LAMINAR–TURBULENT TRANSITION OF SUPERSONIC BOUNDARY LAYER ON A COOLED SURFACE

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Investigations of the effect of Mach number M, unit Reynolds number Re_1, and leading-edge bluntness b on the position of the laminar–turbulent transition for an adiabatically heated model have been the subject of numerous papers (see [1-4], for instance). A review of the work of foreign authors can be found in [5]. The effect of cooling of the model on the supersonic boundary-layer transition has also been investigated in many studies (see [5], for instance), but there have been hardly any systematic investigations on the effect of the above factors on the boundary-layer transition on a cooled surface. Such experiments have usually been conducted for one or two Mach numbers at different Re_1. The effect of leading-edge bluntness of the cooled model on the transition has not been investigated.

In [6] experiments were conducted at three Mach numbers (M = 3.0, 3.5, 4.0), but the results were represented in relative coordinates, and it was impossible to correlate them with respect to Mach numbers. In [7] experiments were also carried out at three Mach numbers (M = 1.9, 2.7, 3.65), but the unit Reynolds number was different for each of these Mach numbers.

The above-mentioned experiments were conducted in different aerodynamic rigs, each of which had its own spectrum of disturbance energy in the working region, which was usually not given. Hence, the data for different rigs cannot be correctly compared.

It should be noted that investigations of the effect of different factors on such an integral characteristic as the transition Reynolds number have not led to sufficient comprehension of the transition mechanism to allow prediction of the position of the transition. Some aspects of the transition, however, have been clarified. In recent years more and more attention has been given to "microscopic" investigations of the transition — the study of the structure of the disturbances, their interaction, composition, etc. While recognizing the full importance of such investigations, we note that for some types of experiments a study of the transition in a wide range of characteristic parameters and under controlled external conditions is still of value. The effect of cooling on the transition is such an experiment.

The results obtained in investigations of the transition on cooled surfaces are very diverse and contradictory. Cooling has been found to have a stabilizing effect, a destabilizing effect, an alternately stabilizing and destabilizing effect, and no effect at all. Some of the observed effects have recently been explained. For instance, it was shown in [8] that the reason for "transition reversal," observed in wind-tunnel experiments, is the hoarfrost covering the model at low temperatures. It was shown experimentally in [9] that for large Mach numbers the transition is determined by disturbances of the second type, on which cooling has a destabilizing effect. Nevertheless, in view of such diverse results it is worthwhile investigating the transition in as wide a range of parameters as possible with a controlled spectrum of external disturbances. Such data can also be used for comparison with the results of calculations.

The aim of the present work was to investigate the effect of cooling on the transition of a supersonic boundary layer on a plate in the range of parameters attainable with the T-325 wind tunnel of the Institute of Theoretical Problems of Mechanics, Siberian Division, Academy of Sciences of the USSR, and to find out how the obtained results correspond with the physical explanations of the transition.

1. The investigations were made in a T-325 wind tunnel having a working section of cross section 200 × 200 mm. A description of this tunnel is given in [10]. The turbulence characteristics of the flow in the T-325 working section are given in [11].

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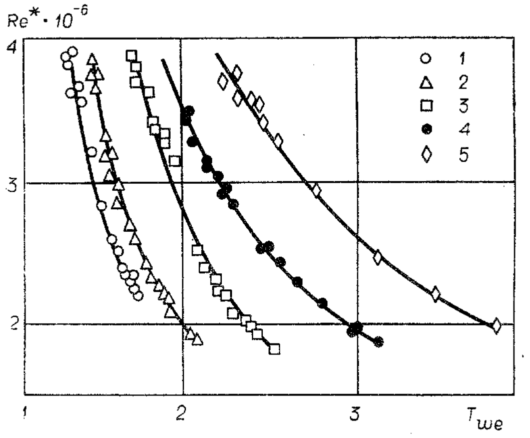

Fig. 1

The flow parameters (temperature in the forechamber, static pressure in the working section, and total pressure in the forechamber) were determined by the standard apparatus with which the wind tunnels are equipped, and we were able to determine Re_1 with a root-mean-square error not exceeding ±2%.

