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Transition Reversal and One of Its Causes

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The results obtained in the present paper by different experimental methods and in different facilities show that the transition Reynolds number increases steadily with decreasing temperature without frost formation on the model surface. If frost appears on the model, transition reversal occurs. It takes place at temperatures corresponding to the beginning of frost formation (i.e., crystallization temperature of water steam). Decreasing this temperature, we delay the beginning of transition reversal. The decrease of the transition Reynolds number is caused by frost roughness. A sharp increase of the Re^* value at low values of T_w on the model surface with frost may be explained by variation of a total frost structure (including frost crystallized from steam of other chemical compounds and elements, e.g., from a CO_2 steam).

Nomenclature

C = relative air humidity
K = dimensionless intensity of light radiation scattered on plate surface
M = Mach number
Re^* = transition Reynolds number based on distance from model leading edge and on freestream conditions
Re_l = unit Reynolds number
T = wall temperature
T_w = temperature factor (wall-to-adiabatic wall temperature ratio)
X = distance from leading edge
λ = wavelength

Introduction

EXPERIMENTAL studies on the influence of surface cooling on the boundary-layer transition at supersonic speeds have been carried out in different types of experimental facilities by different methods and have led to a surprising variety of results. For wind tunnels, the situation as summarized by Morkovin[1] is that transition can be delayed by cooling at low Mach numbers: the transition Reynolds numbers increase with decreasing temperature.[2-5] At high Mach numbers, perhaps at $M>7$, the effect of cooling no longer exists. In some experiments transition reversal is observed[6-9] to occur at different temperatures. In our paper the transition reversal means that Re^* increases with decreasing T_w, then it decreases and then rises again at very low temperature.

A steady increase of Re^* with cooling is in good agreement with the trends predicted by linear hydrodynamic stability theory for the first mode of disturbances.[10,11] On the other hand, the higher modes are not damped by cooling.[12] A weak effect of cooling on the transition Reynolds numbers at high Mach numbers can be explained by excitation of these additional modes.[13] This assumption has been confirmed by direct experimental evidence.[14] Some theoretical attempts to explain the transition reversal phenomenon have been made[15] but analysis[16] has revealed their incorrectness.

Thus, there are now no theoretical grounds that could explain the transition reversal phenomenon even qualitatively. The well-known works only state one or another transition Reynolds number dependence on temperature and do not give any basis for theoretical modeling. The aim of the present work is the determination of the conditions under which the transition reversal occurs.

Apparatus and Methods

The experiments were performed in the supersonic wind tunnels of the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the USSR Academy of Sciences, T-325 and TC. The nozzle blocks and test sections of these tunnels were identical, but stilling chambers were different. The test section was 200 mm high, 200 mm wide, and 600 mm long. The investigations were conducted at Mach numbers $M=4$ and $M=3$ and unit Reynolds numbers $Re_l = 35\times10^6$ and 45×10^6/m.

All measurements were carried out on a stainless-steel flat plate with dimensions 350 mm long, 200 mm wide (wall to wall) and 9 mm thick, which was placed in the center of the test section under a zero angle of attack. The plate leading-edge thickness was approximately 0.1 mm with a leading-edge bevel angle of 20 deg.

The model surface-temperature ratio varied within the range of $0.3<T_w<1.0$. The plate was cooled internally with premixed liquid and gaseous nitrogen. Ten coolant passages were located normal to the flow. The cross section of each passage was 10×6 mm. For the present tests the cooling fluid was fed under pressure into passages on one side of the model and exhausted from the other into the wind tunnel stream through openings in the bottom of the model. The cross-sectional opening of each passage was changed during the tests to achieve uniform temperature of the cooled plate. Examples of the temperature distribution along the model surface are plotted in Fig. 1. The beginning of the cooled section was at a distance of 15 mm from the leading edge and was 125 mm long.

The model surface temperature was measured with 10 stainless-steel constantan thermocouples (one in each passage). The plate served as the common leg, while constantan leads, soldered flush to the plate surface, composed the other legs.

