STUDYING THE EFFECT OF THE TEMPERATURE FACTOR ON THE TRANSITION FROM A LAMINAR TO A TURBULENT REGIME OF FLOW IN A BOUNDARY LAYER

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Based on the generalization of experimental data, we propose a formula for the calculation of the effect of the temperature factor ψ and the transition from a laminar flow regime to one that is turbulent in the boundary layer of a plate; this formula has been confirmed by experiments performed in the following range of parameter variation: $0.5 \le \psi \le 2.6$; $0.2 \le M_\infty \le 3.6$; $0.1\% \le \varepsilon \le 9\%$.

We know that when a surface is streamlined by a gas flow whose temperature (T_∞) differs noticeably from the surface temperature (T_W), i.e., for values of the temperature factor $\psi = T_W/T_\infty$ many times smaller or larger than unity, the structure of the resulting boundary layer changes substantially under the action of ψ [1]. In this connection it is natural to expect that ψ will exert an effect on the transition from the laminar to the turbulent flow regime in a boundary layer.

In the following we present the results from an experimental study into the transition in the boundary layer of a plate for various values of ψ and with fixed values for all remaining parameters. The experiments were performed on two experimental installations at the Physicotechnical Department of the I. I. Polzunov Central Turbine Boiler Institute, in the region of subsonic velocities for a temperature factor $\psi < 1$ and in the region of low supersonic velocities when $\psi > 1$.

Special equipment was used to inject the air into the wind tunnel. Special damping devices were employed to protect the working sections with the nozzles against the vibrations of the input and output air conduits. Cooled ($\psi < 1$) and heated ($\psi > 1$) plates were employed as the working surfaces.

For our studies in the region $\psi < 1$ the blower air was fed through a regenerative air heater in which the air was heated to the specified limits by the hot gases flowing from a combustion chamber. The maximum air temperature beyond the air heater was approximately 270-300°C. The heated air was passed through a flat nozzle with flexible walls and through a rectilinear duct into the working section, one of whose walls was the experimental plate, 460 mm in length, and cooled with running water. To achieve a uniform temperature along the working surface, the plate was segmented, i.e., brass chamber segments – insulated from one another – had been welded to the inside surface of the plate. The cooling water was fed separately into each chamber through orifices in the side walls and it was removed through the top covers of the chambers. By appropriately regulating the feed of water into the chamber, it was possible to achieve a rather uniform temperature along the entire working surface of the plate. The surface temperature was measured with fourteen Chromel–Copel thermocouples imbedded into the plate.

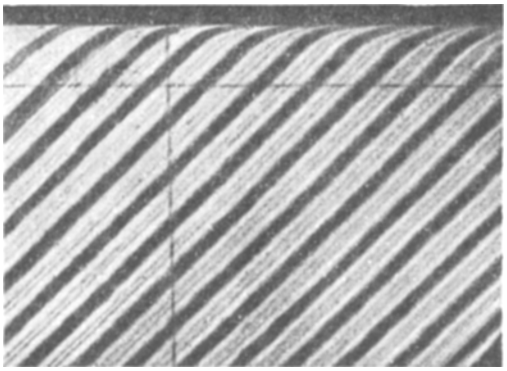

Fig. 1. Shadowgram showing the streamlining of a plate for $M_\infty = 1.45$ and $\psi = 2.4$.

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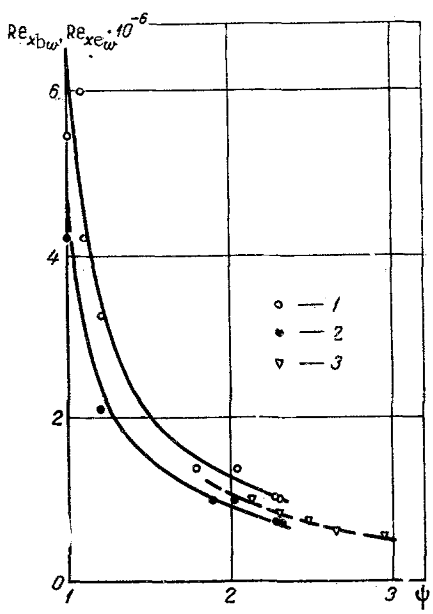

