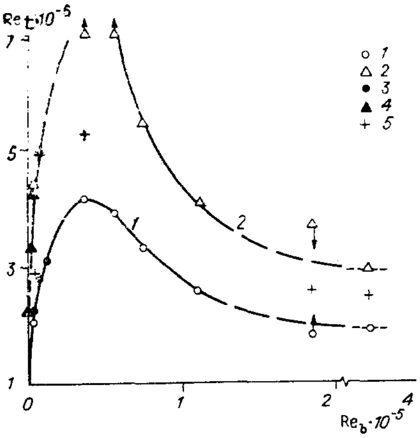

Fig. 2

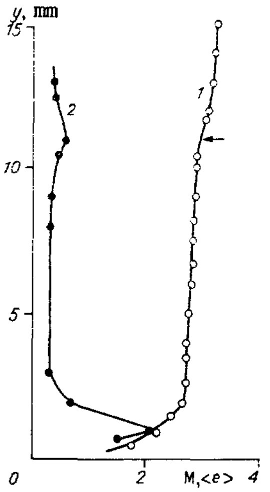

Fig. 3

and inside dimensions of 0.1 × 0.7 mm. To determine the static pressure we used a probe tube with a conical nose and a balance pressure measurement. The outer diameter of the tube was 0.8 mm, the inlet diameter was 0.38 mm, and the distance from the center of the inlet aperture to the probe nose was 11 mm.

Auxiliary experiments were conducted in the T-326 wind tunnel [23]. The test model was a flat plate of length 163 mm, width 70 mm, and thickness 5 mm. The plate material was #3 alloy. The taper angle of the nose part of the model was 7°. The model was mounted at zero angle of attack. The leading edge blunting had two values: 0.1 and 1.5 mm. The leading edge was tapered perpendicularly to the model working surface. Flow visualization around the plate was obtained with the aid of a shadow system (Strioscope, ONERA License D200, France). Photographs were taken with a Zenith-B camera. We recorded the shock wave shape and the location of boundary layer transition.

In the same wind tunnel we tried to measure the stability of the boundary layer to pressure fluctuations on the plate surface using surface sensors (mounted flush with the surface) – type 7031 quartz pressure transducers and Kistler type 5006 charge amplifiers (Swiss), but the attempt was unsuccessful due to the low signal level in the amplitude–frequency analysis. It proved difficult to determine the location of boundary layer transition from the readings of one of the pressure sensors when this varied over a wide range of unit Reynolds number $Re_1 = u/\nu$ and with a fixed sensor location (as was done successfully in [24] with the aid of surface thermal anemometer sensors), because the total pressure fluctuation signal increased almost linearly with increase in Re_1; the change in sensor signal due to boundary layer transition was insignificant compared with the increase in signal due to pressure increase.

Measured Results. The investigations in the T-326 wind tunnel were conducted at an incident stream Mach number of $M_\infty = 6$, stagnation temperature of $T_0 = 423$ K, and total pressure in the fore-chamber of 1000 to $5 \cdot 10^3$ kN/m^2 [unit Reynolds number in the incident stream was $(Re_1)_\infty = (11\text{-}57) \cdot 10^6 \cdot$ 1/m, respectively]. Figure 1 shows photographs obtained using the Strioscope for two values of blunting (0.1 and 1.5 mm). Lines 1 and 3 (broken) refer to the plate with a sharp leading edge (b = 0.1 mm), and the solid lines 2 and 4 refer to the noticeably blunted plate (b = 1.5 mm). Lines 1 and 2 correspond to the shock wave position, and lines 3 and 4 refer to the edge of the boundary layer (for increased visibility the boundary layer thicknesses were increased by a factor of several; the value depends on Re_1). Arrows indicate the start of transition. The investigations confirmed the substantial growth of the boundary layer with increased blunting (due to interaction with the entropy layer). Also notable is the bending of the shock wave for b = 1.5 mm.

