EFFECT OF TEMPERATURE FACTOR AND TURBULENCE OF THE IMPINGING STREAM ON THE TRANSITION IN THE BOUNDARY LAYER WITH GRADIENT FLOW

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An experimental study is made of the start of the transition and the extent of the transition zone in flow over a cooled wing profiled by a stream with an increased degree of turbulence in a wide range of Reynolds numbers.

One of the most important problems in the creation of high-temperature gas-turbine engines is the development of efficient systems for cooling the principal elements of a gas turbine, including the blade apparatus. The means of blade cooling in which the differential distribution of flow rates of the cooling air through the channels takes place in accordance with the local coefficients of heat transfer along the surface of the profile is very promising. The intensity of local heat exchange depends on the mode of flow in the boundary layer. It is known from the theory of hydrodynamic stability that cooling has a stabilizing effect on flow in a boundary layer [1, 6]. However, experiments on the effect of heat exchange on the state of a boundary layer at subsonic velocities are very limited and pertain to the case of nongradient flow [1, 4, 5]. Therefore, it is necessary to study the transition from the laminar to the turbulent boundary layer and the effect of the Reynolds number and turbulence of the impinging stream, the temperature factor, the pressure gradient along the surface over which the flow occurs, and others on the coordinate and the extent of the transition region along the profile.

The experiments were conducted on a wing profile with a chord of 0.515 m, a relative thickness of 14.4%, and a span of 1 m in a T-324 low-turbulence wind tunnel. The profile was mounted in the central part of the working section of the tunnel with a square cross section of 1 × 1 m and a length of 4 m. The surface of the model was cooled with a system of copper pipes 12 mm in diameter soldered along the generatrices to the inner surface of the working section of the profile with a width of 310 mm from an FAK-0,7 refrigeration unit. The cooling pipes were set close together starting from the inlet edge up to a point corresponding to 75% of the chord. The Freon was supplied through a regulating valve and manifold to all the pipes at once.

The surface temperature was monitored with Chromel—Copel thermocouples located in the middle of the working section along the outline of the profile. The thermoelectromotive force was measured with an accuracy of 0.01 mV by a TK-1652-2 digital voltmeter.

The difference in the local heat-transfer coefficients along the bathed surface is caused by a slight change in the temperature factor

$$\psi = T_w/T_s,$$

where T_w is the absolute surface temperature and T_s is the absolute air temperature.

Average values of the temperature factor in the transition region are presented in Table 1. A surface temperature no lower than 0°C was allowed in the tests, since rapid icing over of the surface, which had an important effect on the transition from laminar to turbulent flow in the boundary layer, took place with deeper cooling. The measurements at positive

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TABLE 1. Average Values of Temperature Factor

Grid number	ε, ψ	W, m/sec			
		7,7	11,8	16,2	21,5
Without grid	ε, %	0,050	0,035	0,03	0,03
	ψ	0,910	0,904	0,903	0,903
No. 1	ε, %	0,75	0,62	0,57	0,54
	ψ	0,907	0,908	0,910	0,907
No. 2	ε, %	0,91	0,77	0,69	0,66
	ψ	0,904	0,904	0,909	0,905
Nos. 1 and 3	ε, %	6,5	6,1	5,7	5,2
	ψ	0,900	0,894	—	—

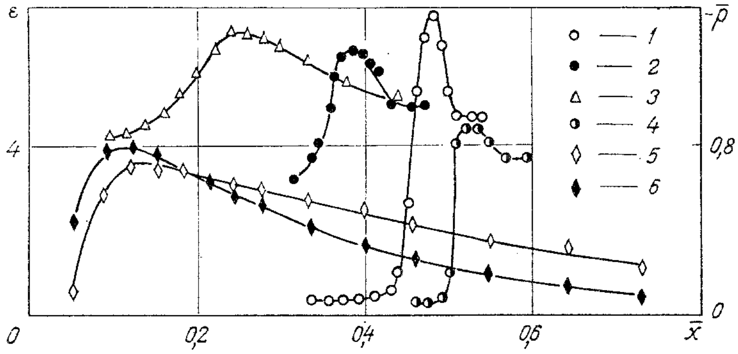

Fig. 1. Position of transition region for different values of the degree of turbulence and the temperature factor (Re = $6.94 \cdot 10^5$): 1) ε = 0.03, ψ = 1; 2) 0.66 and 1, respectively; 3) 5.25 and 1; 4) 0.03 and 0.9; 5, 6) pressure distributions along outline of profile with α = 0° and 3°5', respectively.

temperatures were conducted only until the moment of the precipitation of moisture and they were repeated several times to increase the accuracy of the results.