The two methods used to detect transition were: 1) location of maximum output from a hot-wire traversed near the surface, and 2) location of minimum and maximum pressure from a pitot tube traversed along the model surface. The pitot probe dimensions were 1.3×0.3 mm. A constant-current hot-wire anemometer was used to measure flow disturbances. The length of tungsten hot-wire was approximately 1.5 mm, the diameter was about 0.006 mm. The distance of the hot-wire from the plate surface was 0.25 mm.

Frost formation appeared on the model surface when the model was sufficiently cooled.[2-6] In the present tests cooling fluid was injected into the model after the tunnel was started

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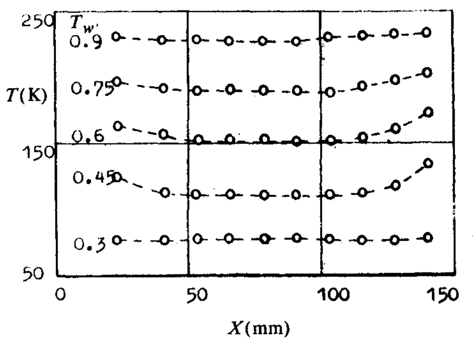

Fig. 1 Examples of temperature distribution along model surface.

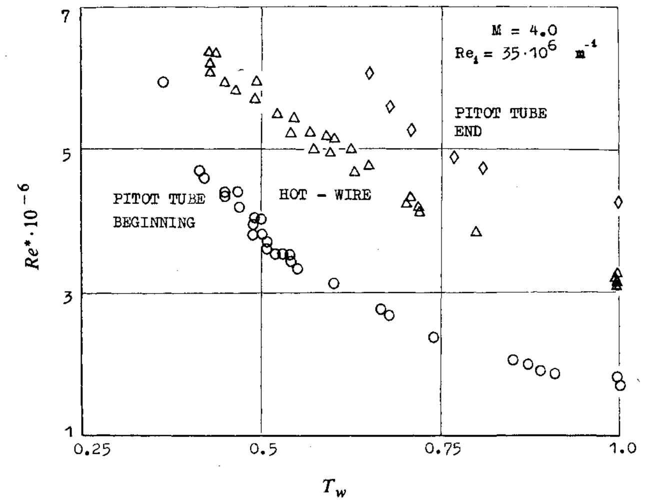

Fig. 2 Variation of transition Reynolds number with temperature factor for pitot probe test ($C = 0.21$ to 0.22) and hot-wire test ($C = 0.33$ to 0.35).

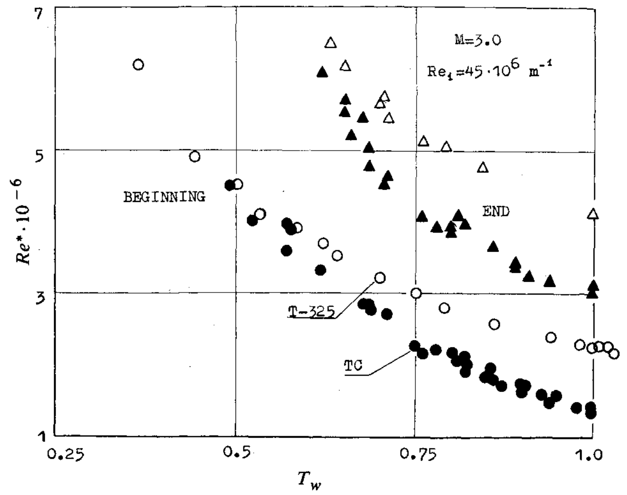

Fig. 3 Variation of transition Reynolds number with temperature factor for test in T-325 ($C = 0.21$ to 0.22) and test in TC ($C = 0.29$ to 0.32).

to prevent frost formation on the model surface. Nevertheless, in some experiments a slight frost appeared at extreme cooling. The temperature of the frost formation depended on the air humidity. In our study the wind-tunnel humidity was not measured. However, the effectiveness of air driers was sufficient to provide the frost-free model surface at $C \approx 0.2$ to 0.3 before drainage. The model was covered by a slight frost at humidity more than 0.3.