The investigations in the T-325 wind tunnel were conducted at $M_\infty = 4$. The location of the start and end of transition of the boundary layer on the model at the same blunting were determined with the aid of a total head tube which was moved along the model surface in the longitudinal x direction. Figure 2 shows the dependence of transition Reynolds number $Re_t = (Re_1)_\infty \cdot x_t$ on the blunting Reynolds number $Re_b = (Re_1)_\infty \cdot b$. The experiments were

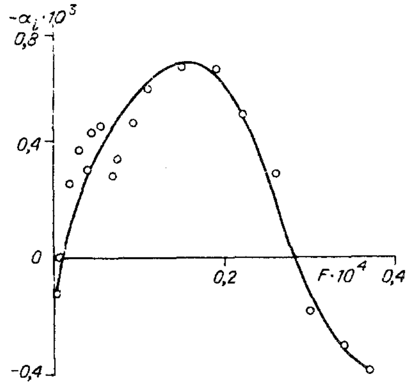

Fig. 4

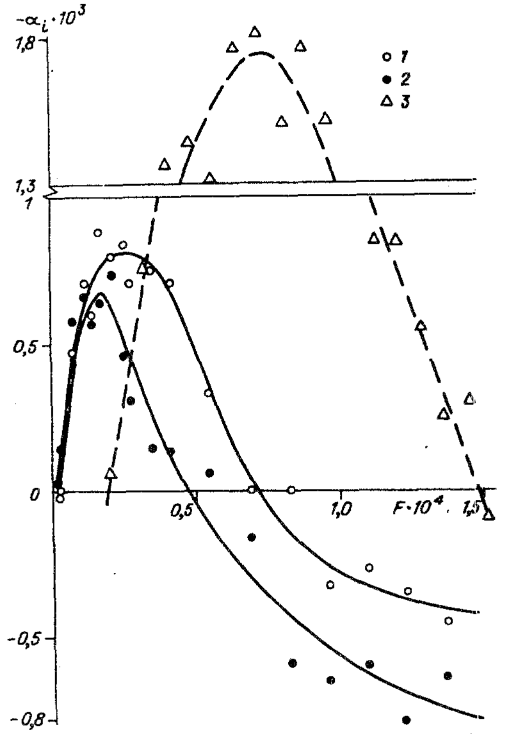

Fig. 5

conducted for $(Re_1)_\infty = 37\cdot10^6$ 1/m and b = 0.1-10 mm. Curve 1 is the start of transition and curve 2 is the end. The arrows on the individual points indicate the direction to the true location of these points on the graph. Points 1 and 2 were obtained in the experiments, and points 3 and 4 were taken from [25] [at $(Re_1)_\infty = 35\cdot10^6$ 1/m] and [26], accomplished in tunnel T-325 earlier. Points 5 correspond to the location of transition as determined using the thermal anemometer and moving the anemometer sensor along the plate at a distance of about 0.3 mm from the surface. The location of transition was determined from the maximum of the dependence of the thermal anemometer rms signal on the longitudinal coordinate. In Fig. 2 one can see a clear reversal of transition with increased blunting and the maximum "extension" of transition occurs for b ≈ 1 mm. With further increase in blunting the flow on the plate tends asymptotically to the flow over a right angle (b = ∞). The location of boundary layer transition behaves accordingly also. The result obtained is analogous to the data of [26-29].

The stability of the boundary and entropy layers was studied with b = 5 and 3 mm. But to investigate the stability of the entropy layer one should determine beforehand the approximate location in the entropy layer of the layer with the integrated (over frequency) maximum amplitude of perturbations $\langle e\rangle_{max}$ for which one could use one of the conclusions of [20]. It states that the knee of the Mach number profile (outside the boundary layer) coincides roughly with the maximum in the profile of perturbations measured with the thermal anemometer. Therefore the profile of M was first determined with a total pressure probe and a static pressure probe. At the edge of the boundary layer it was found that $M_e \approx 2.7$.

From the results of the investigations with $(Re_1)_\infty = 25.3\cdot10^6$ 1/m, b = 5 mm, and x = 80 mm, shown in Fig. 3, it can be seen that the knee in the profile of M occurs at y ≈ 11 mm. As was shown by the measurements of entropy layer stability investigated at that time the maximum value of the rms signal from the sensor wire of the thermal anemometer was also observed at y ≈ 11 mm, i.e., we confirmed the conclusion of [20] used here. In the profile of $\langle e\rangle$ in the shock layer (see Fig. 3) there are two maxima corresponding to the most unstable regions of the boundary layer and the entropy layer. At $M_\infty = 4$ the "boundary layer" maximum is larger than the "entropy" layer by a factor of 3.5, in contrast with [20], where for $M_\infty = 8$ the "entropy" maximum is already larger than the "boundary layer" maximum. This indicates an increase in the role of instability in the entropy layer with increase in M. We note that in this study (as was true in [20]) we obtained a noticeable growth of perturbations in the "critical" part of the entropy layer — $\langle e\rangle_{max}$ at y ≈ 11 mm is larger than the minimum signal (over the whole shock layer) by roughly a factor of 2.