The degree of turbulence of the impinging stream was varied in the range of 0.03-6.5% with turbulizing grids mounted at a distance of 1800 mm from the inlet edge of the profile. Four series of tests were made with different degrees of turbulization of the stream:

1) without turbulizing grids, the turbulence parameters were taken in accordance with [2];
2) with turbulizing grid No. 1, made of wire 0.6 mm in diameter with a square cell of 5 × 5 mm;
3) with turbulizing grid No. 2, made of wire 1.5 mm in diameter with a square cell of 20 × 20 mm;
4) with two turbulizing grids Nos. 3 and 1 mounted at a distance of 500 mm. Grid No. 3 consisted of a lattice of strips 30 mm wide and 0.8 mm thick with a square cell of 140 × 140 mm. It was mounted in front of grid No. 1 for a considerable increase in the degree of turbulence.

In the tests the degree of turbulence varied as a function of the stream velocity; the results of the measurement are presented in Table 1.

The energy spectrum of the turbulent pulsations excited by the grids was different in each series of tests: in the second series 90% of the energy of the disturbances belonged to low frequencies up to 600 Hz; in the third series, up to 800 Hz; and in the fourth, up to 4 kHz.

A series of tests with angles of attack different from zero was made to study the effect of the pressure gradient along the outline of the profile at a cooled surface with increased turbulence of the impinging stream. The static pressures along the outline of the profile

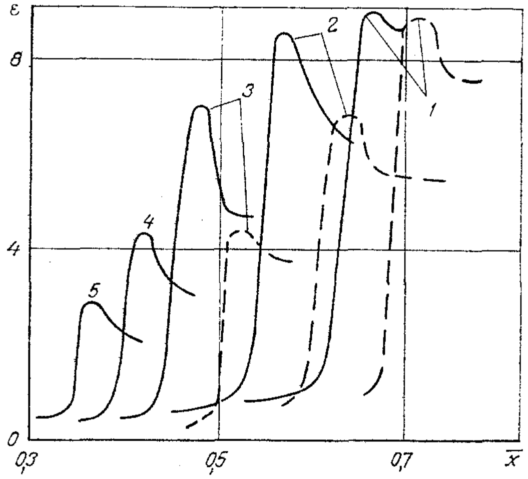

Fig. 2. Curves of rises in degree of turbulence in the transition region: 1) W = 7.8 m/sec; 2) 12; 3) 21.5; 4) 31.8; 5) 49.2; dashed lines: $\psi = 0.9$; solid lines: $\psi = 1$, $\varepsilon = 0.03\%$.

were measured with a battery alcohol manometer connected to drain pipes. The distribution of the pipes corresponds to the coordinates of the thermocouples, but with a shift of 5 mm along the generatrices. The values of the relative static pressures

$$\bar{P}_i = \frac{P_{i\,\mathrm{st}} - P_{i\,\mathrm{st}\,\infty}}{P_{\partial\infty}}$$

along the surface at different angles of attack are presented in Fig. 1. The quantity $P_{\partial\infty}$ was measured with an inclined alcohol manometer with a scale length of 1 m and k = 0.25.

All the measurements of the stream characteristics ahead of the profile and in the boundary layer were made with a DISA-55D00 thermoanemometer set. An FAT-1 spectrum analyzer with an endim 620.0,1 recorder were used to study the structure of the turbulence.

The experimental data were analyzed by the method described in [3].

The sizes of the pulsations in the boundary layer were measured with a thermoanemometer pickup fastened to a coordinator, which made it possible to position the filament at a given distance from the surface in a direction perpendicular to the pipe axis. In connection with the small curvature of the profile in the transition region being studied, the distance to the surface along the normal varied slightly and equalled 0.3-0.4 mm, as in [3], which comprised about 20-30% of the thickness of the boundary layer. This gap was controlled through the electrical contact between a needle fastened to the body of the pickup and the surface of the profile.

With movement of the pickup along the model the temperature in the zone of motion of the filament could fluctuate and the pickup sensitivity could consequently vary. A special study showed that this variation is slight and does not affect the accuracy of the determination of the transition zone.

As in [3], the start of the transition was identified with that point on the profile where surges in the amplitude of the pulsations, observed on the oscillograph screen, first appeared. This point coincided with the start of a sharp increase in the intensity of the velocity pulsations in the boundary layer. The coordinate with the maximum value of the intensity of velocity pulsations in the transition region was taken as the transition "point."

One can also approximately distinguish the point of the end of the transition, characterized by the start of developed turbulent flow. This point was determined from the coordinate of the start of the flat section on the descending branch of the curve of the rise in amplitude of the disturbances in the zone of the transition from the laminar to the turbulent boundary layer.

Curves of the rise in the disturbances in the transition zone as a function of the velocity of the impinging stream and the temperature factor are presented in Fig. 2. The

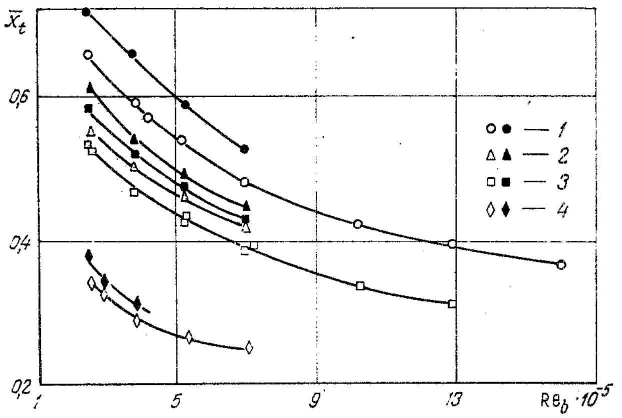

Fig. 3. Position of transition points for α = 0°. Light points: ψ = 1; dark points: ψ = 0.9; 1) without grids; 2) grid No. 1; 3) grid No. 2; 4) grids Nos. 1 and 3 together.

