c_f, coefficient of friction; τ_w, shearing stress at the wall; ρ, density; ν, coefficient of kinematic viscosity; De, Dean number ($Re\sqrt{d/D}$); Re, Reynolds number (ud/ν); φ, angle.

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FLOW IN THE INITIAL SEGMENT OF A TUBE WITH A SHARP LEADING EDGE.

1. PHYSICAL MODEL OF THE FLOW

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Visualization is used to study the three-dimensional structure of detached flow in the initial segment of a circular straight tube with a sharp 90°-angle leading edge. It is demonstrated that at $Re > 75 \cdot 10^3$ there is no attachment of the separated shear layer, while a secondary flow develops at the wall.

The difficulties which arise in attempts at physical interpretation of experimental material on local characteristics of heat exchange and friction in channels of small reduced length with sharp leading edges causing flow separation provide an adequate basis for a critical approach to the opinions being formed with respect to the structure of a flow such as arises within the detachment zone itself, as well as in the region in direct contact farther downstream with that zone. It is commonly assumed that the phenomenon of separation behind a sharp leading edge is the source of the perturbation which results in rapid agitation of the boundary layer and, consequently, in a sharp rise in the intensity of local heat exchange in the segment of assumed flow reattachment. This point of view with respect to the flow behind a sharp leading edge is essentially supported by intuitive concepts which, although seemingly incontrovertible at first glance, have not been confirmed by convincing direct observations.

In this study a soot-kerosene mixture similar to that used in [1, 2] was employed to conduct a visual examination of flow detachment behind a sharp edge in the initial segment of a circular tube. For these experiments we chose the technically popular sharp 90°-angle edge configuration which simulates the entry of a flow into a tube of unlimited extent, through an opening in the wall which extends in the radial direction.

The aerodynamic installation with a 36-mm diameter flowthrough section on which the experiments were carried out is described in [3]. The rapidly demountable initial segment

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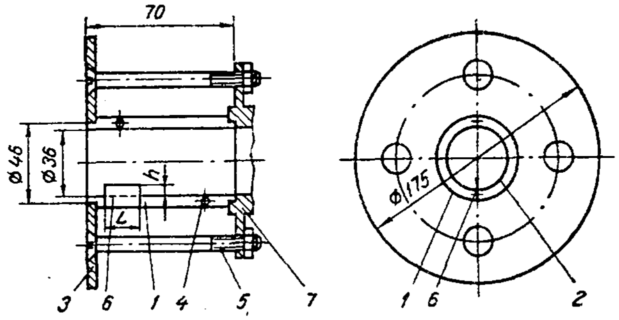

Fig. 1. Diagram of the working section.

(70 mm in length) intended for visualization of the flow is shown in Fig. 1. It consists of two drums 1 and 2 whose contacting surfaces have been polished and fitted with guide pins 4. The removable face flange 3 fits around the drums at their leading edge and functions to lock the working section by means of pins 5 to flange 7 of the stand, where the drums are pressed into a socket housing. In a number of tests, the working section was fitted out with a steel plate baffle 6 whose lower extremity was placed inside the drum housing. In the axial direction the baffle ranged in length from L = 35 to 66 mm; its height above the inside surface of the wall is h = 7-12 mm, and its thickness $\delta = 0.1$ mm. After assembly of the installation, the drum housing is hermetically sealed. Prior to passing air through the working section, we coated small areas on the inside surface of one of the drums, or the side wall of the baffle, with the soot-kerosene mixture. The experiments were performed for three fixed values of the Reynolds number: $\mathrm{Re} = 78 \cdot 10^3$, $98 \cdot 10^3$, and $115 \cdot 10^3$.

Figure 2a is a photograph developed during the course of the experiment in which the soot-kerosene mixture was applied to the drum surface of the inlet segment in the form of a band or stripe oriented in the direction of the flow. Section A_4, to the left of which the flow at the wall moves in a direction counter to the main flow, is situated at a distance $X/d \approx 0.87$ from the inlet. The trails of this reverse movement of soot particles end at section A_1 at the edge of the region with a solid black background that is in contact with the leading edge. The signs of forward and reverse flows at various segments of the wall can be more accurately tracked if the band of the soot-kerosene mixture is not applied in the direction of the flow, but at some angle to the tube axis (Fig. 2b).

