EXPERIMENTAL INVESTIGATION OF THE THREE-DIMENSIONAL STRUCTURE OF DETACHED FLOW IN AN AXISYMMETRIC ANNULAR DIFFUSOR

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It is shown experimentally that stream detachment in an annular diffusor has a stabilized, three-dimensional, periodic structure.

1. It is well known that detachment of the boundary layer is often accompanied by three-dimensional effects. Many papers have appeared in recent years in which phenomena of such a type are described, when the flow loses two-dimensional properties in the wall zone owing to stream detachment and becomes three-dimensional. Most of them are devoted to a description of various examples of external streamline flow the detachment and subsequent attachment of the stream: flow of a subsonic stream over a concave curved wall, flow over a body with a front stagnation point, flow with closed detached zones. In all the cases enumerated above, three-dimensional effects were discovered, characterized by the formation in the wall zone of Taylor–Görtler vortices the axes of which are parallel to the main stream while the size is of the same order as the thickness of the boundary layer. A similar system of periodically spaced (in the wall zone) vortices, comparable with the boundary layer in thickness, was discovered by the authors of [1], in which the results of an investigation of flow over the outer shell of the mixing chamber of an ejector in the zone of stream attachment at a zero ejection coefficient are described. This effect is a consequence of the loss of stability by the boundary layer as it turns abruptly as a result of the disruption of equilibrium between centrifugal forces and pressure forces.

2. Measurements of total pressure made along the circumference and over the height of the channel showed that with subsonic axisymmetric flow at the entrance to a diffusor with a large expansion angle, the stream at the exit from it has a three-dimensional, stabilized, periodic structure [2]. These properties of the detached flow were subsequently studied.

3. We investigated the flow in two axisymmetric annular diffusors with the same ratio of areas, $n = F_{ex}/F_{en} = 2.0$, and an expansion angle $\Psi = 16°$ at the periphery, differing in the value of the radius of the transition from the cylinder to the cone at the periphery of the entrance: For the first diffusor R_{per} = 40 mm (diffusor I), while for the second R_{per} = 288 mm (diffusor II).

The experiments were conducted on the installation, a diagram of which is given in Fig. 1. Range of variation of the Reynolds numbers $Re = \rho u l/\nu$: from $Re_{min} = 9.1 \cdot 10^5$ (for λ_{en} = 0.3) to $Re_{maxI} = 2.72 \cdot 10^6$ ($\lambda_{max} = 0.9$) for diffusor I and to $Re_{maxII} = 2.87 \cdot 10^6$ ($\lambda_{max} = 0.95$) for diffusor II. The maximum velocity at the entrance was determined by blocking the channel.

4. According to the measurement data, there is a uniform undistrurbed stream at the entrance to the diffusor and the boundary layer is turbulent. A detailed investigation of the flow showed that stream separation from the walls, having a complicated three-dimensional periodic structure, which changes somewhat as the curvature of the wall decreases at the entrance to the diffusor, is observed in both diffusors. Six zones of reduced pressure on the periphery are observed at the exit from diffusor I (Fig. 2a). In the stream core are six zones of increased pressure, arranged in pairs along the perimeter with a period of ~120° between pairs and shifted by ~60° relative to the first zones. At the exit from diffusor II (Fig. 2b) we recorded three zones of reduced pressure at the periphery and three zones in the core of the stream. A comparison of Fig. 2a and b shows that with an increase in the radius of the transition, the length of the zones of reduced pressure at the periphery and the hub is reduced, the hydraulic losses in the diffusor are decreased in the process, but the three-dimensional periodic character of the flow is preserved.