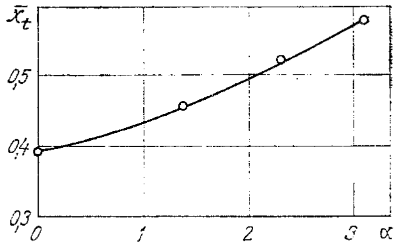

Fig. 4. Dependence of coordinates of transition points on angle of attack with grid No. 2. α, deg.

distances from the inlet edge along the outline of the profile, normalized to the chord, are laid out along the abscissa:

$$\bar{x} = x/b;$$

the degree of turbulence of the pulsations in the boundary layer is laid out along the ordinate.

In the course of the experiment a considerable decrease in the degree of turbulence of the disturbances in the boundary layer was observed with an increase in the velocity of the impinging stream and a decrease in the temperature factor.

The location of the points of the start and end of the transition allow one to judge the variation in the extent of the transition zone under different conditions of flow over the profile. With an increase in the Reynolds number Re = Wb/ν of the impinging stream from $2.5 \cdot 10^5$ to $16 \cdot 10^5$ the transition region at an isothermal surface decreased by 40%. The effect of the temperature factor in the investigated interval (ψ = 1-0.9) on the extent of the transition zone at fixed Reynolds numbers was slight.

An important increase in the size of the transition zone was observed upon turbulization of the stream. Curves of the rise for ε equal to 0.03, 0.66, and 5.25% are plotted in Fig. 1 as an illustration. The expansion of the transition region with an increase in the degree of turbulence of the impinging stream occurs because of a considerable shift of the point of the start of the transition toward the nose of the profile, whereas the coordinates of the point of the end of the transition shifted much less. Thus, with ε = 5.25% the point of the start of the transition shifted by 330 mm, while the point of the end of the transition shifted by less than 50 mm. The earlier start of the transition can be explained by the high level of the amplitudes of the disturbances penetrating into the laminar boundary layer.

The coordinates $\bar{x}_t$ obtained in modes with different degrees of turbulence and the maximum surface cooling obtained are plotted in Fig. 3 for all the series of tests with a zero angle of attack. As already indicated above, the transition coordinates $\bar{x}_t$ for all the modes studied were determined from the position of the extremum on the curves of the rise in the disturbances in the transition region of the boundary layer:

$$\bar{e} = \frac{e}{e_{s.t}},$$

where e is the amplitude of the disturbances in the transition zone and $e_{s.t}$ is the amplitude of the disturbances at the point of the start of the transition.

It was established experimentally that the velocity of the impinging stream has an important effect on the location of the transition points on the profile; for example, with an increase in Re from $2.5 \cdot 10^5$ to $16 \cdot 10^5$ for $\varepsilon = 0.03\%$ the x_t coordinate shifted upstream by 160 mm. A similar effect is seen at increased degrees of turbulence, but the higher ε, the weaker it is. It must be noted that the dependence $\bar{x}_t = f(\mathrm{Re})$ becomes flatter with an increase in the velocity of the impinging stream (Fig. 3).

Despite the fact that the temperature factor was varied slightly in the experiments (down to 0.9), laminarization of the boundary layer was observed in all the modes. Under the conditions of flow over a cooled profile without turbulizing grids the x_t coordinate shifted toward the inlet edge by an average of 26 mm, with the effect of cooling being more noticeable with a decrease in velocity. Qualitatively similar results were also obtained with an increased turbulization of the stream, but the dependence on the temperature factor decreases with an increase in ε: for example, the effect of ψ decreased by 2.5 times with a 10-fold increase in ε.

The effect of the pressure gradient along the outline of the profile is shown in Fig. 4. A slight change in the angle of attack led to considerable movement of the transition region, which is connected with the reorganization of the velocity curves along the outline of the profile and over the thickness of the boundary layer.

A cycle of studies was carried out without turbulizing grids and with grid No. 2 on an isothermal and a cooled profile at an angle of attack of 1°22'. The results of the experiment fully correspond to the data obtained at a zero angle of attack.

Thus, the experiments conducted made it possible to establish that there is considerable laminarization of the boundary layer upon the cooling of the surface of a profile over which flows both a low-turbulence stream and a stream with an increased degree of turbulence, as well as the dependence of the extent of the transition region on the velocity of the impinging stream, the temperature factor, and the turbulization of the flow.

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