The investigated model was a flat plate 450 mm long, 200 mm broad, and 9 mm thick with leading-edge bevel 20° [8]. The leading edge was blunted at a right angle to the plate surface, and b is the thickness of the blunt end. The model was cooled with a mixture of liquid and gaseous nitrogen. The temperature on the model surface was determined by means of ten stainless steel—Constantan thermocouples. The error of determination of the temperature factor T_W (the ratio of the surface temperature to the recovery temperature) for each thermocouple did not exceed ±1%. To plot the relation $Re^* = f(T_W)$ for each value of transition Reynolds number we determined the mean surface temperature between the leading edge of the model and the transition point. The transition Reynolds number was calculated from the distance to the leading edge of the plate and the free-stream velocity and viscosity.

The position of the laminar—turbulent transition on the model was determined from the distribution of total pressure along its surface. We used a total-pressure tube with external dimensions 1.3 × 0.3 mm and internal dimensions 1.1 × 0.2 mm, a DMI-1 gauge, and an IVP-2 converter. The tube slid over the surface of the model. The distribution of the signal was registered on a recorder, in which the horizontal movement of the pen was synchronized with the movement of the pressure probe. As the beginning and end of the transition we took the position of the minimum and maximum, respectively, of the obtained plot of the DMI-1 signal against the longitudinal coordinate. The error of determination of the transition Reynolds number did not exceed ±6%.

It should be noted that when the transition is measured by a total-pressure probe the position of the minimum of the obtained curve depends on the relative thickness of the probe and, probably, on its shape and the size of the internal orifice. Pridanov et al. [12] proposed an empirical relation which allowed a correction to be made to the results obtained by probes of different height in the case of a thermally insulated plate. Estimates made from the formulas in [12] showed that the relations obtained in the present work were still of the same nature when corrections were made for the relative size of the probe, but the correctness of the formulas for the case of a cooled surface has not been verified, and, hence, no corrections were made.

As investigations [8] showed, the transition reversal obtained in some investigations of the effect of cooling on the transition is due to the hoarfrost appearing on the model surface, whose height, growth rate, and induction temperature depend on the air-humidity in the experiment. In view of this we conducted the present investigations at extremely low humidity (the relative air humidity before drying was $\chi = 0.11\text{–}0.22$). As a result an appreciable layer of hoarfrost appeared only in the experiments at M = 2 and large unit Reynolds numbers, i.e., at high density and, accordingly, high absolute air humidity in the working section of the wind tunnel. Hence, the investigations of the effect of Mach number were conducted at relatively low (which was the greatest possible in view of the above considerations) unit Reynolds number $Re_1 = 25 \cdot 10^6\ m^{-1}$.

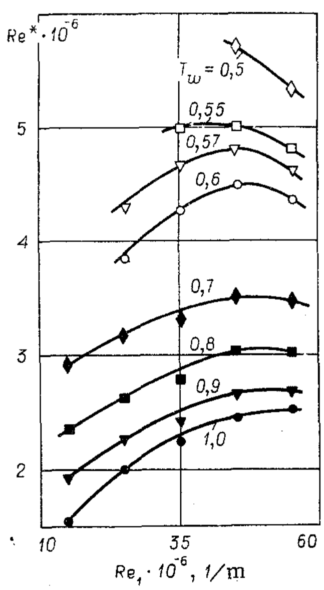

Fig. 2

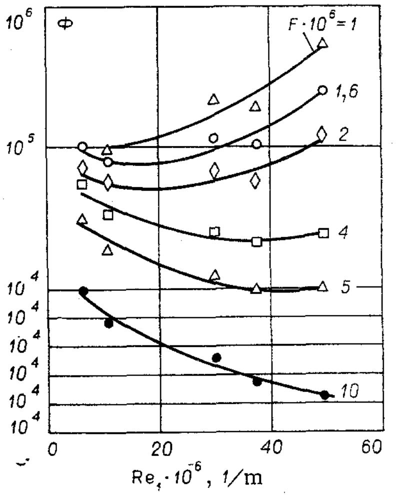

Fig. 3

2. In the first series of experiments we investigated the effect of Mach number on the position of the transition region when the surface of the model was cooled. The measurements were made at unit Reynolds number $Re_1 = 25 \cdot 10^6$ m^{-1} and leading-edge bluntness b = 0.10 mm. The results are given in Fig. 1, where T_{we} is the ratio of the surface temperature to the static free-stream temperature; Re* is the transition Reynolds number, determined from the start of the transition region; points 1-5 correspond to M = 2.0, 2.5, 3.0, 3.5, and 4.0.