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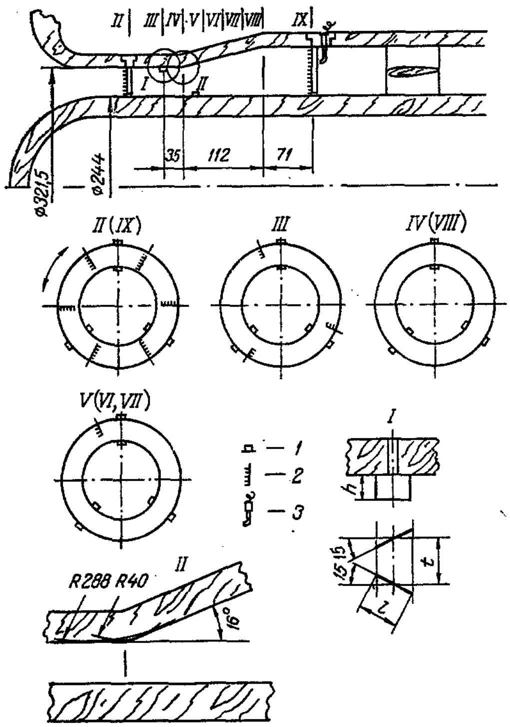

Fig. 1. Diagram of the installation and cross sections of it. Arrangement of vortex generators in the flow-through part: 1) static-pressure receiver; 2) total-pressure receiver; 3) pulsation sensor.

It should be noted that the pair of zones of increased pressure in the core that was recorded in diffusor I is converted into one zone in diffusor II, and its position in the exit channel is the same as the position of the pair in diffusor I.

Making the stream near the peripheral wall visible showed that in the wall region there are flow zones due to detachment of the boundary layer and corresponding to the periodic zones in the main stream. In Fig. 3 we present the results of making the flow visible near the peripheral wall in diffusor II. The stream direction is shown by arrows. It is seen that the dye streams enter the diffusor undisturbed. Then, with the change in wall curvature, the wall layer is deformed and the streams are redistributed, forming bunchings which end in vortices located on the lines designing the onset of detachment, which have the form of the sinusoidal curve 1. We draw attention to the fact that in the given case, beyond the convex sections of this curve one observes six zones (curve 2), called vortex zones below, periodically arranged in pairs along the involute of the peripheral cone. The directions of rotation in two adjacent vortices are opposite. In the case investigated in the present work, the size and spacing of these vortex zones are an order of magnitude larger than the thickness of the boundary layer (vortex spacing λ/δ_{bl} = 50.5, vortex diameter d/δ_{bl} = 30). Evidently, the nature of the formation of vortices in this case differs from the nature of the formation of Görtler vortices and of the vortices described in [1]. The measurements of pulsations of the total pressure showed that at those places where the detachment zones touch the main stream, small-scale formations are observed.

It must be noted that the measurements of the static-pressure distribution at the entrance to the diffusor and at the exit from it and the measurements of the distribution of pulsations P* at the exit, along the perimeter and the radius, indicate the similarity of the flow structures in the two diffusors (this is also confirmed by making the stream at the hub visible). Here stream detachment in the diffusor is not observed; its onset lies beyond the exit from the diffusor. There are three detachment zones in all, and their arrangement is periodic. An increase in the radius of the transition only results in their attenuation. Vortex zones at the hub are not observed.

The reduction in the size of the detachment zones at the periphery and the hub with an increase in the radius of curvature of the wall at the entrance leads to a decrease in the total-pressure losses by 30-40% in the entire range of stream velocities investigated.