We subsequently investigated the stability of the entropy layer. The measurements were made in the layer with maximum value of <e>, close to the "critical" part of the entropy layer. The experiments were conducted for $R = (Re_x)^{1/2} = 1423$ [$(Re_1)_\infty = 25.3 \cdot 10^6$ 1/m] and b = 5 mm. The results are shown in Fig. 4. Here $F = 2\pi f/(Re_{1\infty} \cdot u_\infty)$ is the dimensionless frequency parameter (f is the frequency of the perturbations, u_∞ is the velocity in the unperturbed stream); and $\alpha_i = -0.5d/(\ln A_f)/dR$ is the degree of growth of the perturbations in the entropy layer in a specific frequency range (from 3 to 70 kHz), i.e., the existence of an inviscid instability was obtained experimentally even for $M_\infty = 4$.

The following series of experiments was conducted to investigate boundary layer stability for b = 5 and 3 mm, and unit Reynolds number at the edge of the boundary layer of $(Re_1)_e$ $7.8 \cdot 10^6$ 1/m (Fig. 5). The values of F and α_i were computed from the parameters at the edge of the boundary layer. The points 1 correspond to the data for b = 5 mm {$R_e = [(Re_1)_e \times x]^{1/2} \approx 765$}, the points 2 correspond to the data with b = 3 mm ($R_e \approx 777$), and the points 3 correspond to data with b = 0.02 mm ($R_e = R = 780$). The points 3 were taken from [30, 31], where the experiments were conducted in T-325 on exactly the same plate as in the present experiments. It follows from Fig. 5 that for increased blunting from b = 0 the degree of growth of the perturbations first decreases and, then, increases (analogous to the result of [32]). This "reversal" corresponds completely to the "reversal" of transition shown in Fig. 2. Here we note that the entropy layer, beginning at a certain blunting, destabilizes the first mode of perturbations in the boundary layer, which is in full agreement with one of the conclusions of the theoretical study in [18].

Thus, it has been shown experimentally that growth of the entropy layer (with increased model blunting) destabilizes both the perturbations in the entropy layer itself and (starting at a certain degree of blunting) perturbations of the first mode in the boundary layer, i.e., the entire shock layer at $M_\infty = 4$ is destabilized.

The author thanks A. D. Kosinov and G. P. Klemenkov for help with this work.

LITERATURE CITED

1. V. V. Lunev, Hypersonic Aerodynamics [in Russian], Mashinostroenie, Moscow (1975).
2. D. Yakura, "Theory of entropy layers and nose blunting in hypersonic flow," in: Investigation of Hypersonic Flow [Russian translation], Mir, Moscow (1964).
3. V. I. Timoshenko, Supersonic Flow of a Viscous Gas [in Russian], Naukova Dumka, Kiev (1987).
4. Gisbrekht, Shtilp, and Merkirkh, "Schlieren visualization of an entropy wake," RTK 10, No. 12 (1972).
5. Archer and Betteridge, "The entropy layer on a plate with a flat face in supersonic flow at angle of attack," RTK, 13, No. 2 (1975).
6. Horstman, "Viscous hypersonic flow over slender blunted cones," RTK, 8, No. 10 (1970).
7. Merti, "Hypersonic flow over concave surfaces of bodies with blunt leading edges," RTK, 13, No. 9 (1975).
8. V. Ya. Neiland and L. A. Sokolov, "Influence of the entropy layer on boundary layer separation in hypersonic flow," Uch. Zap. Tsentr. Aero. Gidro. Inst., 9, No. 3 (1978).
9. Sullivan and Kozyak, "The influence of the entropy layer on flow on a constant pressure hypersonic boundary layer," RTK, 11, No. 5 (1973).
10. Yu. G. El'kin, Yu. N. Ermak, I. I. Lipatov, and V. Ya. Neiland, "Absorption of the entropy layer on a blunt cone in hypersonic flow of a viscous gas," Uch. Zap. Tsentr. Aero. Gidro. Inst., 14, No. 1 (1983).
11. V. Ya. Neiland and L. A. Sokolov, "Influence of the entropy layer in hypersonic flow over aerodynamic control surfaces," Uch. Zap. Tsentr. Aero. Gidro. Inst., 6, No. 1 (1975).
12. Popinsky, "Computation of the compressible laminar boundary layer on a sharp cone at angle of attack, allowing for absorption of the entropy layer," RTK, 13, No. 9 (1975).
13. Yu. N. Ermak, N. P. Kolina, and A. Ya. Yushin, "Heat transfer on the side surface of a blunt cone with absorption of the entropy layer by a laminar and turbulent boundary layer," Zh. Prikl. Mekh. Tekh. Fiz., No. 5 (1985).
14. N. P. Kolina, Yu. Yu. Kolochinskii, and A. Ya. Yushin, "The influence of absorption of the entropy layer on heat transfer in supersonic flow over a blunt circular cone," Uch. Zap. Tsentr. Aero. Gidro. Inst., 16, No. 3 (1985).

