EFFECT OF PERTURBED FLOW ON THE TRANSITION FROM THE SUPERSONIC LAMINAR BOUNDARY LAYER TO THE TURBULENT

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16. Abstract

Results of experimental studies on the effect of various factors on the transition of a supersonic boundary layer are discussed. It is shown that in supersonic wind tunnels, a significant effect on the transition of the boundary layer on a model is exerted by the scale of acoustic perturbations, which is proportional to the boundary layer displacement thickness of the working section. Experimental data obtained over a wide range of variation of flow parameters in aerodynamically similar test installations with different dimensions of the working section are generalized by means of a correlation parameter based on the displacement thickness.

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EFFECT OF PERTURBED FLOW ON THE TRANSITION FROM THE SUPERSONIC LAMINAR BOUNDARY LAYER TO THE TURBULENT

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Many investigations have been carried out in recent decades, /153** whose results permit a deeper understanding of the nature of the onset of turbulence. This very complex problem is often studied with the example of the development of instability and the transition from the laminar boundary layer to the turbulent, where the process proceeds most orderly. One of the particular cases of this kind is the transition boundary layer with the flow around a flat plate in wind tunnels. However, the wide use of wind tunnels for investigating the transition in the boundary layer does not exclude the effect on this process of the so-called tunnel effects, particularly the turbulence of the oncoming flow or perturbations of the tunnel walls generated by the turbulent boundary layer. This situation produces the well-known indeterminacy in the investigation of the effect of various factors on the transition process, which leads to contradictory interpretations of the results obtained by a number of investigators. Thus, for example, the problem of the effect on the transition in the boundary layer of some dimensional parameter, which according to the established terminology is

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called the unit Reynolds number $Re_1 = (U/\nu)_\infty$, m^{-1}, is discussed in the literature. Figure 1 presents as an illustration the most typical data obtained in various experimental installations (the numeration corresponds to the installation number in Table 1). A growth in the Reynolds number at the end of the transition region $Re_n^к$ is observed with increasing unit Reynolds numbers over a wide range of flow parameters $M_\infty = 3.7$; $Re_1 = (10 - 70) \cdot 10^6$ m^{-1}. Rather detailed surveys of the results of experimental