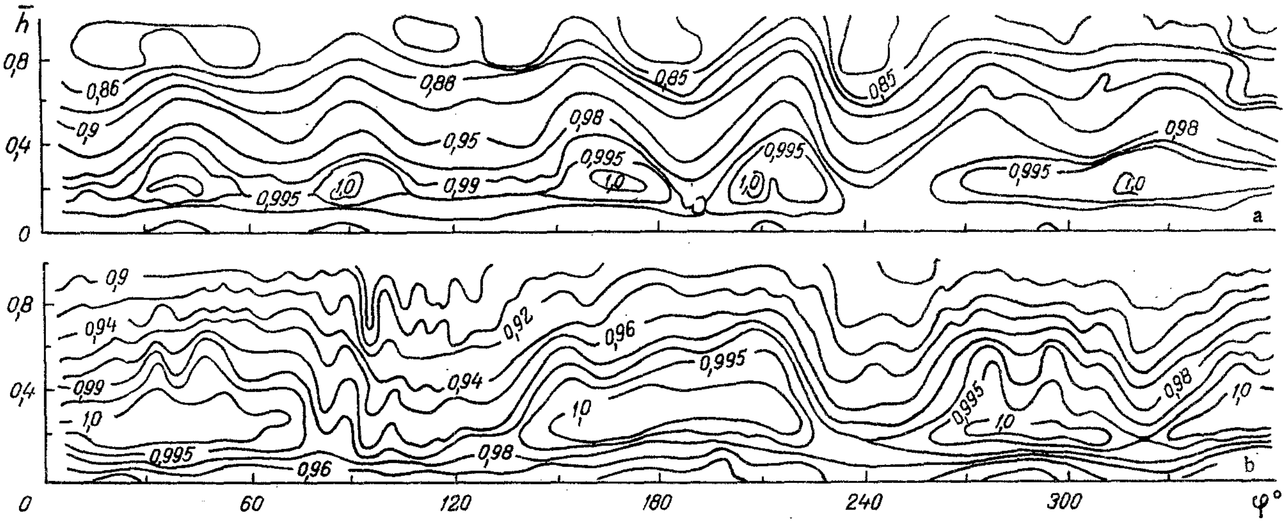

Fig. 2. Total-pressure fields at the exit: a) diffusor I ($\lambda_{en} = 0.6$); b) diffusor II ($\lambda_{en} = 0.6$).

5. With multiple repetition of the tests on making the stream visible, the flow patterns remained unchanged. The clearness of the visible patterns and their good reproducibility indicate that detached flow in a diffusor is stabilized and steady.

To clarify the causes of stabilization of the three-dimensional detached flow, we varied the construction of the flow-through part of the diffusors. We investigated the influence of an increase in the thickness of the boundary layer (by lengthening the entrance section) and the influence of additional disturbances at the entrance on the detachment by installing 12 posts having a relative thickness $\bar{c} = c/l = 0.1$, where c = 5 mm is the thickness of a post and l = 50 mm is the axial length of the post. The experiments showed that the structural changes used above did not lead to noticeable reformation of the flow or a shift in the zones of increased and reduced pressure along the perimeter or along the radius in the exit channel. Specially run tests that errors in the fabrication of the channel (technological nonaxisymmetry) also do not affect the character of flow in the diffusor or the arrangement of the zones of reduced pressure on the isobars. Nor do the patterns obtained by making the flow visible change.

Tests were run to clarify the influence of conditions at the exit from the diffusor on the flow structure. In the model there are six posts, distributed over a length $2h_{ex}$ from the exit from the diffusor, in the cylindrical channel. The encumbrance of the channel that they produce does not exceed $0.1F_{ex}$. Decreasing the number of posts did not alter the flow structure in the diffusor, as shown by the results of measurements of the total pressure and the results of making the stream visible. In a test with 30° shifts of the posts along the perimeter, a shift of the centers of the vortex zones in the wall layer at the exit by about 30°, owing to the posts was observed. The arrangement of the zones of reduced and increased pressure in the images was not altered in this case. This indicates that the posts influence the stabilization of detachment in the diffusor, despite their considerable distance from the exit from the diffusor. The structural features of the model did not permit us to remove the posts or move them to a greater distance from the exit. In this connection, we cannot draw a final conclusion about the reasons for stabilization of the zones of stream detachment inside the diffusor or their periodicity along the perimeter.

Thus, the test data show that for the diffusor channel under consideration, the structure of the detached flow does not depend on the past history.

A description of the periodic structures observed must, evidently, be based on an analysis of flow stability, which is an independent problem.

It can be noted that, with the loss of stability, the subsonic detached flow in the diffusor will probably be influenced by the part of the channel located downstream. The possibility of such influence is indicated by the results of [3], where it was shown for inviscid flow that the detachment region developing in the expanding part of the channel penetrates without limit into the cylindrical part located downstream.