Fig. 2

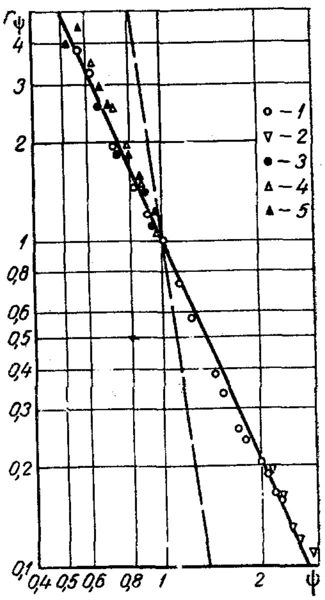

Fig. 3

Fig. 2. Re_{xb} and Re_{xe} as functions of ψ: 1) experiments performed at the I. I. Polzunov Central Turbine Boiler Institute; $M_\infty = 1.4$ (Re_{xe}); 2) experiments of the I. I. Polzunov Central Turbine Boiler Institute; $M_\infty = 1.4$ (3 and 2, Re_{xb}); 3) the Higgins and Pappas experiments; $M_\infty = 2.4$.

Fig. 3. The function $r_\psi = r(\psi)$: 1) experimental data of the I. I. Polzunov Central Turbine Boiler Institute; 2) experimental data after Higgins and Pappas; 3) experimental data after Van-Driest for $M_\infty = 1.9$; 4) the same, for $M_\infty = 2.7$; 5) the same, for $M_\infty = 3.6$.

The transition region for supersonic velocities and a temperature factor $\psi > 1$ was investigated in a wind tunnel with removable working sections positioned in the field or view of an IAB-451 optical shadow system. The experimental plate – 500 mm in length and 40 mm in width – served as the upper wall of the rectangular working section. The side walls of the working section were fitted with windows for the installation of two pairs of glass shields from the shadow instrument. This made it possible to study the boundary layer over virtually the entire plate.

The actual heated portion of the working segment was made of 1Kh18N9T stainless steel. Asbestos-cement insulation was used to insulate the plate from the remaining portions of the experimental setup. The plate was heated with ac current from a special transformer by means of which it was possible to vary the current strength over a wide range. To reduce the nonuniformity of heating over the length of the plate, the latter was fabricated with a variable thickness, thus making it possible to maintain a virtually constant temperature along the plate surface. The surface temperature T_w was measured with the fourteen Chromel –Copel thermocouples attached to the plate by means of capacitor welding.

To have the working section streamlined so that the boundary layer would increase from the leading edge of the plate, the boundary layer in each of the experiments was suctioned off from the upper wall of the conduit ahead of the experimental plate through a special suction slit. Moreover, in the experiments with the shadow device the boundary layer was drawn off from the side walls (with the glass shields) to reduce the distorting effect of the layer on the shadowgram.

The ultimate purpose of this experiment was to determine the effect of the temperature factor on the origin and extent of the transition region. As is well known, the transition of flow in the boundary layer on a plate from the laminar to the turbulent flow is shown most clearly in the velocity distribution in the boundary layer. The increase in the thickness of the boundary layer in the transition region produces a pronounced change in the velocity profile of that region. Accordingly, the experiment to investigate the transition was methodologically formulated in the

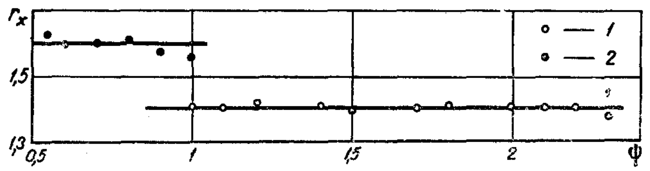

Fig. 4. The function $r_x = r(\psi)$: 1) $\varepsilon = 0.1\%$; 2) $\varepsilon = 1.4\%$.

following manner. A pneumometric method was used in the "hot" tube experiments with a temperature factor $\psi < 1$ for the determination of the velocity profiles in the layer. The dynamic-head and temperature fields were measured at 20-25 points on the boundary layer, with a constant velocity U_∞ and at the temperature of the free stream.

The measurements were carried out with a microtube and a microthermocouple; the front end of the microtube was flattened to a thickness of 0.36 mm, and the diameter of the hot thermocouple junction was 0.5 mm. A special positioning device that was accurate to 0.01 mm was used to move the tiny measuring devices across the boundary layer. At the instant that the front end of the microtube (or of the hot junction of the thermocouple) came into contact with the plate surface was monitored electronically. The pressure distribution along the plate was measured at 21 points, through drainage orifices with a diameter of 0.5 mm.