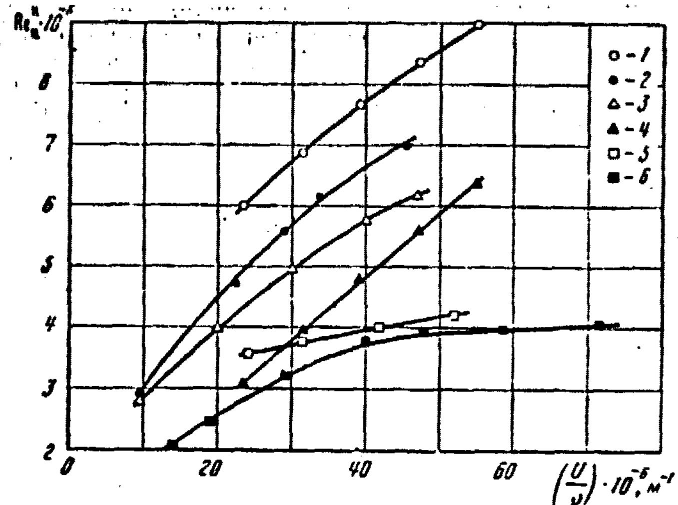

Figure 1

TABLE 1

No.	Installation	Working section dimen., m	Mach no.	$\left(\frac{U}{\nu}\right)_\infty \times 10^{-6}$ м$^{-1}$	Model	b, мм	Source
1	AEDC VKF-E	0,3×0,3	5,0	24,0—55,0	Cone	—	[3]
2	ONERA R′ och	0,135	6,9	10,0—45,0	Ogival cylind.	—	[18]
3	The same	0,135	6,9	10,0—45,0	Cone-cylinder	—	[18]
4	Ballistic trajectory	—	4,34	23,4—55,0	Cone	—	[17]
5	T-313	0,6×0,6	4,03	24,0—52,0	Wing profile	0,1	[8]
6	T-325	0,2×0,2	3,0	14,0—72,0	Flat plate	0—0,18	[7]
7	AEDC PWT-16S	4,88×4,88	3,0	1,0—4,35	Hollow cylin.	0—0,23	[3]
8	AEDC VKF-D	0,3×0,3	3,0	3,9—23,5	The same	0—0,09	[3]
9	NASA-Lewis	0,3×0,3	3,0	3,9—23,5	»	0	[16]
10	AEDC VKF-A	1,02×1,02	3,0	5,9—23,5	»	0—0,09	[3]
11	T-313	0,6×0,6	3,0	14,0—50,0	Flat plate	0—0,10	[7]
12	T-313	0,6×0,6	2,5	10,7—16,6	The same	0,10	[7]
13	T-313	0,6×0,6	3,5	10,8—15,7	»	0,10	[7]
14	T-313	0,6×0,6	4,0	24,0—60,0	»	0,10—0,15	[7]
15	T-313	0,6×0,6	5,0	10,8	»	0,10	[7]
16	T-313	0,6×0,6	6,0	10,7—11,4	»	0,10	[7]
17	T-325	0,2×0,2	2,5	14,0—40,0	»	0,10—0,18	[7]
18	T-325	0,2×0,2	3,5	14,0—60,0	»	0,10—0,18	[7]
19	T-325	0,2×0,2	4,0	20,0—50,0	»	0,05—0,18	[7]
20	AEDC YKF-A	1,02×1,02	5,0	5,9—23,5	Hollow cylin.	0,033—0,053	[3]

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investigations of this phenomenon are presented in [1, 2]. It should be noted only that the experimental data on this problem published at present is contradictory in nature, and it is not yet clear how to take into account or exclude the effect of this parameter.

Systematic investigations of the phenomenon of the boundary layer transition both to study the effect of the variety of factors as well as to reveal the nature of the effect of the unit Reynolds number on the transition in the boundary layer were begun in 1970 at ITPM SO AN SSSR by the initiative and under the direct supervision of V. V. Struminskiy. The combined effect of a number of factors on the transition in the boundary layer and the complexity of isolating one of them in pure form makes very difficult the analysis of the available data, particularly if they are obtained in different installations and even by different methods.

The majority of published experimental data has been obtained with the use of methods for measuring the transition based on the determination of the distribution of such quantities as the heat /154
flow, surface friction and total pressure. Works [3, 4] are devoted to the problem of the convergence of these methods. A comparison of two methods for measuring the transition region based on the determination of the distribution of the total pressure P_0' and the mean-square stress of a thermoanemometer sensor e* revealed a signi- /155
ficant divergence of the typical points of these distributions, which can be explained by the different sensitivity of the methods to the processes occurring in the transition region. While the position of the extrema in the first case is determined by the sensitivity to the rearrangement of the velocity profile in the boundary layer, the maximum of the mean-square stress distribution corresponds to the highest frequency of the passage of turbulent spots at the given point. One can assume that the maximum in the distribution of P_0' corresponds to intermittance coefficients close to $\gamma = 0.75$, whereas the maximum value of e* corresponds to $\gamma = 0.5$. Thus, comparison of transition data obtained by different methods is not always correct and leads to significant scatter in the

experimental data without referring to the essence of the phenomenon. The experimental results presented here were obtained from the position of the maximum on the distribution curve for the total pressure, the distance to which from the leading edge was taken as the end of the transition region.

On the other hand, to study the regularities of the effect of individual factors on the transition, it is advisable to carry out systematic investigations in experimental installations with thoroughly studied flow characteristics. /1

The results of the experimental investigations to be considered were obtained in the supersonic wind tunnels of the ITPM SO AN SSSR T-313 and T-325, in which the flow characteristics have been thoroughly studied [5, 6]. Special measures were undertaken in the T-325 to reduce the level of turbulence in the oncoming flow, as a result of which there is a rather low level of all three modes of perturbations at the inlet to the supersonic nozzle: pressure pulsations do not exceed 90 dB; temperature fluctuations — 0.02%; longitudinal component of velocity pulsations — 0.03%. With such a low level of turbulence available in the forechamber, one can assume that only perturbations generated in the working section have an effect on the transition in the boundary layer of the model. Thus, of the enumerated factors affecting the transition in the boundary layer, the effects of truncation of the leading edge of the model, the Mach number and the unit Reynolds number, which was varied only due to the change in pressure in the forechamber in our case, are the most interrelated and difficult to separate because of this.

