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EFFECT OF INSTABILITY ON BOUNDARY LAYER DETACHMENT

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When fluid or gas flows around a body, a thin boundary layers forms near its surface. The behavior of this boundary layer is determined by hydrodynamic resistance. If the boundary layer is detached from the surface, the resistance increases sharply [1, 2]. In order to reduce this resistance, the detachment must be stretched out; that is the boundary layer line detachment must be shifted as far as possible to the aft critical point, so that the region of stagnant flow (the wake) behind the body is narrowed. In this regard, investigations of nonstationary fluid around a body are of current interest. The acceleration of a cylindrical body into a quiescent fluid has been examined [2]. Undetached flow around the body was observed immediately after the acceleration started. Then, after the cylinder traveled a distance s = 0.351 R (where R is the cylinder radius), the flow detached near the aft critical point of the body. The detachment gradually moved forward along the flow and increased the wake behind the body. After a certain time, a pair of vortices appeared behind the body, which grew and continually broke off to form a vortical wake. As measurements show [3], the hydrodynamic resistance coefficient is minimized in the case of undetached flow. This leads to the importance of investigating nonstationary flow around bodies.

Currently, boundary layer dynamics for bodies accelerating into a flow of fluid or gas have not been studied enough. Here it must be kept in mind that acceleration into a quiescent fluid is different than into a flowing one, where, as a rule, the boundary layer detachment already exists, and it is necessary to follow its behavior as the body accelerates.

It has been shown [1, 4] that for a nonstationary boundary layer, the velocity profile inside it is defined by the parameter

$$\lambda = (\delta^2/\nu)(U' + \dot{U}/U),$$

where δ is the boudnary layer thickness; ν is the kinematic viscosity; U is the flow velocity at the boundary with the boundary layer; $U' = \partial U/\partial x$ is the velocity gradient (x is the coordinate along the arc of the meridional cross section of the body); and $\dot{U} = \partial U/\partial t$ is the time derivative of the velocity (acceleration). This equation shows that the growth rate of the boundary layer, its structure, and the position of the detachment line will depend on the magnitude and sign of the relative acceleration $\dot{U}/U$, which in the nonstationary boundary layer plays the same role as U'.

The investigations were conducted in a hydrodynamic tunnel whose working section is a square channel 40 × 40 mm made of transparent material. A device which can accelerate the body into the flow is mounted in the working section (Fig. 1). The device is constructed as follows. The flow body (a cylinder) 1 is fastened to the end of a steel tube 2, which passes through the body to the forward point on the cylinder. The tube carries water with a fluorescent dye to the forward point, in order to make the boundary layer visible. In turn, the tube 2 passes through a directing tube 3, which is rigidly fastened to a support 4, which is fastened from two opposite sides to the channel walls 5. A mounting assembly 6 is rigidly connected to the tube 2. A control thread 7 and the flow cylinder, are pulled back along guide wires 8, which prevent the cylinder form rotating around the axis, and stretch springs 9. At a given moment in time, the thread is broken and the flow body is accelerated by the compressing spring into the flow.

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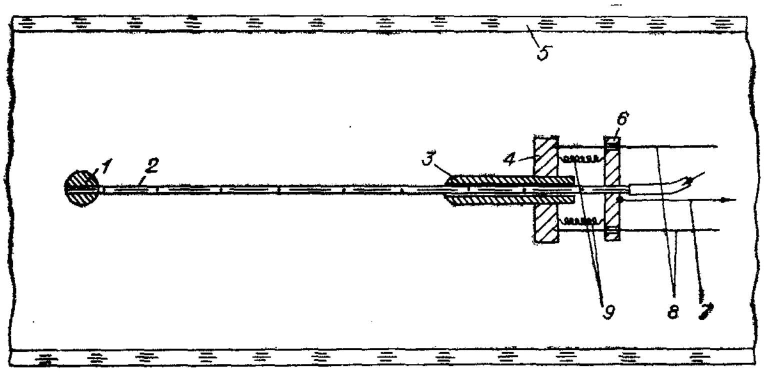

