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STABILITY OF A HIGH-SPEED BOUNDARY LAYER

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At present a direct relationship between development of turbulence and loss of stability of an initially laminar boundary layer is generally accepted. The qualitative effect of various factors on the position of the point of transition from a laminar form of motion to turbulent is on the whole predicted correctly by stability theory. This has been confirmed by results of many studies at infrasonic and moderately supersonic (Mach number M = 2-5) flow velocities. However, at higher supersonic velocities (M > 5) experimental studies of boundary layer stability are very few in number and have all been performed with one and the same AEDC/B aerodynamic tube (at The Arnold Center) (see, e.g., [1]).

1. The present study will theoretically and experimentally investigate the stability of a boundary layer at high supersonic flow velocities. The experiments were performed in the T-327A nitrogen tube of the Institute of Theoretical and Applied Mechanics of the Siberian Branch, Academy of Sciences of the USSR at Reynolds number $(Re_1)_\infty = (u/\nu)_\infty = (0.7\text{-}1)\cdot 10^6$ 1/m, forechamber braking temperature T_0 = 1100-1260 K, and pressure $p_0{}^\Phi = (11.6\text{-}13.2)\cdot 10^6$ Pa. The nitrogen purity level was 10 molecules of oxygen per million nitrogen molecules.

The working model was a polished steel plane plate 330 mm long and 8 mm thick, having the form of a trapezoid (nose width 62, trailing edge width, 32 mm). The leading edge was beveled at an angle of 7° and blunted to b = 1 mm. A copper—constantan thermocouple was used to measure model surface temperature in the region where boundary layer stability characteristics were determined. The surface temperature changed only slightly — by 2%. Its mean value $T_{(w)}$ = 297 K. Because of the temperature change the braking temperature factor varied over the range $T_w = T_{(w)}/T_{aw}$ = 0.28-0.32 (where T_{aw} is the reconstruction temperature). The plate was installed in two positions — at $\omega_0 = 0$ (the plate regime) and $\omega_0 = 7°$ (the wedge regime) (ω_0 is the angle of plate inclination relative to the unperturbed flow). Boundary layer stability was determined by a TPT-4 dc thermoanemometer. An amplitude—frequency analysis of the signals was also performed using U2-8 selective amplifiers, a V6-9 voltmeter, a GZ-112/1 signal generator, and filament-type thermoanemometric sensors

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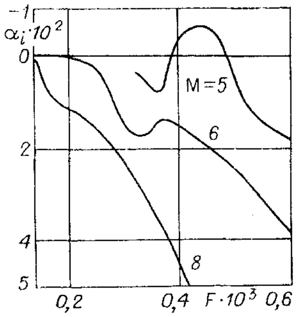

Fig. 1

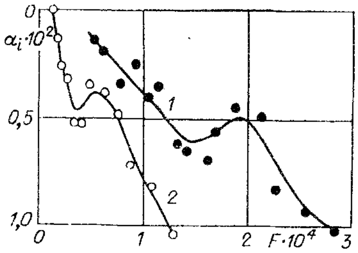

Fig. 2

with gold-plated tungsten filament 6 μm in diameter and 1.5 mm long. A positioner was used to move the thermoanemometer sensor simultaneously in two directions — along the longitudinal and normal coordinates of the model.

Pneumometric measurements (to determine M at the edge of the boundary layer and the distribution of the velocity head and velocity across the boundary layer) were performed with a tensometric total pressure sensor with input orifice 2 mm in diameter.

For the flow studied the viscous interaction parameter (for interaction between the boundary layer and the external nonviscous flow) $\overline{\chi} \simeq M_\infty^3/(\mathrm{Re}_\infty)^{1/2} = 18 > 1$, i.e., there is strong interaction. The boundary layer affects the external flow in just the same manner as thickening of the body (by the amount of the boundary layer displacement thickness). For example, for a planar plate the boundary layer induces a head shock wave. The total flow rotation angle $\omega = \omega_0 + d\delta^*/dx$ (where ω_0 is the local angle of deviation of the body from the unperturbed flow direction, $\Delta\omega = d\delta^*/dx$ is the additional flow deviation corresponding to the boundary layer displacement thickness δ^*, and x is the longitudinal coordinate).