The effect of the dimensions of the working section on the position of the boundary layer transition was detected for flow around a hollow cylinder in [3]. The authors of this work expressed the assumption that the dependence of the transition process on the unit Reynolds number can be explained by aerodynamic noise radiated by the turbulent boundary layer of the tunnel walls. Figure 2 presents the results of these investigations for a fixed truncation of the leading edge of the model of $b \simeq 0.1$ mm as compared with the data of [4]. Curves 1 - 5 correspond to experiments in wind tunnels denoted in Table 1 by the numbers 7, 10, 5, 8, and 6, respectively. After expanding the range of the variation in the unit Reynolds number, the authors of [4] not only confirmed the hypothesis expressed in [3] with their results, but also drew attention to the fact that for values of $Re_1 > 40 \cdot 10^6$ m^{-1}, the effect of this parameter on the transition weakened significantly or ceased altogether. This effect was displayed previously in wind tunnels with large dimensions of the working section and at small values of the Mach number M_∞, which is also illustrated in Figure 3, where

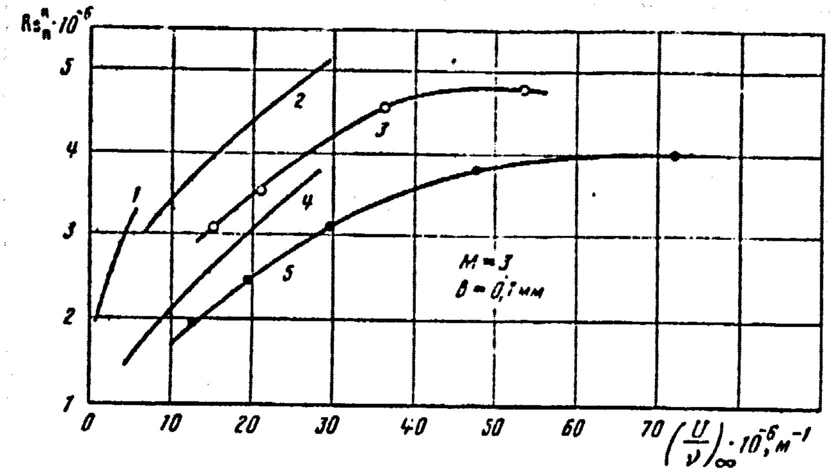

Figure 2

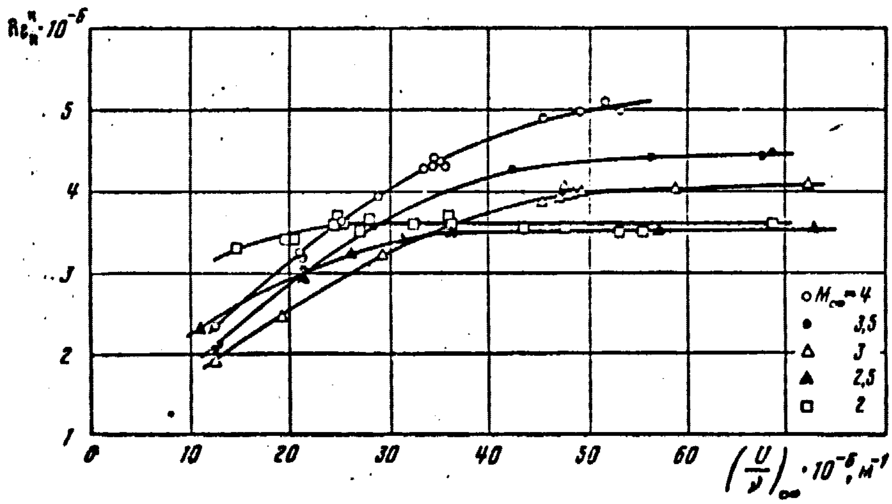

Figure 3

the results of the experiments of [7] on the transition on a flat plate over a wide range of M_∞ and Re_1 are presented. It should be noted that the dependence $Re_n^*(M_\infty)$ has a clearly expressed minimum, whose position shifts toward smaller M_∞ with increasing unit Reynolds number (the dashed curve in Figure 4).