Fig. 1

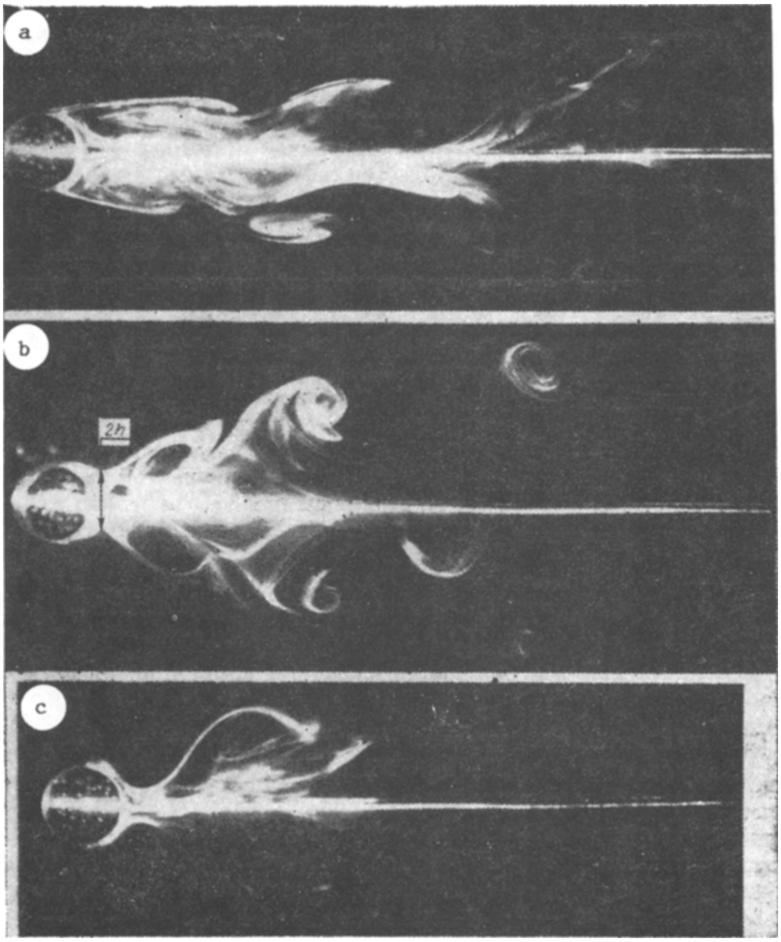

Fig. 2

The boundary layer and the wake behind the body are visualized with the aid of fluorescent dyes, which are added in small amounts to water which is fed through the tube 2 to a region next to the leading edge of the flow body. The fluorescing molecules are excited by a blue laser and give off a bright yellow-green light. This method guarantees good contrast and brightness of the picture of the flow around the body and makes it possible to study the dynamics boundary layer detachment. On the merits of the visualization method, it should be added that the dye concentration in the water is insignificant (<0.01%) and makes no practical change on the water density and viscosity; that is, it does not perturb the investigated hydrodynamic flow. The blue laser beam, which excites of the fluorescent dye, is shaped into an "optical knife," which illuminates a given plane of the flow body and the surrounding region, including its wake. The flow pattern was recorded using still and motion photography, with a film exposure time of 2 msec.

The experiments were conducted for various flow velocities (up to 5 m/sec) for cylinders of various diameters (from 0.5 to 1.0 cm) to produce Reynolds numbers from 10^3-$5 \cdot 10^4$; that is,

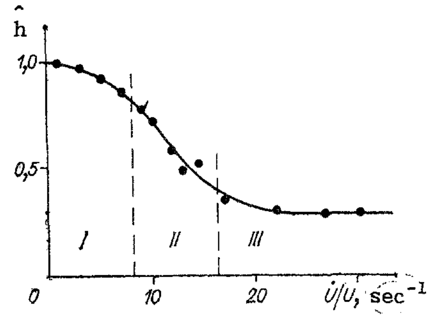

Fig. 3

a laminar boundary layer was investigated, although the external flow was both laminar and turbulent.

Figure 2 shows photographs of water flow around the cylinder at rest (a) and accelerating into the flow (b, c). Frame b shows the moment when the cyinder gave a small jerk against the flow. In this case a pair of vortices were observed to shake off, which were drawn below into the flow. Afterwards the detachment point of the boundary layer shifted backwards to the aft critical point, and the wake thickness 2h decreased by $\sim$30%. Frame c shows the moment when the cylinder is moving with an acceleration $\dot{U} = 6.2$ m/sec^2 and a velocity U = 0.3 m/sec (with respect to the incident flow), so that $\dot{U}/U = 20.6$ sec^{-1}, which coincides with the value of U' to within an order of magnitude. The wake behind the cylinder is narrowed significantly at these values of $\dot{U}/U$, and the dimensionless width of the wake $\hat{h} = h/R \sim 0.3$ in this flow regime.

By comparing the photographs a-c, it can be seen that when the cylinder is accelerated into the fluid flow, the detachment line of the boundary layer is displaced by a large distance towards the aft critical point, and the wake behind the body is narrower for a body accelerating into the flow than for one surrounded by a stationary flow (a). In those cases when $\dot{U}/U$ computed from the velocity is reduced and becomes less than U', the detachment line of the boundary layer again is gradually displaced upwards to its stationary position, and the wake behind the cylinder also gradually widens.