The results of the visualization, which are shown in Fig. 2a, b, are qualitatively not new. For example, similar results were achieved in [4, 5] for observations of surface flow in the initial segments of a rectangular channel and a circular tube, with a sharp 90°-angle leading edge. Section A_4 is treated in [4, 5] as the point of reattachment for a boundary layer which was separated at the leading edge, while the dark-background region in contact with the leading edge is regarded as an accumulation of soot particles carried away by the reverse flow. It will be shown below that such an interpretation of the observations requires further refinement.

Figure 2c shows the results of an experiment in which a 2-mm wide stripe of the soot-kerosene mixture was applied vertically at the leading edge of the baffle, at the inlet to the tube. On the downstream portion of the uncoated baffle we find clear evidence of the three-dimensional trajectory of soot particles swept away by the detaching shear layer 3. The shape of this trajectory clearly shows that after initial compression of the flow core 1 the separating shear layer is not pressed against the wall, but toward the tube axis. Consequently, the separation region 2 at the wall is, on the whole, not closed on the right, and analysis of the surface visualization data from Fig. 2a, b must deal not with reattachment, but with the development of a secondary flow at the wall, at some distance from the inlet.

The photograph in Fig. 2d was obtained from the experiment in which the entire side surface of the baffle was coated with the soot-kerosene mixture; the baffle's leading edge was positioned in the inlet section of the tube. The lighter-colored image of band 3, thicker in the middle, shows the trajectory of the shear layer separated at the leading edge and moving at a speed relatively faster than that of flow core 1. Just as in Fig. 2c, over the entire length of the baffle ($X/d \approx 0.96$), the detaching shear flow separates the flow core from the zone at the wall. Dark spots 2 at the inlet represent the trail of a compara-

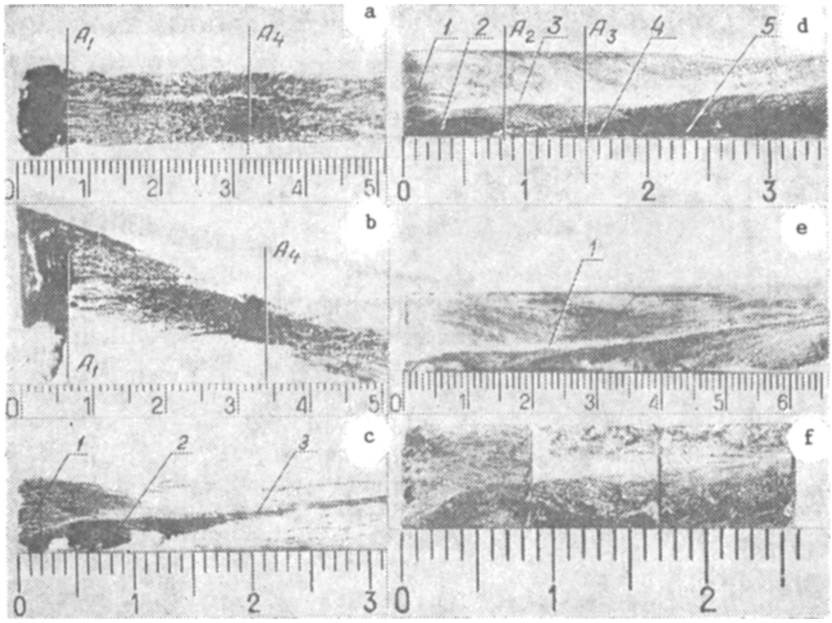

Fig. 2. Visualization results: a) coating of wall surface with a band in the direction of the flow, and Re = $78\cdot10^3$; b) coating of wall surface with a band at an angle to the direction of the flow and Re = $115\cdot10^3$; c) coating spots on the side wall of the baffle and on its leading edge, with Re = $115\cdot10^3$, L = 35 mm, h = 7 mm; d) complete coating of the baffle and Re = $98\cdot10^3$, L = 35 mm, h = 7 mm; e) complete coating of the baffle and Re = $115\cdot10^3$, L = 66 mm, h = 12 mm (1 – shear layer); f) combination of data from three experiments in which the completely coated baffle with L = 8.5 mm, h = 7 mm was positioned sequentially at various distances from the leading edge, Re = $115\cdot10^3$.