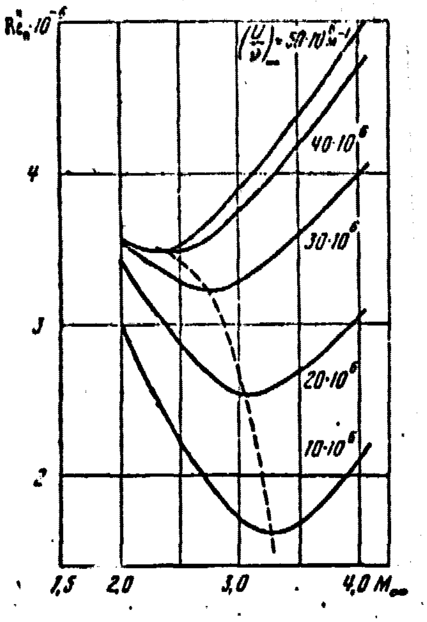

Figure 4

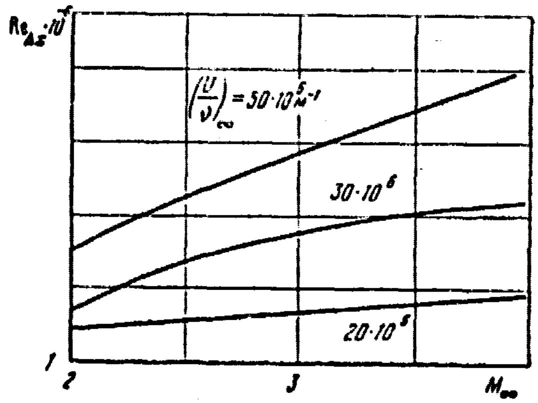

Figure 5

The results of these experiments also indicate that the effect of increasing M_∞ leads to an increase in the extent of the transition region and to an increase in the Reynolds number $Re_{\Delta x}$, determined along the length of the transition region (Figure 5).

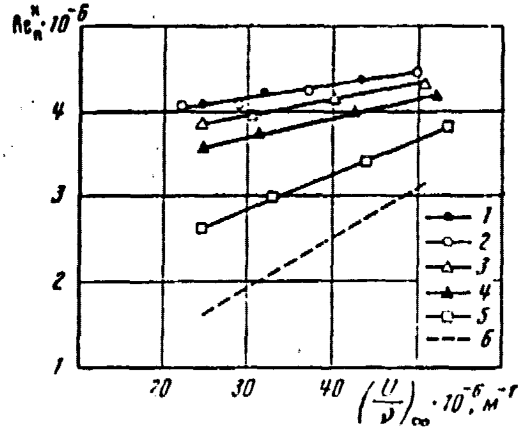

Figure 6

1 — b = 1 мм; 2 — 0,5 мм; 3 — 0,3 мм; 4 — 0,2 мм; 5 — 0,1 мм; 6 — b = 0 (extrapolation)

The effect of the unit Reynolds number and the truncation of the leading edge on the boundary layer transition for flow around a parabolic profile with a relative thickness $\bar{c} = 0.05$ is presented in Figure 6 for $M_\infty = 4$. These data indicate the significant increase in Re_n^* with increasing thickness of the leading edge b from 0.1 to 1 mm. The growth rate of the

Reynolds number of the transition decreases with increasing b. The investigations of [8] showed that truncation of the leading edge leads to the formation of a favorable static pressure gradient at the surface of the wing, and consequently to significant decrease in the Reynolds number at the edge of the boundary layer, which aids stabilization of the laminar boundary layer and broadening of the extent of the transition region. The degree of the effect of truncation of the leading edge on the transition is not free of the effect of other factors. Although the nature of the effects of certain factors on the boundary layer transition (the Mach number and Re_1, the thickness and sweepback of the leading edge, perturbations of the free flow, etc.) can differ, their combined effect, as a rule, is limited to a shift of the transition region downstream. This is also confirmed by the results of the investigations of [9], in which particular attention was given the combined effect of the sweepback angle of the leading edge of the wing profile and the unit Reynolds number. Figure 7 presents the values of Re_n^k depending on Re_1 for different sweepback angles for χ at M = 3 and 4. Even in this case, a systematic increase in Re_n^k with increasing unit Reynolds number is observed, while the tendency of the growth of Re_n^k weakens with increasing χ. /157 /158

