GENERAL CHARACTERISTICS OF SUPERSONIC VORTICAL BOUNDARY LAYERS

M. G. Morozov

UDC 532.526:532.527

Results are shown of a study concerning the velocity profile, the velocity of discrete vortices, and the thickness of supersonic vortical boundary layers. Measurements were made with the Mach number M = 1.7-3.0 and with the Reynolds number Re = $4.4 \cdot 10^5$-$4 \cdot 10^7$.

1. The study of supersonic air streams around a flat surface in [1] has revealed that in certain cases the boundary layer breaks up during attachment and curls into a regular sequence of vortex trains forming a vortical boundary layer.

An overall picture of such boundary layers can be obtained by means of instant schlieren photographs as those shown in Fig. 1. One sees here a distinct periodic structure and a rapidly increasing thickness of the boundary layer after attachment behind the rectangular separation zone. An analysis of the schlieren photographs showing the flow past notches of various depths reveals a relation between the scale dimension of generated discrete vortices and the notch depth. Many photographs of two-dimensional models in a stream with the Mach number M = 1.7-2.0 and with the Reynolds number varying over a wide range at the separation point have been evaluated, showing that the vortex pitch l_v increases with increasing notch length L (Fig. 2). On the same diagram are also plotted data for a three-dimensional model with axial symmetry. As L increased, the vortices appeared more blurred on the photographs. At L = 70 cm they were only faintly noticeable, while at L = 80 mm there were no vortices recorded at all and the boundary layer became more or less homogeneous. It is evident, according to Fig. 2, that, although l_v clearly increases with increasing L, there is no definite relation between the two dimensions. No relation between l_v and the Reynolds number has been detected either, although the latter was varied in those experiments through almost two orders of magnitude. This, together with the range of test points (range of variation) marked by vertical segments in Fig. 2, indicates nevertheless that the process of vortex formation is inherently unstable. The following relation, however, may be considered valid to the first approximation:

$$l_v = pL,$$

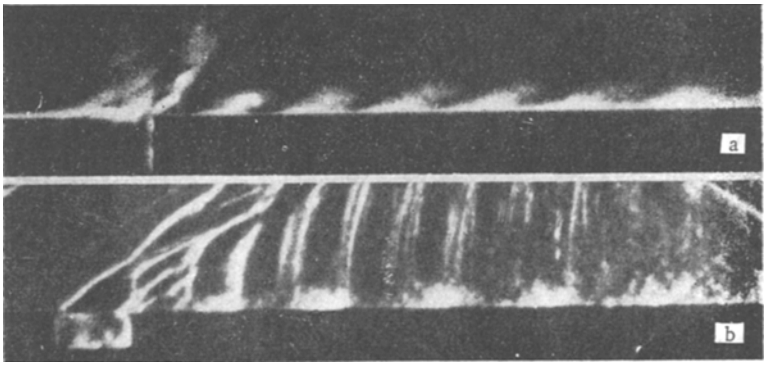

Fig. 1. Schlieren photographs of a vortical boundary layer with M = 1.8: a) horizontal knife edge; b) vertical knife edge.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 22, No. 5, pp. 885-889, May, 1972. Original article submitted June 18, 1971.

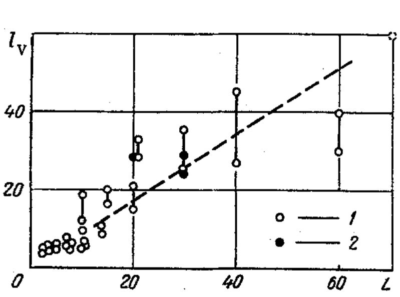

Fig. 2

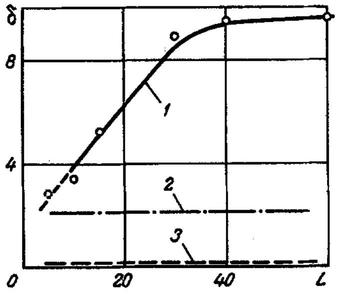

Fig. 3

Fig. 2. Vortex pitch l_v (mm) as a function of the notch length L (mm): 1) two-dimensional model; 2) three-dimensional model with axial symmetry.

Fig. 3. Boundary-layer thickness δ (mm) as a function of the notch length L (mm): 1) experiment; 2) turbulent boundary layer; 3) laminar boundary layer, calculated.

with p denoting the vortex pitch (somewhere between 0.5 and 1.9 in those experiments). Further studies may possibly yield, instead of p, a criterial dimensionless parameter similar to the Strouhal number.