Results and Discussion

1) The first series of investigations was carried out in the wind tunnel T-325 at $M = 4$ and $Re_1 = 35 \times 10^6$/m. In these experiments the data obtained by different methods were compared. The results of measurements are plotted in Fig. 2. In both cases there was almost no frost on the model surface.

Special attention was paid to the temperature range $0.4 < T_w < 0.65$, within which the transition reversal was observed in some work.[6,7] In our experiments the transition Reynolds number increased steadily with decreasing temperature, in good agreement with conclusions of Refs. 2-5. This behavior of transition Reynolds number changing with T_w decreasing corresponds to the hypothesis that transition of laminar flow to a turbulent one is initiated by instability of the laminar flow with respect to small disturbances. Theoretical calculations of the stability characteristics[10-12, 17] show that the Reynolds number of the stability loss increases monotonously with surface cooling.

2) The second series of experiments was performed at $M = 3$ and $Re_1 = 45 \times 10^6$/m in different wind tunnels, T-325 and TC. All the measurements were carried out by the pitot probe.

Figure 3 shows the results of this study. There was almost no frost on the model surface during experiments. These results corroborate the conclusion about a steady increase of Re^* with T_w decreasing.

For a heat-insulated plate the transition Reynolds numbers obtained in TC are much less than numbers obtained in T-325. The influence of the cooling on the transition in TC tests has proved to be stronger. Re^* values obtained in these facilities draw closer to one another as the temperature decreases and coincide at low values of the surface temperature.

This fact can be explained as follows: wind tunnel T-325 is the modernization of TC in the sense that some measures had been taken in order to decrease the turbulence level in the test section (greater stilling chamber, damping screens, greater contraction, etc.). The studies carried out in Ref. 18 have shown that the turbulence in the test section of T-325 is determined by an acoustic mode, i.e., by sound radiated by a turbulent boundary layer on the walls of the nozzle and test section. The freestream vorticity fluctuations are much smaller than the sound mode in T-325.

These sound waves are significantly amplified by a supersonic boundary layer.[12,19] According to Ref. 12, transition in a supersonic boundary layer irradiated by sound is caused by vorticity waves of the Tollmien—Schlichting type which are generated by sound waves near the neutral stability curve. The cooling of the surface causes the motion of the neutral stability curve to higher Reynolds numbers and the disturbance amplification rates decrease, which leads to delay of transition. Apparently this mechanism of transition takes place in tests carried out in T-325.

It is known that surface cooling influences the interaction of sound and supersonic boundary layer weakly,[12] but it damps the waves of the Tollmien—Schlichting type to a considerable extent. Therefore, because Re^* values obtained in T-325 and TC coincide at low values of the surface temperature, we suppose, with good reason, that acoustic modes are close to each other in these tunnels. If they differed, they would show themselves in differences of Re^* at all T_w values. This supposition is also proved by the fact that the test sections and nozzle blocks are perfectly equal in T-325 and TC. The only difference between these wind tunnels is that the freestream vorticity fluctuations in TC are much bigger than they are in T-325. The vorticity and entropy modes generate the waves of the Tollmien—Schlichting type in the boundary layer near the leading edge of the model.[20] These disturbances, added to the disturbances generated by sound, cause an early transition on the heat-insulated plate during the study in TC. When cooling the model surface the neutral stability curve moves to higher Reynolds numbers. Vorticity disturbances generated at the leading edge reach the neutral stability