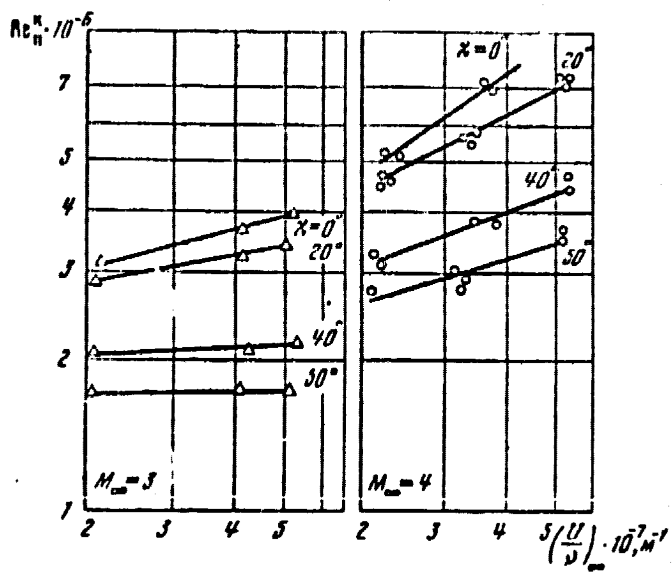

Figure 7

Among the set of factors affecting the boundary layer transition, the most difficult to monitor is the effect of the unit Reynolds number, which in accordance with the hypothesis expressed in [3] is caused by acoustic perturbations generated by the turbulent boundary layer at the walls of the working sections of the wind tunnel. Figure 8 presents the results of the measurement of the mean-square pressure

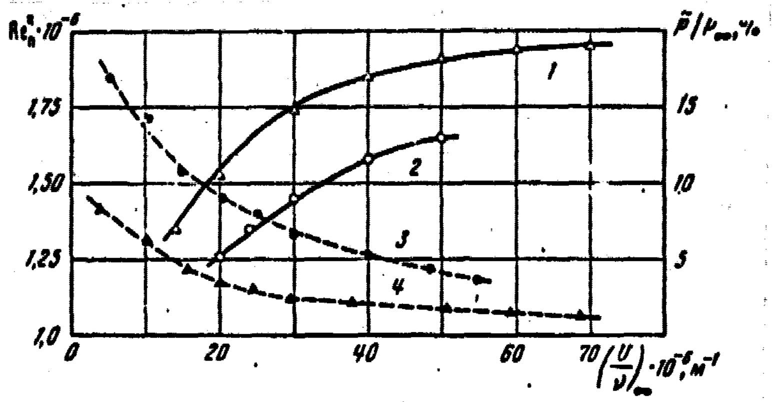

Figure 8

1 — $Re_{п}^{к}$, $M_{\infty} = 4$; 2 — $Re_{п}^{к}$, $M_{\infty} = 3$; 3 — $\tilde{p}/p_{\infty}$, $M_{\infty} = 3$; 4 — $\tilde{p}/p_{\infty}$, $M_{\infty} = 4$

pulsations at the walls of the working section of the T-325 wind tunnel at M = 3 and 4 over a wide range of variation of the unit Reynolds number. They are compared with the data on the boundary layer transition at a flat plate, which were obtained in this same installation. It is seen that here is a qualitative correspondence in the nature of the change in the transition Reynolds number and the magnitude of the pressure pulsations. With increasing unit Reynolds number, the level of acoustic perturbations generated by the turbulent boundary layer at the walls of the working section decreases and there is a simultaneous increase in the transition Reynolds number. The change in $Re_{п}^{к}$ practically ceases where the intensity of these perturbations depend weakly on Re_1. /159

An analogous pattern is also observed in the T-313 wind tunnel with larger dimensions of the working section. This situation is the basis for assuming that the change in the transition Reynolds number with increasing Re_1 is due mainly to the generation of acoustic perturbations by the turbulent boundary layer at the walls of the tunnel. The most convincing proof of this assumption would be data on the transition obtained in wind tunnels with a laminar boundary layer at the walls of the working section.

It was shown in [3, 4] that, other conditions being equal, the transition Reynolds number also depends on the dimensions of the working section of geometrically similar wind tunnels. This can be related to the fact that the scale of the perturbations in each installation is proportional to its dimensions and, as follows from the theory of G. Taylor [10], the transition is determined not only by the intensity, but also the scale of the perturbations in the external flow.

Moreover, it was shown in [11] that besides the usual factors affecting the transition, significant additional parameters are the dimensionless frequency $\beta\nu/U^2$ or the wavelength $U\lambda/\nu$ and orientation θ, which characterize the perturbation spectrum. Thus, it is necessary to take into account the scale and spectral composition of the perturbations in analyzing experimental data on the transition.