For all Mach numbers the transition Reynolds numbers increased monotonically with reduction of surface temperature. The increase in Re* with reduction of T_{we} was greatest for M = 2.0. With increase in Mach number the effect of cooling was reduced.

The reduction of the effect of cooling with increase in Mach number may be due to enhancement of the interaction of the supersonic boundary layer with sound. Turbulence in the T-325 working section is due mainly to the sound emitted by the turbulent boundary layer on the nozzle walls and the working section [11]. According to [13], the transition in a supersonic boundary layer irradiated by sound is due to Schlichting—Tollmien vortex waves, which are formed from sound waves in the vicinity of the neutral stability curve. The sound waves themselves are intensified by the supersonic boundary layer, and this intensification is greater, the greater the Mach number [13, 14]. When the surface of the model is cooled the neutral stability curve is shifted into the region of large Reynolds numbers [15, 16], and the intensification of the disturbances is reduced, which leads to delay of the transition. Cooling has much less effect on the interaction of the boundary layer with sound. As the neutral curve moves into the region of large Re the transition begins to be determined more and more by low-frequency sonic disturbances, which can be greatly intensified. This leads to an increase in disturbances in the boundary layer and to reduction of the rates of increase in Re* with reduction of T_{we}. This process will be manifested most distinctly when the Mach number is increased.

3. The second series of experiments was conducted at M = 4.0 and leading-edge bluntness b = 0.10 mm for $Re_1 = (15; 25; 35; 45; 55) \cdot 10^6$ m^{-1}. For each value of Re_1 we obtained a plot of $Re^* = f(T_w)$, similar to those illustrated in Fig. 1. Figure 2 shows the point corresponding to the obtained relations.

At low Re_1 the effect of cooling was a little greater and the maximum of the relations $Re^* = \varphi(Re_1)$ on cooling was shifted from the region of high Re_1 into the region of lower Re_1. Such behavior of Re* is perfectly consistent with measurements of the energy spectra of the pressure fluctuations in the working section of the T-325 wind tunnel for M = 4.0, obtained in [11] and shown in Fig. 3, where $\Phi(F)$ is the energy of the pressure fluctuations corresponding to a given dimensionless frequency of pressure fluctuations F. For convenience of comparison the origins of coordinates for each curve in Fig. 3 are shifted upwards with increase in dimensionless frequency so that the upper coordinate grid corresponds to $F = 10^{-6}$.

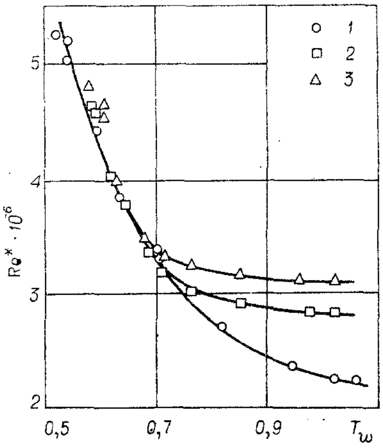

Fig. 4

The scale for all the graphs is the same and corresponds with the upper scale. The points in Fig. 3 correspond to the averaged curves in [11].

A change in Re_1 does not alter the nature of the development of disturbances in the linear region [17], and the transition is determined mainly by the initial intensity of the fluctuations in some frequency band determined by the complex of acting parameters (mean flow, spectral composition of external disturbances, conditions of formation of disturbance spectrum in boundary layer, etc.). For T-325 wind tunnels and for a thermally insulated flat-plate model the transition is determined by frequencies with $F \sim 10^{-5}$ [11]. For this frequency the energy of pressure fluctuations decreases with increase in Re_1 (see Fig. 3) and, in correspondence with this, the transition Reynolds number for $T_w = 1.0$ increases (see Fig. 2). The data shown in Fig. 3 represent the initial conditions for the disturbances. In the case of a constant laminar boundary layer the smaller the initial pressure fluctuations, the more distant the transition.