In the experiments performed the Reynolds number $R = (\mathrm{Re}_x)^{1/2} = [(u/\nu)_e x]^{1/2}$ was varied over the range 480-600 (u is the flow viscosity, $\nu = \mu/\rho$ is the kinematic viscosity, ρ is the density, and the subscript e indicates that the parameters are taken at the edge of the boundary layer). In flow over the body the effect of the model blunting b is significant when $x/bM_\infty^3 \ll 1$ or $M_\infty^{3/2}/(\mathrm{Re}_b)^{1/2} \ll \overline{\chi}$. In the present experiments these quantities were $0.32 \sim 1$ and $10 \sim \overline{\chi}$, i.e., the effect of leading edge blunting on the nonviscous flow field was insignificant. Rarefied gas flows [2] have their own unique features. In the present studies the Knudsen number Kn = 0.034 and 0.041, i.e., gas flow with slip occurred. The gas slip velocity at the wall $u_R = w_R/u_e$ varied from 0.07 to 0.1-0.15.

In all experiments boundary layer stability measurements were performed in a layer $u/u_e = 0.4$, which was close to the lower "critical" layer with generalized inflection point $\left(\frac{d}{dy}\left(\frac{1}{T}\frac{du}{dy}\right) = 0\right.$, y being the normal coordinate). These were used to determine the rate of perturbation increase $\alpha_i = \frac{1}{A_f}\frac{x}{\sqrt{\mathrm{Re}_x}}\frac{dA_f}{dx}$ (where A_f is the perturbation amplitude for each dimensional frequency f) as a function of dimensionless frequency $F = 2\pi f/(\mathrm{Re}_1 u)$. The uncertainty in dimensionless frequency determination $\delta_F = \pm 1.8\%$, and $\delta_{\alpha_i} = \pm(15\text{-}22)\%$. The latter value is relatively high due to a decrease in thermoanemometer signal/noise ratio as compared to studies at M = 2-4. For the present study it was assumed that the signal in the boundary layer and the thermoanemometer noise were not correlated with each other and that the boundary layer signal at each frequency could be found from $e_{\mathrm{sign}} = \sqrt{e_\Sigma^2 - e_{\mathrm{noise}}^2}$. Studies were performed for the dimensional frequency range f = 3-50 kHz.

Before the experiments analogous functions $\alpha_i = \alpha_i(F)$ for flows similar to the experimental ones were calculated theoretically. The technique of [3] (described in greater detail in [4]) for numerical calculation of the rate of perturbation increase in the boundary layer upon heat exchange was used as a basis.

The flow of a compressible thermally conductive gas in a two-dimensional boundary layer was considered (see, e.g., [5] for the system of equations). Calculations were performed

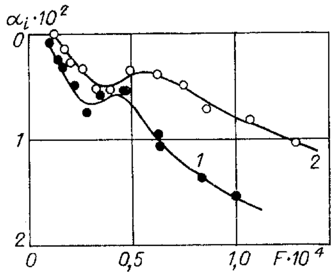

Fig. 3

for nitrogen and a specified body temperature. Flow on the plate was considered gradient-free and gas slip at the wall was neglected. To determine the perturbation increase coefficients the system of stability equations in the Dan–Lean approximation [6] was used with the following boundary conditions: vanishing of perturbations in the longitudinal and normal velocity and temperature on the wall, and attenuation of the same at infinity. The following were assumed: Prandtl number Pr = 0.72, adiabatic constant $\gamma = 1.41$, viscosity change with temperature ($\mu = cT^{3/2}/(T + T_s)$, c = const, T_s = 104 K).

The results of integration provided information on perturbations in the form of functions $\alpha_i = \alpha_i(R, F, \chi)$ ($F = \overline{\omega}/R$, $\overline{\omega}$ being the circular frequency, χ, the perturbation propagation angle, i.e., the angle of inclination of the wave relative to the main flow, $R = (u_e x/\nu_e)^{1/2}$ Reynolds number).