15. S. V. Manuilovich and M. E. Sidoryuk, "The asymptotic theory of hypersonic flow over blunt half-bodies," Uch. Zap. Tsentr. Aero. Gidro. Inst., 17, No. 3 (1986).
16. L. A. Sokolev, "The influence of the entropy layer on propagation of unsteady perturbations in the boundary layer," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1983).
17. L. A. Sokolov, "The influence of the entropy layer on propagation of unsteady perturbations in the boundary layer with self-induced pressure," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1984).
18. E. Reshotko and M. M. Khan, "Stability of the laminary boundary layer on a blunted plate in supersonic flow," IUTAM Symp. on Laminar-Turbulent Transition, Stuttgart, Germany, 1979, Springer, Berlin (1980).
19. M. V. Morkovin, "Transition at hypersonic speeds," ICASE, NASA Langley Research Center, Hampton, VA, March (1987).
20. K. F. Stetson, E. R. Thompson, J. C. Donaldson, and L. G. Siler, "Laminar boundary layer stability experiments on a cone at Mach 8; Pt 2: blunt cone," (Paper AIAA No. 84-0006), New York (1984).
21. G. I. Bagaev, V. A. Lebiga, V. G. Pridanov, and V. V. Chernykh, "The T-325 supersonic wind tunnel with reduced turbulence level," in: Aerophysical Investigations [in Russian], Inst. Teor. Prikl. Mekh. Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1972).
22. G. I. Babaev, V. A. Lebiga, and A. M. Kharitonov, "Study of noise in a supersonic boundary layer," Symp. on Physics of Acoustic and Hydrodynamic Phenomena [in Russian], Nauka, Mosocw (1975).
23. V. D. Grigor'ev, G. P. Klemenkov, A. I. Omelaev, and A. M. Kharitonov, "The T-326 hypersonic wind tunnel," in: Aerophysical Investigations, Inst. Teor. Prikl. Mekh. Sib. Otd. Akad. Nauk SSSR (1972).
24. S. A. Gaponov and V. I. Lysenko, "Development of perturbations near a surface immersed in a supersonic stream," Zh. Prikl. Mekh. Tekh. Fiz., No. 6 (1988).
25. V. I. Lysenko and A. A. Maslov, "Transition of a laminar supersonic boundary layer to turbulence with surface cooling," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1981).
26. V. G. Pridanov and V. V. Chernykh, "Experimental investigation of the influence of leading edge blunting of a flat plate on transition in the boundary layer," in: Gasdynamics and Physical Kinetics [in Russian], Inst. Teor. Prikl. Mekh. Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1974).
27. K. F. Stetson and G. H. Rushton, "Shock tunnel investigation of boundary layer transition at M = 5.5," AIAA J., 5, No. 5 (1967).
28. A. Martellucci, B. L. Maguire, and R. S. Neff, "Analysis of flight test transition and turbulent heating data, Pt. 1. Boundary layer transition results: Final report," S. 1 (1972) (CR/NACA N 129045).
29. E. J. Softley, B. C. Graber, and R. E. Zempel, "Experimental observation of transition of the hypersonic boundary layer," AIAA J., 7, No. 2 (1969).
30. V. I. Lysenko and A. A. Maslov, "The influence of cooling on stability of a hypersonic boundary layer [in Russian]," Preprint No. 31, Inst. Teor. Prikl. Mekh. Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1981).
31. V. I. Lysenko and A. A. Maslov, "The effect of cooling on supersonic boundary layer stability," J. Fluid Mech., 147, No. 10 (1984).
32. A. D. Kosinov, A. A. Maslov, and S. G. Shevel'kov, "Experimental investigation of the influence of leading edge blunting on a flat plate on the development of three-dimensional waves in the supersonic boundary layer," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1987).