An attempt was made to interpret the dependence of the vortex pitch on the Mach number. With l_v depending on the length of the separation zone (notch), the latter was held constant for the purpose of this analysis.

As the Mach number increased, the vortices became blurred and then hardly noticeable at $M \approx 2.5$. When $M > 3$, the vortices had almost disappeared entirely. A closer analysis has shown that no basic relation seems to exist between the scale dimension of vortices and the Mach number (or the Reynolds number) within the range of values covered in the experiment, regardless of the scatter of test points in Fig. 2, and that, in line with the earlier comment, this scatter must rather be attributed to the inherent instability of the process.

It has been established that vortical boundary layers break up rather fast. Under the influence of viscous forces over a distance of (7-12) l_v from the attachment edge, the vortices become blurred and the periodicity of the boundary-layer structure vanishes.

2. As the length of the separation zone increases, the thickness of a laminar boundary layer behind the separation zone increases more rapidly than its thickness at the front edge. In order to study this phenomenon and also to get a general idea about the average-velocity profiles, measurements were made from which total-pressure profiles in such boundary layers could be plotted. Naturally, such an experiment made using a total-pressure micronozzle was not concerned with the structural periodicity of the boundary layer and with the taper of the stream.

Total-pressure profiles were obtained at several sections along the stream, on the basis of models with various notch lengths L. At the separation point the boundary layer was laminar with $Re = 2.4 \cdot 10^6$. The Mach number of the oncoming stream remained within the 1.74-1.83 limits.

Any probe near the wall will indicate a pressure different from the actual total pressure. The problem concerning the effect of wall proximity on the readings of a Pitot tube has not yet been solved properly to this very day. Consequently, the analysis of our data was based on the still generally acceptable assumption that at a distance from the wall equal to one and a half the height of the probe tip the measured pressure begins to correspond to the actual total pressure.

The total-pressure profiles thus obtained were useful for a quite accurate determination of the boundary-layer thickness δ as well as of its variation with varying notch length L and with varying distance along the plate. The boundary-layer thickness was defined as the distance from the wall where the velocity differed by 1% from the velocity in the main stream. The results of these measurements are shown in Fig. 3, where the boundary-layer thickness has been plotted as a function of the notch length over a distance b = 93-100 mm from the separation point.

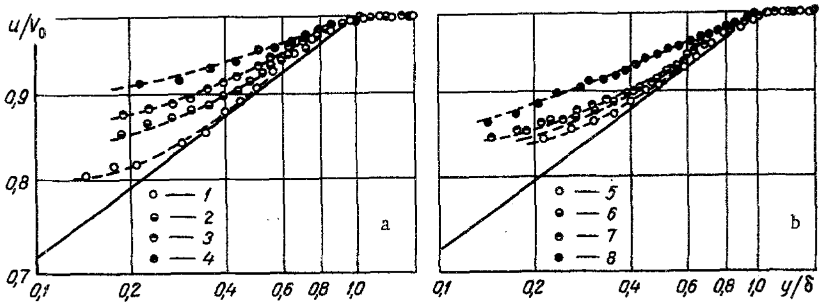

Fig. 4. Velocity profiles for $x \approx 35$ mm (a) and for L = 40 mm (b): 1) L = 60 mm; 2) 40 mm; 3) 30 mm; 4) 16 mm; 5) b = 55 mm; 6) 68.5 mm; 7) 93.5 mm; 8) 123.8 mm, according to the 1/7th-power law (solid line).

One observes here not only a rapid initial rise of δ with increasing L but also a large excess thickness of the developed vortical boundary layer over the thickness of a corresponding boundary layer which would have existed under similar circumstances at a smooth plate without notches (lines 2 and 3 in Fig. 3). According to this diagram, at L > 40 mm the vortical boundary layer is approximately 4.5 time thicker than a corresponding turbulent boundary layer and 30 times thicker than a corresponding laminar boundary layer. This phenomenon can be interpreted as a result of the curling of the boundary layer into discrete vortices. The noted initial rising of δ with the distance from the back edge is explained by the quite rapid departure of generated vortices from the wall. We note that in the other study concerned with a thick boundary layer at the separation point, the schlieren photographs did not indicate such a rapid rise of δ behind the separation zone.

The characteristic velocity profiles shown in Fig. 4 have been calculated from the total-pressure profiles, assuming a smooth variation of the stagnation temperature from the temperature of restoration at the wall to the temperature of stagnation in the free stream. The vertical axis represents the ratio of velocity u to velocity V_0 of the unperturbed stream, the horizontal axis represents the ratio of the vertical coordinate y to the boundary-layer thickness. The profiles shown in Fig. 4a apply to the section at an approximately constant distance from the back edge of the notch ($x \approx 35$ mm) under varying horizontal dimensions of the separation zone.