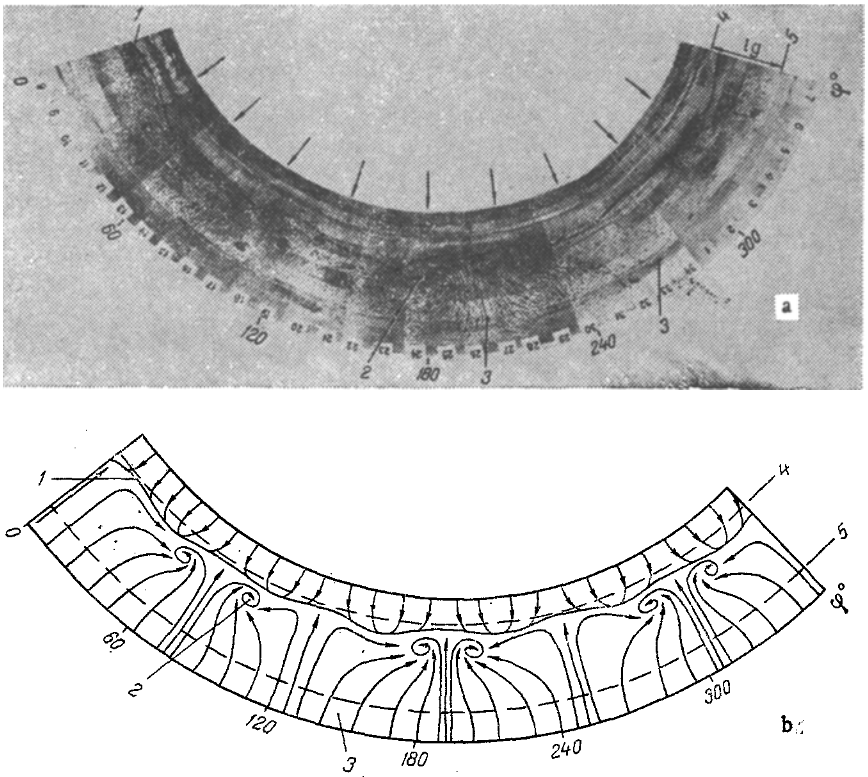

Fig. 3. Results of making the flow visible in the wall zone at the periphery of diffusor II (λ_{en} = 0.6): a) flow pattern obtained by dye injection; b) flow diagram: 1) line of onset of detachment; 2) vortex zone; 3) zone of return flow; 4) entrance to diffusor; 5) exit from it.

6. In the course of the experiments, we installed vortex generators, which has the form of plates (see Fig. 1) and were comparable in size with the thickness of the boundary layer at the entrance [4, 5], in the flow-through parts of the diffusors I and II to act on the stream detachment. Making the stream visible, in diffusor II in this case, showed (Fig. 4) that three zones of attached flow appeared in the diffusor, arranged periodically along the perimeter between three detachment zones, which were shifted toward the exit from the diffusor. Runoff lines are found in the zone of attached flow, indicating the influence of vortices, similar to Taylor–Görtler vortices, at these places. In this case the sizes of the vortices and their spacing are of the same order as the thickness of the boundary layer ($d/\delta_{bl} \simeq 2$). The appearance of a zone of attached vortical flow in the diffusor may indicate that the vortices coming down from the generators, by supplying additional energy to the boundary layer, are able to deflect the stream through a large angle, but this energy is not sufficient to eliminate the detachment. It is interesting that even here the detached flow is periodic, and its period is the same as that in diffusor II without generators, ~120°. The presence of zones of attached flow is reflected in the amount of the total-pressure losses in the diffusor, which is decreased by about 30-40% in the entire investigated range of stream velocities in comparison with the analogous value obtained for diffusor II without generators [6]. The mounting of vortex generators makes it possible to obtain σ_d = 0.965 for λ_{en}= 0.6 and σ_d = 0.995 for λ_{en} = 0.3 in diffusor II.

7. From measurements of the pressure inside the diffusors, we plotted the distribution of lines of constant values of the reduced stream velocity, averaged over the perimeter, in meridional cross sections of the diffusors (Fig. 5). A comparison of the data for different cases shows that stream acceleration is observed, as one would expect, at the entrance to diffusor I, which is connected with the small radius of the transition at the periphery and the abrupt deflection of the stream. This results in the fact that stream detachment begins at one fourth the length of the diffusor, and the detachment propagates along the entire diffusor and is recorded when measuring the total pressure in the exit channel.