With such a procedure we were able to determine the velocity in the boundary layer from the familiar equation

$$u = \sqrt{\frac{2k}{k-1}\,\frac{p}{\rho}\left(\frac{p_0}{p}\right)^{\frac{k-1}{k}} - 1}\,. \tag{1}$$

The velocities in the boundary layer were calculated with consideration of the temperature distribution through the thickness of the layer; that temperature was measured with the microthermocouple.

The transition region for the temperature factor $\psi > 1$ was studied with a shadowgraph involving the use of a defocused grid, a method based on measuring the deviations of a beam of light from the unperturbed trajectory as it passed through a medium exhibiting a gradient component of the refractive index normal to the beam.† The deviation of the light beams in this case corresponds to the first derivative of the density with respect to distance (i.e., to the density gradient). We know that the density in this case can be determined for any point of the boundary layer by the expression

$$\rho = \rho^* + \int\limits_{M^*(x^*,y^*)}^{M(x,y)} \left(\frac{\partial\rho}{\partial x}\,dx + \frac{\partial\rho}{\partial y}\,dy\right), \tag{2}$$

where ρ^* is a known density at some point of the boundary layer (usually, for the value of ρ^* we take the density at the outside edge of the layer).

In our case, in studying the streamlining of a plate it proved to be possible to neglect the longitudinal density gradient; in this case, formula (2) assumed the form

$$\rho = \rho_{ed} + \int\limits_{y=\delta_{ed}}^{0} \frac{\partial\rho}{\partial y}\,dy. \tag{3}$$

The density gradient $\partial\rho/\partial y$ was determined from the isophote shift δ_y and from the light-beam deviation angle ε (determined from that shift), which is proportional to the density gradient and equal to $\varepsilon = \delta_y / \mu f_1 (f_1/\Delta + 1 - a/f_1)$. The magnitude of the isophote shift δ_y and the corresponding dy for various points of the boundary layer were measured on the shadowgram images outlined on a large scale.

To determine the density ρ_{ed} at the boundary of the layer, during the course of the experiment we determined: the head, the stagnation temperature, and the pressure distribution on the plate. Interpretation of the shadowgrams – one of which is shown in Fig. 1 for purposes of illustration – gave us the density profiles in the cross sections of the boundary layer. The flow parameters on the basis of the shadowgram interpretations were calculated by means of formulas from gas dynamics. Thus the reduced velocity at each

†The optical portion of the experiment was performed by Engineer L. A. Fel'dberg.

following point of the layer is defined as

$$\lambda = \frac{u}{a_*} = \sqrt{6\left(1 - \frac{\rho}{\rho_0}\right)^{k-1}}. \tag{4}$$

Experiments to study the effect of heat transfer on the transition in the boundary layer were performed at Mach numbers $M_\infty = 0.25$-0.3 and $M_\infty = 1.40$-1.45 for the unperturbed flow. With $M_\infty = 0.3$ the Reynolds number amounts to $(4 \cdot 10^5$-$2 \cdot 10^6)$, where as a result of a change in the free-stream temperature the temperature factor ψ varied from 0.55 to 1. With $M_\infty = 1.4$ the temperature factor varied from 1 to 2.7, and the Reynolds number varied from $Re_\infty = 10^6$ to $8 \cdot 10^6$.

For the parameters characterizing the transition region in the boundary layer in our analysis of the experimental data we chose the values of the Reynolds numbers at the points of the beginning and end of transition (Re_{xb} and Re_{xe}, respectively) as well as the relative extent of the transition region

$$r_x = \frac{Re_{xe}}{Re_{xb}}. \tag{5}$$

These parameters had been introduced earlier [2] in the examination of the transition process for streamlining with $\psi \approx 1$.

Analysis of the experimental data demonstrated that the coordinate for the beginning of transition is a strong function of the temperature factor. A reduction in ψ leads to increased flow stabilization in the boundary layer and to an increase in Re_{xb}, and conversely, with an increase in ψ the values of Re_{xb} diminish.

As an example, Fig. 2 shows the experimental values of Re_{xb} and Re_{xe} for a change in the temperature factor in the range $\psi = 1$-2.4 and for values of $M_\infty = 1.45$. As we can see from the figure, the increase in ψ from $\psi = 1$ to $\psi = 2.4$ leads to a reduction in Re_{xb} by almost an order of magnitude. The same graph shows the experimental values of Re_{xb}, obtained after Higgins and Pappas [3] for $M_\infty = 2.4$. As we can see, the curves are equidistant. Similar relationships were also derived for $\psi < 1$ and $M_\infty \approx 0.2$.