The profiles in Fig. 4b apply to sections at different distances b from the front edge of the L = 40 mm notch. For comparison, the solid lines on the diagram indicate the profile according to the 1/7th-power law.

All profiles appear "flatter" than the 1/7th-power profiles of a turbulent boundary layer. Another feature here is characteristic of all the boundary layers covered in this study: the velocity profiles become "flatter" farther away from the attachment point. This indicates that the stream is accelerated over a definite distance near the wall after attachment.

The hypothetical affinity between velocity profiles of equal distances from the attachment point was also verified, by measuring this distance with L as the scale factor. No perfect identicity but a definite similarity of such profiles has been established by this procedure.

According to the measurements, ths stream is accelerated at the wall through a distance of approximately 3L from the back edge. The profile then becomes steady. On first thought, an acceleration of the stream seems to violate the theory that some deceleration should occur after attachment of the free boundary layer. If one remembers that at a solid wall the velocity of a vortex train relative to the ambient medium is proportional to the vortex intensity, however, then the observed acceleration becomes understandable. Under the influence of viscous forces, indeed, the intensity of vortices generated during attachment decreases and thus their relative velocity also decreases. Moreover, the oncoming stream carries them away at an increasing speed and this results in an accelerated flow at the wall. The same viscous forces at the end of the acceleration zone impede a full stabilization of the velocity [2].

3. Among the most important parameters characterizing vortex trains in a stream is the ratio of their velocity V_v to the oncoming stream velocity V_0. The velocity of a vortex train (the absolute velocity of vortices along the plate) was in each case found by evaluating many kinematograms of the boundary layers shot at a rate of $2.5 \cdot 10^5$ frames per second.

The test data for $M \approx 1.8$ and $Re \approx 2.4 \cdot 10^6$ are marked by a wide scatter of values. The range of scatter here covers also the range of values for $M = 2.15$-2.30 and the results of velocity measurements at $M = 2.5$ with a turbulent boundary layer ($Re \approx 4 \cdot 10^7$) at the separation point. The range of test values overlaps the range of measurement error due to the imprecise separate typical features of photographed vortices and due to the tolerance limits in the shutter timing. In view of this, one may consider the scatter of values to be inherent to the very phenomenon of a vortical boundary layer. With varying flow conditions such as the size and the shape of notches, the Reynolds number at the separation point, the thickness of the boundary layer, and the Mach number of the free stream, however, the bulk of all test points lies within $V_V/V_0 = 0.8$-0.9, even though the total range is wider and equal to 0.7-0.95. With such a range of values, of course, it is impossible to detect an acceleration of the stream along the initial zone as indicated in the velocity profiles. This acceleration can, apparently, be detected by measurement and statistical evaluation of the local vortex velocities. The values of V_V obtained by a processing of kinematograms represent values averaged over a rather long distance of vortex travel.

A comparison of the velocity profiles with the velocities V_V representing the intrinsic velocities of vortex centers will make it possible to approximately estimate the distance h from a vortex center to the wall and then to establish another vortex-train parameter, namely the ratio of vortex pitch to the distance from the wall: $l_* = l_V/h$. If the value $V_V/V_0 = 0.85$ is taken as the average for this ratio, then $h/\delta = 0.35$-0.10 or even less according to Fig. 4. (The presence of a viscous sublayer is disregarded). Knowing l_V and the corresponding values of δ, one finds the approximate range $l_* = 10$-40 or above. On account of the difficulties in determining h, it is not possible at this time to find the exact value of l_*.

It is to be noted that in this study we have considered the average characteristics of vortical boundary layers. The true pattern is much more complicated because of the flow instability.

NOTATION

M	is the Mach number;
Re	is the Reynolds number;
L	is the length of separation zone (of notch);
V_0	is the velocity of free stream;
V_V	is the velocity of vortices along the surface;
l_V	is the vortex pitch;
h	is the distance from vortex center to wall;
b	is the distance from the front edge of the notch to the test section;
$p = l_V/L$	is the vortex pitch referred to notch length;
x	is the distance from the back edge of the notch to the test section;
y	is the space coordinate;
u	is the velocity coordinate;
δ	is the boundary-layer thickness.

LITERATURE CITED

1. M. G. Morozov, Izv. Akad. Nauk SSSR, Mekhan. i Mashinostr., No. 2, 42 (1960).
2. M. G. Morozov, Inzh. Fiz. Zh., 20, No. 5 (1971).