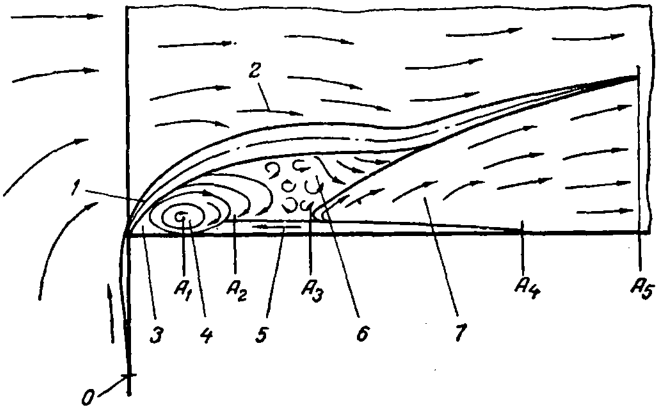

Fig. 3. Model of detached flow in the initial segment of a tube, behind a 90° sharp leading edge.

tively slow clockwise rotating large-scale spinning-top vortex toward whose root base the reverse flow 4 layer is moving. It should be pointed out that the edge of the vortex in section A_2 is located downstream of section A_1, while the rotation of the soot particles within the vortex can be seen directly from the tube inlet as part of the experimental visualization process. In section A_3 near the wall, a wedge-shaped secondary flow region 5 begins to form, expanding downstream. If we were to transfer the coordinates of section A_4 from Fig. 2a, b to Fig. 2d (with zero velocity at the wall), it would become obvious that the reverse flow at the segment of the inlet section between sections A_1 and A_4 could be treated solely as a unique feature of secondary flow, rather than as proof of reattachment.

Experiments with extended baffles (Fig. 2e) show that the secondary flow merges into the core of the flow, beyond the limits of the working section, i.e., when $X/d > 2$. Thus, the level of flow core agitation apparently only slightly affects the structure and parameters of turbulence in the near-wall region close to the leading edge.

The observations illustrated in the photograph of Fig. 2d, e give rise to some misgivings as to their accuracy, since the structure of the detached flow is unavoidably deformed to some extent by the appearance of corner zones formed by the baffle and the tube wall, as well as by the interaction of the baffle boundary layer and the flow at the wall. A series of experiments has therefore been carried out with a constant Reynolds number in which short baffles were sequentially positioned at various distances from the inlet, said distances chosen so as to make possible subsequent restoration of the general flow pattern near the wall by piecing fragments together. The results of the experiments involving this procedure of three sequential baffles are shown in Fig. 2f. Qualitatively, the data of Fig. 2d-f are in satisfactory agreement.

Figure 3 shows a model (constructed on the basis of visualization results) of detached flow in the inlet section of a tube, behind a sharp 90°-angle leading edge. The first boundary layer 1 is formed at the surface of the face wall, starting from some point 0. Bending around the sharp edge, the boundary layer separates and as a consequence of compression it moves along a trajectory gradually approaching the axis of the tube at a velocity greater than that of the flow core 2. A rotating spinning-top vortex 4 appears because of viscous interaction with the detaching shear layer at the sharp edge. The edge of this vortex lies in section A_2. A dead zone 3 precedes the vortex region. The vortex acts as a pump at the segment between sections A_1 and A_4 to displace the mass of the thin surface film 5 toward the vortex, and subsequently to deposit this mass into the detaching shear layer 1 and in region 6 with disordered chaotic motion. Secondary flow 7 generated by the detaching shear layer begins in section A_3. In section A_5 the detaching shear layer becomes diffuse and merges into the core of the flow. It follows from our proposed model that the velocity profiles exhibiting a bend within the limits of the inlet section exist at the wall in the segment between sections A_3 and A_4, while the velocity maxima are located along the trajectory of the detaching shear layer.

Based on geometric and regime indicators, the model shown in Fig. 3 must be included among the cases in which the inlet edge of the initial segment of a smooth channel exhibits a sharp profile or very slight rounding, while the Reynolds number approaches 10^5. Consequently, separation of flow with subsequent reattachment is possible only when the shape of the edge is deformed so as to produce rather smooth contours, or if the Reynolds numbers are very small.

NOTATION

X, longitudinal coordinates, mm; d, flowthrough diameter of the working section, mm; L, h, and δ, the length, height, and thickness, respectively, of the baffle, mm; Re, Reynolds number calculated from the average flow rate. Subscripts: 1-5, section numbers.

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