Analysis of the movies of the cylinder being accelerated into the flow was used to construct a graph of the position of the detachment point of the boundary layer versus the relative acceleration (Fig. 3). The position of the detachment point is characterized by its distance h from the horizontal axis (see Fig. 2); in Fig. 3 this quantity is dimensionless: $\hat{h} = h/R$. Figure 3 is divided into three characteristic sections. Section I is characterized by small values of the relative acceleration, and the width of the wake is at a maximum, close to the value for stationary flow around the cylinder. This occurs when the acceleration is small (close to zero) or even when it is large and the value of U is large enough to make $\dot{U}/U$ small (much less than U'). Section II corresponds to intermediate values of $\dot{U}/U$ and is characterized by a larger role of the relative acceleration in the flow process around the cylinder. The detachment line of the boundary layer gradually shifts to the aft critical point. In this case the wake behind the body gradually narrows. Section III corresponds to large values of $\dot{U}/U$, for which $\hat{h}$ is minimum, and the flow around the cylinder is almost undetached, because the detachment line of the boundary layer is shifted way back to the aft critical point and the wake behind the body becomes very narrow. The clearest effect of displacing the detachment line backwards is observed for small values of U, where even a small acceleration $\dot{U}$ gives a large value of $\dot{U}/U$, comparable to the velocity gradient U'. This regime can also be reached for at large velocities, when the acceleration is large enough to make the relative acceleration comparable or larger than U'. The described behavior occurs for both laminar and turbulent flow. The effect of displacing the detachment line to the aft critical point of the cylinder is observed for all ranges of flow velocity.

The nonstationary boundary layer was also investigated when the cylinder was decelerated in the flow. Here the detachment line was observed to displace forwards to the leading edge of the flow body, and the wake behind the cylinder widened (Fig. 4). A resistive strain gage, mounted in the acceleration device (see Fig. 1) made it possible to measure the resistance of the body. The hydrodynamic resistive force of the cylinder was transmitted through the tube 2 to the strain gauge, which operated in deflection. Experiments established that the hydrodynamic resistance coefficient decreased by ~30% for positive acceleration as compared to the case of stationary flow at the same velocities.

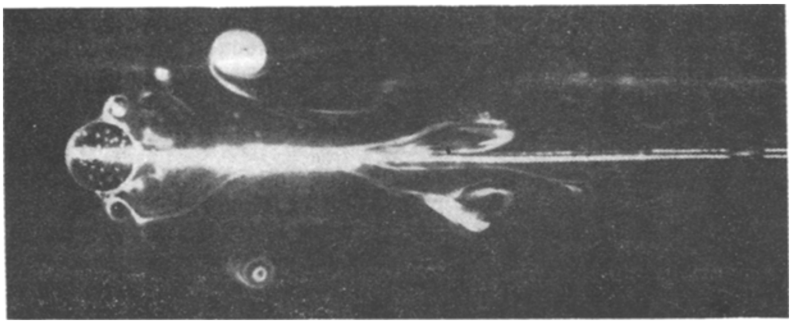

Fig. 4

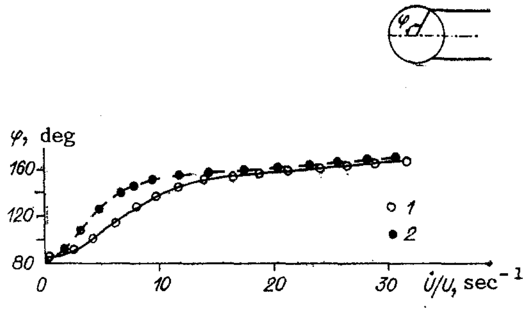

Fig. 5

Results have been presented [5] of an investigation of the nonstationary boundary layer around a sphere, which also is characterized by a displacement of the detachment curve of the boundary layer during acceleration. Experimental data for a cylinder and a sphere (points 1 and 2) are presented in a generalized form in Fig. 5, in which the position of the detachment curve of the boundary layer is described by the angular coordinate ϕ. A comparison of curves for a cylinder and a sphere shows that the displacement of the detachment line is much sharper for a sphere than for a cylinder and occurs for smaller values of the relative acceleration $\dot{U}/U$. This is explained by the fact that the sphere has a smaller velocity gradient U' than the cylinder, so it is much easier to compensate it with a smaller value of $\dot{U}/U$.

These results can be applied in designing various technological apparatus with stationary flow around various bodies. For example, chemical technology uses catalytic processes in which components of the reacting mixture flow around catalyst granules. A thin boundary layer is formed near the granules, which determines the rate and direction of the chemical reactions. Making the flow nonstationary (with the use of acoustic waves or vibrations within the reactor) can provide conditions under which flow around the bodies is more complete (the boundary layer is not detached), which can increase the chemical reaction rate. Here the hydrodynamic resistance should also be reduced, because each catalyst granule makes a contribution to the total flow resistance.

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