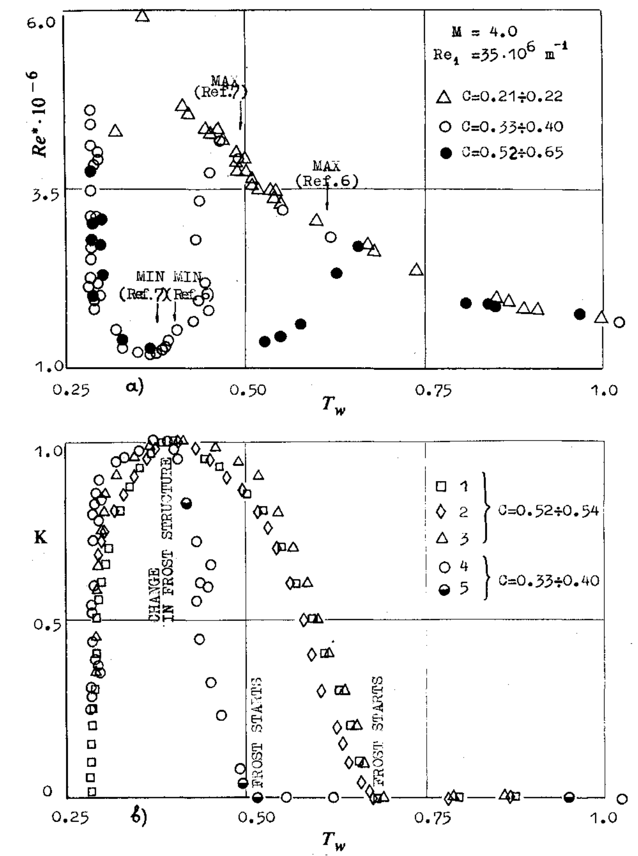

Fig. 4 Variation of a) Reynolds number of transition initiation and b) light radiation scattered on plate surface, with temperature factor and relative air humidity.

curve when they damp so that they become insignificant. The mechanism of transition typical for T-325 begins to prevail. Thus, in our experiments the surface cooling of the model plays a role of measures having been undertaken in T-325 designing for suppressing the vorticity and entropy modes. But in T-325 the vorticity and entropy modes are suppressed in the entire test section, while in our case they are suppressed only in the boundary layer of the model.

3) The next series of experiments was carried out in the wind tunnel T-325 at Mach number $M=4.0$ and $Re_l=35\times10^6$/m under conditions when the model was covered with a heavy frost ($C=0.52$ to 0.65) and when it was practically without it ($C=0.21$ to 0.22). All the measurements were carried out by the pitot probe.

Figure 4a shows the results of this study. Re^* values at $C=0.21$ to 0.22 are seen to increase steadily with decreasing T_w up to 0.35. A distinct transition reversal was observed on the model covered with a heavy frost ($C=0.52$ to 0.65).

Nonmonotonous dependence $Re^*=f(T_w)$ obtained in the present series is completely similar to results of Ref. 6. Positions of the minimum and maximum according to Ref. 6 are marked by arrows (Fig. 4a). It is noted in Ref. 6 that the model was covered with frost which perhaps was the cause of the transition reversal as stated in our work. In Refs. 6, 7, and 21 a rapid rise of Re^* values takes place at $T_w\approx0.3$.

In Ref. 9 the transition reversal was observed at $M=8.2$. The temperature factors for reversal minimum and maximum were approximately half those in Refs. 6 and 7; however, the recovery temperature was twice as much. In all the tests carried out in wind tunnels where a transition reversal was obtained, it appeared in the temperature range 80 to 190 K.

Due to the results of studies carried out in Refs. 4 and 22 on an influence of the single-element roughnesses on the transition with cooling in supersonic boundary layer, we suppose that the decrease in Re^* values with decreasing T_w within the range $0.4<T_w<0.65$ is caused by roughness created by frost. The increase in Re^* for $T_w<0.4$ on the model covered with frost may depend on the change of the frost structure and on its decreasing roughness. The following experiments give some arguments for this assumption.

4) At the Mach number $M=4.0$, $Re_l=35\times10^6$/m and $C=0.52$ to 0.54, i.e., under conditions when the transition reversal has been obtained, the scattering of light beam on the plate surface with growing frost has been explored. The measurements were performed in T-325.

The beam of laser LG-52 with wavelength $\lambda=6328$ Å was directed to the model surface in a pretransition region. The scattered radiation was collected by means of an object-glass on the photomultiplier cathode in front of which the interference $\lambda=6328$ Å filter and a slit were put. The model surface mainly mirrored the light. The intensity of scattered light increases by more than one order when frost appears. Therefore, the beginning of frost formation may be fixed accurately.