For M > 4 and $T_w \approx 0.3$ [7, 8] flow instability can be produced by practically any second (high-frequency) perturbation mode (the flow is stable with respect to first mode perturbations, which are analogous to Tollmin–Schlichting waves in an incompressible liquid). Second mode perturbations (intrinsic acoustic perturbations) are a variety of acoustical resonance in a flow with shear [9, 10]. It was demonstrated in [7] that oblique perturbations of this type ($\chi \neq 0$) are more stable than two-dimensional perturbations ($\chi = 0$). Therefore the stability characteristics were calculated for $\chi = 0$.

2. Figure 1 shows results of calculating the effect of Mach number in the range M = 5-8 on the rate of perturbation increase (R = 580, $T_w = 0.26$, T_0 = 1300 K). The intense stabilizing effect of M is evident. The frequencies corresponding to the least stable oscillation decrease.

Figure 2 shows analogous, but experimental data (T_w = 0.30-0.28, T_0 = 1170-1260 K, R = 481-558). The stabilizing effect of M can also be seen here (curve 2 lies below curve 1). The qualitative change in the $\alpha_i(F)$ curves of Figs. 1, 2 for various M values is identical.

Figure 3 shows experimental curves of perturbation increase vs. frequency for T_w = 0.32 (T_0 = 1100 K, R = 600, curve 1) and 0.28 (T_0 = 1260 K, R = 558, curve 2). The destabilizing effect of cooling on the second mode is evident, corresponding to the results of theoretical [7, 8] and experimental [3, 11] studies.

In comparing Figs. 1 and 2 as well as Fig. 3 and the corresponding calculation expressions it is obvious that the qualitative change in perturbation increase for variation of M and the temperature factor is identical for the calculated and experimental data.

Thus the experimental results, qualitatively confirming theoretical results for the second perturbation mode, indicate that M has a stabilizing effect on stability of a high-speed boundary layer while cooling has a destabilizing effect. For $R \leq 600$ the flow on a smooth planar plate and a wedge is stable and the boundary layer is laminar.

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NONSTATIONARY INTERACTION MODE IN A FLUCTUATING BOUNDARY LAYER

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The limit properties of the Cauchy problem for a partial integrodifferential equation describing the nonstationary interaction in a fluctuating boundary layer are examined for large Reynolds numbers Re [1]. It is shown that if the minimal value of the surface friction stress per period in front of the interaction domain is negative and greater in order of magnitude than $Re^{-1/8}$, then a range of wave numbers are extracted in the perturbed solution spectrum for which excitation of appropriate harmonics occurs in a bounded time interval. The physical mechanism of the excitation is discussed as an appearance of an instantaneous flow instability. A classification is presented of the limit flow modes in the case when the minimum of the unperturbed friction is positive and much greater than $Re^{-1/8}$.

1. INTRODUCTION

The flow with interaction in a fluctuating boundary layer is studied in [1] in an incompressible fluid around a flat plate with a small local surface deformation. An asymptotic theory of the flow for large Re was constructed under the assumption that the stream outside the boundary layer does not change direction during the whole time period while the minimum of the unperturbed friction stress on the plate in front of the domain of interaction is a quantity equal to $O(Re^{-1/8})$ in order of magnitude. It turns out that an investigation of three characteristic interaction modes is required to a lesser degree, in order to construct a solution uniformly suitable in time. Most interesting is the nonstationary interaction realized in a time interval of duration $O(Re^{-1/16})$ when the unperturbed friction on the plate is almost a minimum. The flow in this interval is described by the Cauchy problem formulated in [1] for the nonlinear partial integrodifferential equation

$$\frac{\partial B(X, T)}{\partial T} = -\gamma \frac{\partial}{\partial X} \int_{-\infty}^{X} \Big\{ [B(\xi, T) + f(\xi)] [T^2 + \sigma + H_0 (B(\xi, T) +$$

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