However, there is no available information on the spectral characteristics of the flow perturbations in any of the supersonic installations. Nonetheless, this deficiency in information does not eliminate the necessity of systematizing and generalizing the available experimental data. When perturbations generated by the turbulent boundary layer of the tunnel walls predominate, one can assume that the scale of these perturbations is proportional to the displacement thickness δ^* of this boundary layer. We introduce the correlation parameter $(Re_n^{\kappa})_0/(Re^*)^n$, where $(Re_n^{\kappa})_0$ is the Reynolds number at the end of the transition region in the boundary layer of a flat plate with a sharp leading edge; Re^* is the Reynolds number along the separation thickness of the boundary layer of the walls of the working section of the tunnel.

Statistical analysis of the results of transition measurements [12] has shown that the scatter of experimental values does not exceed ± 15% of n = 0.25. Figure 9 presents transition data obtained in six wind tunnels at M = 3 and b = 0. The numeration corresponds to experiments carried out in the wind tunnels indicated in Table 1 by the numbers 6 - 11, respectively. It is seen that the introduction of this correlation parameter permits generalizing the results of measurements in different tunnels and representing them in a form independent of the unit Reynolds number. Consequently,

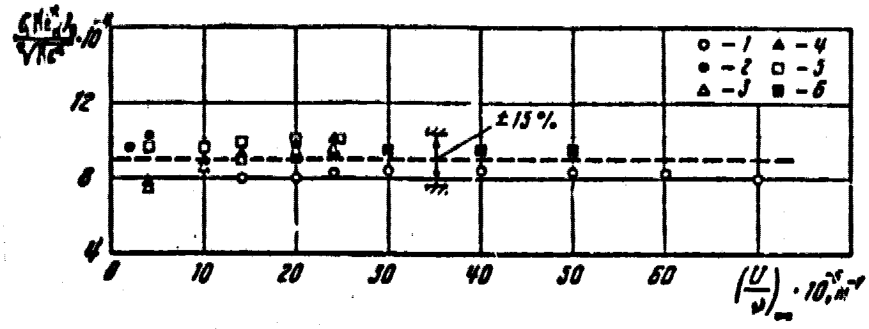

Figure 9

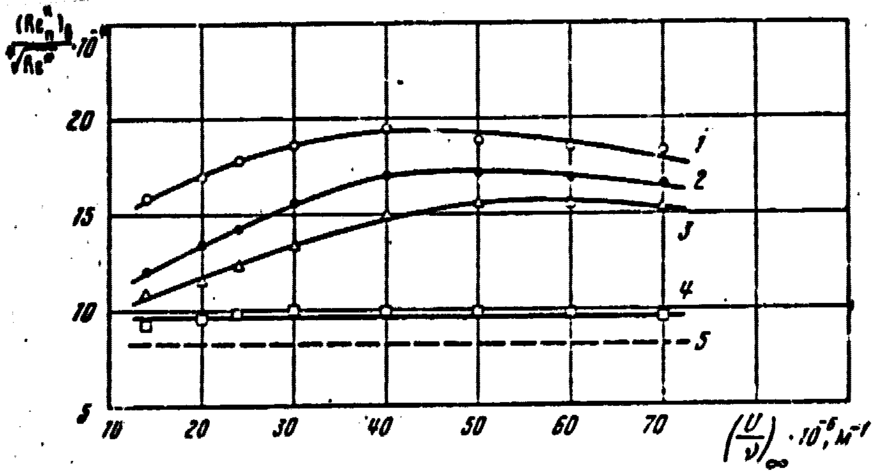

Figure 10

after eliminating the effect of the truncation of the leading edge /161
on the transition by extrapolation to b = 0, one can also take into account the effect of perturbations generated by the boundary layer of the tunnel walls, or in the prevailing terminology, the effect of the unit Reynolds number. However, if data on the transition in the boundary layer of a plate with finite thickness of the leading edge are represented with the help of this parameter, the effect of the unit Reynolds number appears nonetheless for values of b > 0.02 mm. This is easily seen in Figure 10, where the dependence $\mathrm{Re}_n^{*}/\sqrt[4]{\mathrm{Re}^{*}} = F[(U/\nu)_{\infty}; b]$ is presented for M = 3 (curves 1 - 5 correspond to the values b = 0.18, 0.10, 0.05, 0.02, and 0 mm). The curve corresponding to b = 0 was obtained by extrapolation. An analogous dependence was also observed for M = 4. One can assume that acoustic perturbations generated by the turbulent boundary layer of the walls of the working section and the perturbations produced by the leading

edge of the model, although different in origin, interact with each other. The presented dependence is the result of this interaction.