The value of the signal depends on the surface temperature. Figure 4b shows the results of three experiments of this series. The ordinate of this figure is $K=(K_w-K_0)/(K_{max}-K_0)$, where K_w is the signal of photomultiplier for a cooled plate, K_0 is the signal of photomultiplier for a heat-insulated plate, K_{max} is the maximum signal for a cooled model. Numerals 1 and 2 are the numerals of the experiments where the model was cooled from $T_w=1.0$ to $T_w=0.3$. Numeral 3 belongs to the experiment where the model with frost was heated from $T_w=0.3$ to $T_w=1.0$.

The value of K began to increase when frost appeared on the model, in our case at $T_w=0.67$ to 0.70. A further cooling was characterized by a sharp increase of K. Its maximum value was at $T_w=0.40$ to 0.41. With increasing cooling the value of the photomultiplier signal decreased, but the nature of its decrease was different and it apparently depended on the cooling rate. A sharp decrease of signal (in case 1 to $K\approx0$) took place at $T_w\approx0.3$. Similar dependence occurred in all the performed experiments.

The change of intensity of light scattering may be caused not only by varying of the frost roughness height, but by the form of crystals. These experiments show that some change of frost structure at $T_w\approx0.4$ occurs. Perhaps this is melting or change of structure analogous to the change of frost structure depending on time[23] (first the crystals grow, then the intervals between them are filled in by ice-air mixture, and then the surface becomes smooth). Possibly, some change of structure caused by the influence of some chemical transformations occurs. For example, the crystallization temperature of carbon dioxide steam at static pressure in the test section at $M=4.0$ corresponds to $T_w\approx0.43$, i.e., the temperature of the maximum photomultiplier signal. The change of intensity of light scattering correlates with the change of the transition Reynolds number (Fig. 4a) well.

5) A new series of experiments was carried out at $C=0.33$ to 0.40 where the transition measurements (Fig. 4a) were performed simultaneously with the scattering measurements (Fig. 4b, numeral 4). Every point in Fig. 4a corresponds to the point in Fig. 4b (except points 5, where transition was not measured). In this series of experiments the beginning of frost formation was delayed up to $T_w=0.51$ ($T=134$ K), and the beginning of transition reversal was delayed too. In other respects a picture analogous to that received by measuring at $C=0.5$ to 0.6 was obtained. The maximum photomultiplier signal was at $T_w=0.37$ to 0.39 ($T=96$ to 101 K). The transition reversal position obtained in this series corresponds to results of Ref. 7 (the minimum and maximum positions due to results of Ref. 7 are marked by arrows in Fig. 4a). It should be noted that for $C=0.2$ at $T_w=0.32$ one point fell out of the monotonous dependence. Probably, this is the beginning of a new transition reversal, which takes place at a very low temperature because of late appearance of frost (scattering was not measured in this case).

By comparing Figs. 4a and 4b, the data indicate that at $K=0$ Re^* values steadily increase with decreasing T_w. Re^*

decrease begins at $K \approx 0.2$. The minimum of Re^* occurs at $K = 1.0$. A sharp decrease of light scattering and a sharp increase of Re^* values are characteristic at $T_w = 0.3$.

Conclusions

The results obtained in our work by different experimental methods and in different facilities show that without frost formation on the model surface the transition Reynolds number monotonously increases with decreasing temperature. The transition reversal begins after frost appearance on the model. It takes place at the temperature of crystallization of water steam. Decreasing this temperature delays the beginning of transition reversal. The decrease of the transition Reynolds number is caused by frost roughness. A sharp increase of Re^* values at low values of T_w on the model with frost may be explained by the change of a general structure of frost (both frost crystallized from water steam and frost crystallized from other chemical compounds and elements steam, e.g., from steam of CO_2, included).

This explanation of the transition reversal appearance at a deep cooling of the surface may be true, at least for tests in wind tunnels. It is necessary to note that in some experiments carried out in ballistic ranges (e.g., see Ref. 24) non-monotonous dependence of the transition Reynolds number on temperature factor was obtained (first it was falling, and then it was the increase of Re^* with decreasing T_w). This dependence can be associated with transition reversal. However, test values of temperature of the model surface were rather high (in spite of rather low values of temperature in an environmental chamber), and the appearance of frost on the model was not available. The question on the transition reversal obtained in ballistic ranges is to be further studied.

Acknowledgments

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