As pointed out above, experiments for $\psi < 1$ and for $\psi > 1$ were performed on various experimental installations with various values of M_∞ and for the turbulence of the free stream. However, if we introduce the parameter r_ψ into our examination, this parameter representing the ratio of Re_{xb} for a given ψ, ε, and M_∞ to the value of Re_{xb} for the same values of ε and M_∞, but with $\psi = 1$, i.e.,

$$r_\psi = \frac{(Re_{xb_w})_\psi}{(Re_{xb_w})_{\psi=1}}, \tag{6}$$

all of the experimental data, as we can see from Fig. 3, can be generalized by a single relationship. This relationship is well approximated by the formula

$$r_\psi = \psi^{-2.3}, \tag{7}$$

indicated in Fig. 3 by the side line. This same graph shows the experimental data of Higgins and Pappas for $M_\infty = 2.4$ and the data of Van-Driest et al. [5] on the streamlining of cones for $M_\infty = 1.9$, 2.7, and 3.6 and a degree of turbulence $\varepsilon = 0.4$-9%.

As we can see, all of the experimental points are in completely satisfactory agreement with the solid line corresponding to formula (7), which indicates the substantial universality of this relationship and the possibility of extending the proposed scheme for the effect of the temperature factor on the transition over a wide range of variation in the Mach numbers M (from $M_\infty = 0.2$ to 3.6), for a wide range of variation in the degree of turbulence (from $\varepsilon = 0.4$ to 9%), and for a wide range of variation in the temperature factor (from $\psi = 0.5$ to 3.0).

The dashed line in this graph shows the results from the conversion to the proposed coordinates (r_ψ, ψ) of the theoretical relationships derived by Van-Driest [6] on the basis of an examination of the conditions of stability loss in the laminar boundary layer. As we can see, the dashed line differs substantially from the solid line, thus indicating that the conditions for stability loss in the laminar boundary layer differ from the conditions of the actual occurrence of transition, for which we require substantial development of perturbations, governing the beginning of a noticeable restructuring the velocity profiles in the boundary layer. However, we should take note of the fact that the theory in [6] correctly reflects the trend and nature of the effect on the transition of the temperature factor, and it correctly notes the fact that the values r_ψ are independent of the Mach number M.

Thus, to account for the effect of the temperature factor on the beginning of the transition we can recommend the formula

$$(\mathrm{Re}_{xb_w})_\psi = \psi^{-2.3}(\mathrm{Re}_{xb_w})_{\psi=1}. \tag{8}$$

Analysis of the experimental data on the extent of the transition region leads to the conclusion that with respect to the temperature factor there exists unique self-similarity in the process of transition, after it has begun. This self-similarity is expressed in the fact that the parameters R_{xb_w} and Re_{xe_w} vary with ψ equidistant and the value of r_x is not determined by ψ, but by the value of the flow turbulence. To illustrate the foregoing, Fig. 4 shows the values of r_x, determined in the experiments for various values of ψ. The open points refer to experiments at low turbulence ($\varepsilon \approx 0.1\%$), while the filled circles refer to experiments at a turbulence of $\varepsilon \approx 1.4\%$. As we can see, in the first case r_x = const = 1.4, while in the second case r_x = const = 1.6. These values of r_x are equal to the corresponding values obtained earlier in experiments with $\psi \approx 1$ where we investigated the effect of turbulence on transition in the boundary layer [4]. Thus we can assume that within the limits of our investigation the change in the temperature factor does not affect the value of the parameter r_x. The coordinate of the end of the transition in the case of plate streamlining for any value of ψ can thus easily be determined from the relationship

$$(\mathrm{Re}_{xe_w})_\psi = (\mathrm{Re}_{xb_w})_\psi r_x. \tag{9}$$

Summarizing the above, we can draw the conclusion that the temperature factor ψ strongly affects the stability of the laminar layer and, consequently, it strongly affects the beginning of transition. The uniqueness in the effect of ψ on the development of the transition process after it has begun lies in the fact that if we choose the parameter r_x as the characteristic for the extent of the transition region, its value will be independent of ψ and it will be determined exclusively by the turbulence of the flow.

NOTATION

p	is the static pressure;
p_0	is the total head;
ρ	is the density;
f_1, Δ, a	are the parameters of the optical system;
Re_x	is the Reynolds number.

Subscripts

w	denotes the conditions at the wall;
ed	denotes the parameters at the edge of the layer;
b	denotes the beginning of the transition region;
e	denotes the end of the transition region;
∞	denotes the free-stream parameters.

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