Moreover, elimination of the effect of the truncation of the leading edge by extrapolation to b = 0 requires in each case a large number of experiments with variation of the value of b. Thus, it is advisable to generalize the available experimental data in the form of the dependence $(\mathrm{Re}_n^{*})_b/\sqrt[4]{\mathrm{Re}^*} = f(\mathrm{Re}_b)$, where $\mathrm{Re}_b = \mathrm{Re}_1 b$. More than 100 experiments analyzed in this manner are presented in Figure 11 (the numeration corresponds to the tunnel numbers in Table 1). The results obtained in different wind tunnels on the boundary layer transition at a flat plate are generalized with a spread of ± 15% over a rather wide range of flow parameters. This scatter of the data can evidently be considered satisfactory if one keeps in mind that the presented transition data were obtained by various methods.

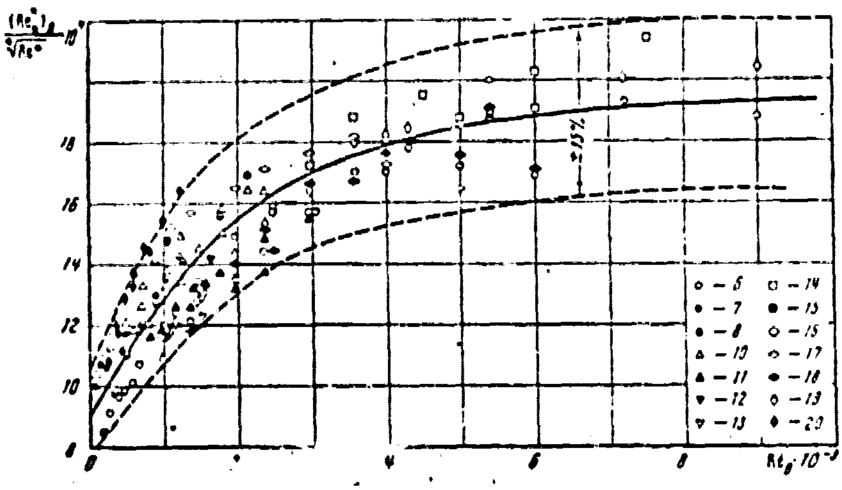

Figure 11

The approximation of this empirical dependence permits predicting the position of the transition region in the boundary layer for the indicated conditions in the investigated range of parameters. The inconvenience is only that it is necessary to know the characteristics of the boundary layer at the walls of the working section of the tunnel.

Let us consider as an illustration two examples of the application of the proposed correlation parameter in analyzing experimental data on the transition of a compressible boundary layer. Figure 12 presents experimental data on the extent of the region of the boundary layer transition which is formed in the vicinity of the line of intersection of flat faces at a right angle [13]. The use of the correlation parameter in analyzing data obtained over some range of the unit Reynolds number permitted eliminating the effect of acoustic perturbations on the transition in the case of interaction of the boundary layers with flow around the dihedral angle. The transition region developed in the interaction zone from the leading edge of the angle line to values corresponding to the extent of the transition region with flow around a flat plate under comparable conditions.

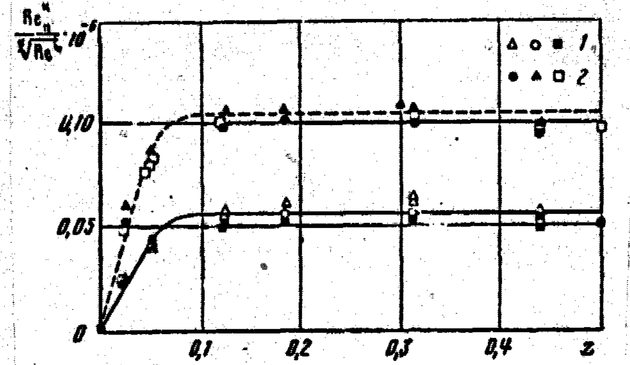

Figure 12

1 - beginning of transition;
2 - end of transition

In order to model the structure of the boundary layer under laboratory conditions more precisely and also to compare experimental data obtained in different installations more correctly, the necessity often arises of creating turbulence of the boundary layer at the models. In connection with this, the effectiveness of different agitators has been studied by a number of investigators [14 - 16]. /162
However, comparison of the available data obtained in various installations, as a rule, did not lead to acceptable results because of the uncontrollable effect of acoustic perturoations generated by the turbulent boundary layer of the walls of the working section. Figure 13 presents the results of experimental data on investigation of the effectiveness of several types of agitators, which were obtained in various wind tunnels and are analyzed with the help of the proposed correlation parameter. The numeration in the figure