The velocity in the stream core is considerably higher than the calculated velocity because of the fact that the detachment zone occupies a larger volume. The picture is altered

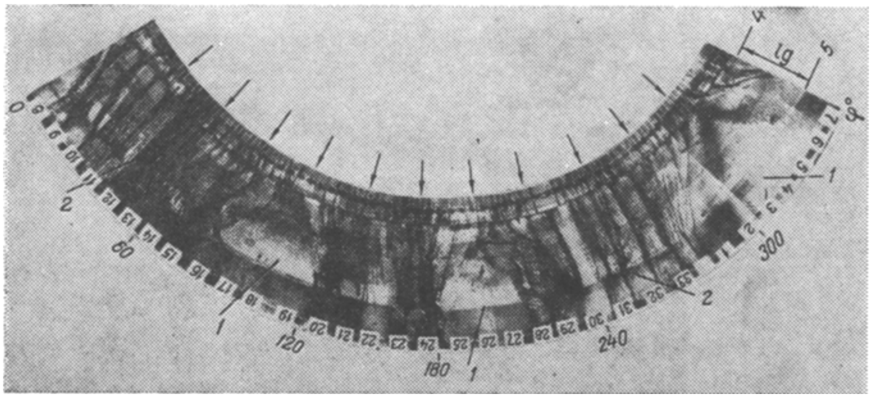

Fig. 4. Flow pattern in the wall zone at the periphery of diffusor II with vortex generators ($\lambda_{en} = 0.6$): 1) detachment zone; 2) attached flow; 4) entrance to diffusor; 5) exit from it.

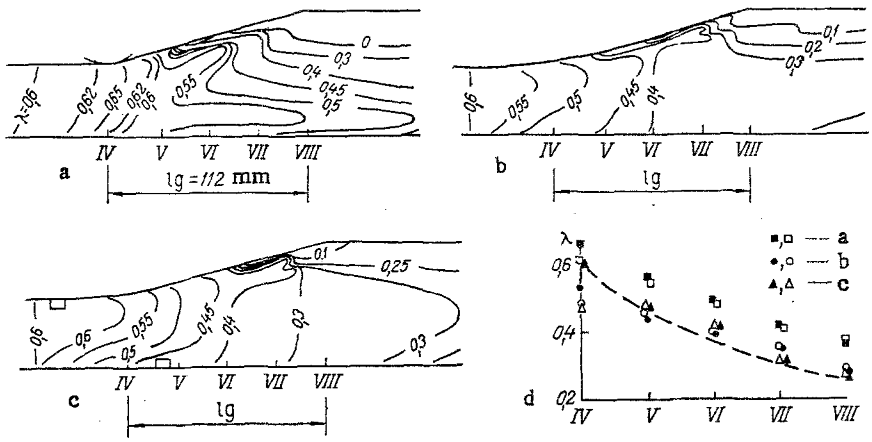

Fig. 5. Distribution of stream velocities, averaged over the perimeter, along the length of the diffusor: a) in diffusor I; b) in diffusor II; c) in diffusor II with vortex generators; d) in the stream core; dashed line) hydraulic calculation; dark points) periphery; light points) at the hub of the annular channel.

in diffusor II. Here there is no stream acceleration at the entrance, the stream deceleration is smoother than in diffusor I, and the onset of detachment is shifted toward the exit.

When vortex generators are set up, there is a further shift in the onset of detachment toward the exit. Its zone is narrower, and it is not observed in the exit channel. The deceleration of the stream is smoother in this case, and the velocity level at the exit approaches the calculated value.

NOTATION

n, expansion ratio of the diffusor channel; $F_{ex,en}$, areas of exit and entrance cross sections, respectively; R_{per}, radius of the transition to a cone at the entrance; Ψ, expansion angle of the diffusor at the periphery; Re($\rho u/\nu$), Reynolds number, where ρ is the air density, u is the velocity at the entrance to the diffusor, l, is the length of the entrance channel, and ν is the kinematic viscosity of the air; λ_{en}, coefficient of reduced velocity of the stream; λ, spacing between vortices; δ, thickness of the boundary layer at the entrance; d, diameter of a vortex; P*, total pressure; $\bar{c}$, relative thickness of a post; $\sigma = P^*_{ex}/P^*_{en}$, coefficient of recovery of total pressure in the diffusor.

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