Reduction of the surface temperature changes the state of the laminar boundary layer as an intensifier of external disturbances. The neutral curve is shifted into the region of large Re and the range of unstable frequencies and their values are reduced [15, 16]. The transition begins to be determined by disturbances with frequencies $F < 10^{-5}$, for which the relation $\Phi = \Phi(Re_1)$ has a minimum (see Fig. 3), in correspondence with which the relation $Re^* = \varphi(Re_1)$ has a maximum (see Fig. 2).

We can trace the correspondence of the results in Figs. 2 and 3 more clearly if we use estimates of F for the case of complete stabilization of the boundary layer by surface cooling [15, 18]:

$$\alpha \to 1/\sqrt{\mathrm{Re}},\ c \to 1-1/\mathrm{M},$$

where α is the wave number of the disturbance; c is its phase velocity. Then

$$F = \alpha c/\sqrt{\mathrm{Re}} \sim 1/\mathrm{Re},$$

i.e., doubling, for instance, of the transition Reynolds number will halve the dimensionless frequency determining the transition. For $Re_1 = 50 \cdot 10^6$ m^{-1} and $T_w = 1.0$ the number $Re^* = 2.5 \cdot 10^6$, and $F \sim 10^{-5}$, whereas for $Re^* = 5 \cdot 10^6$ and $T_w = 0.55$ we have $F \sim 0.5 \cdot 10^{-5}$. For $F \sim 0.5 \cdot 10^{-5}$ the minimum of $\Phi = f(Re_1)$ is observed when $Re_1 \sim 40 \cdot 10^6$ m^{-1}, where the maximum of $Re^* = \varphi(Re_1)$ for $T_w = 0.55$ occurs.

This correspondence of the data in Figs. 2 and 3 suggests that the effect of cooling on the transition is greatest at the stage of linear development of the disturbance.

4. The third series of experiments was conducted at M = 4.0 and $Re_1 = 35 \cdot 10^6$ m^{-1} for different values of leading-edge bluntness of the plate. The results of this series are shown in Fig. 4. Points 1-3 correspond to values of b = 0.10, 0.20, and 0.36 mm. The leading-edge bluntness delays the transition and makes the relation $Re^* = f(T_w)$ less steep in the case of slight cooling ($T_w \sim 1.0$). However (if we assume that the curves for $0 \leqslant b < 0.10$ mm are arranged relative to one another like the obtained curves), with greater cooling the relations $Re^* = f(T_w)$ for $b \neq 0$ smoothly merge with the relation $Re^* = f(T_w)$ for b = 0. The smaller the leading-edge bluntness the more rapidly (at large T_w) the curves for $b \neq 0$ and b = 0 merge.

The obtained data suggest that for small leading-edge bluntness the zone of the effect of bluntness on the transition is finite and proportional to the bluntness. With reduction of surface temperature, however, the transition region leaves this zone, and bluntness has no more effect on the transition.

This conclusion does not contradict the main physical ideas on the mechanism of the effect of bluntness on the position of the transition region. When a supersonic stream flows past a blunt body a detached shock wave is formed in front of it. This shock wave: leads to a change in the average velocity and density profiles due to the pressure gradient near the leading edge and the entropy layer, which affects the nature of the development of disturbances in the boundary layer; affects the external disturbances, which undergo changes as they pass through the shock wave, and the initial conditions for development of turbulence are thus altered. With increase in the Reynolds number of the laminar flow due to cooling the effect of bluntness on the characteristics of the mean flow becomes less and less: The pressure gradient is reduced, and the effect of the entropy layer is reduced by entrainment of more and more new air masses into the boundary layer; the shock wave comes closer and closer to the Mach line and the disturbances pass through it without significant alteration, i.e., an increase in Reynolds numbers leads to a reduction of the effect of bluntness.

Thus, in the range of investigated parameters in tests in a T-325 wind tunnel cooling of the model surface leads to a monotonic increase in the transition Reynolds number. An increase in Mach number reduces the effect of cooling. The changes in transition Reynolds numbers in relation to Re_1 correspond to changes in the energy spectra of external disturbances. Leading-edge bluntness protracts the transition and reduces the effect of cooling when the temperature factor T_w is close to 1; with reduction of T_w the effect of leading-edge bluntness on the position of the transition is reduced and gradually disappears. All the effects observed in this investigation are qualitatively consistent with the conclusions of linear theory of hydrodynamic stability and confirm the hypothesis that the effect of cooling on the transition is manifested primarily in the effect on the stage of linear development of disturbances.

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