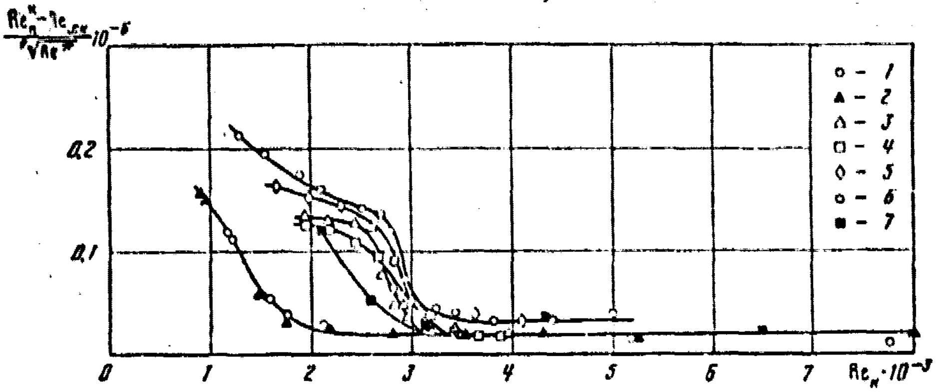

Figure 13

corresponds to the wind tunnel numbers in Table 2. The agitator effectiveness is determined here by the dependence of the Reynolds number along the distance between the end of the transition and the position of the agitator ($Re_n^{H} - Re_{xk}$) on the Reynolds number over its height Re_k. For the types of agitators under consideration, the transition in the boundary layer approaches the agitator directly for $Re_k > 3000$ ($k/\delta^* > 2$), and a further increase in its height does not have a significant effect on the position of the transition.

TABLE 2

No.	Tunnel	Agitator	k, мм	x_k, мм	M_∞	$\left(\frac{U}{\nu}\right)_\infty \times 10^{-4}$	Model	Source
1	T-313 (0,6 м)	Sand	~	3,0	3,0	27	Plate	[14]
2	T-325 (0,2 м)	»	~	3,0	3,0	27	»	[14]
3	IPL (0,508 м)	Spheres	0,253	165,0	2,81	~	Cone	[15]
4	IPL (0,508 м)	»	0,251	139,0	2,81	~	»	[15]
5	AEDC (0,305 м)	»	0,254	125,2	3,0	~	»	[16]
6	AEDC (1,018 м)	»	0,254	124,5	3,0	~	»	[16]
7	AEDC (0,305 м)	»	0,381	124,7	3,0	~	»	[16]

Taking into account the effect of acoustic perturbations with the help of the correlation parameter has permitted generalizing the data of various authors and revealing the degree of effectiveness of various types of agitators. One can isolate two regions:
a) the region $Re_k < 3000$, where the type of agitator and also the truncation of the leading edge of the model affect the transition;

b) the region $Re_k > 3000$, where the effect of the agitator is exclusive. This situation has particular value in selecting an effective boundary layer agitator without significantly increasing the wave impedance.

Thus, the presented interpretation of data on the transition in a supersonic boundary layer permits assuming that the so-called unit Reynolds number effect is a consequence of acoustic perturbations whose source is the turbulent boundary layer formed at the walls of the working section of the wind tunnel. Thus, their effect on the flow in the vicinity of the model must be taken into account in analyzing and comparing experimental data. It should be kept in /163
mind that the effect of these perturbations extend not only to the transition but also to the boundary layer separation. Limited data on this problem are contained in the survey [2]. Detailed investigation of this problem and also confirmation of the possibility of using the proposed correlation parameter to eliminate the effect of the unit Reynolds number on detached flow are necessary.

The experimental data were obtained along with V. M. Kornilov, V. V. Chernykh, and V.G. Pridakov, to whom the author expresses his appreciation.

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