EXPERIMENTAL STUDY OF A NONSTATIONARY BOUNDARY LAYER

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The flow past a sphere as it accelerates in a stream of fluid is studied. Depending on the magnitude and sign of the acceleration the line of boundary-layer separation shifts to the forward or rear stagnation point.

When a stream of liquid or gas flows past a body a thin boundary layer, whose behavior determines the hydrodynamic drag, forms near its surface. The drag increases substantially, as a rule, when the boundary layer separations from the surface of the streamlined body [1, 2]. In order to reduce the drag it is necessary to delay the separation, i.e., move the line of boundary-layer separation as far back as possible, to the rear stagnation point.

In view of this studies of unsteady (nonstationary) motions of bodies in liquids are of some interest. A number of papers, which have been reviewed in [1], experimentally and theoretically studied accelerating motion of a body when it begins to accelerate in a liquid at rest. For a cylinder, for example, it has been established that immediately after the motion begins flow without separation ensues and then after some time boundary-layer separation occurs at the rear stagnation point. With time the separation point moves up along the stream, increasing the wake. A vortex wake forms behind the body some time after sufficiently high Reynolds numbers ($\mathrm{Re} \cong 100$) are reached. In other words, flow without separation occurs initially in accelerating motion of a body in a liquid at rest.

While a fair number of studies have been made of the accelerating motion of different bodies in a liquid of gas at rest, the flow past bodies as they accelerate in a stream has virtually not been investigated.

Struminskii [3] concluded that in the case of a nonstationary boundary layer the velocity profiles inside the boundary layer are determined uniquely by the value of the parameter

$$\lambda = \frac{\delta^2}{\nu}\left(U' + \frac{\dot{U}}{U}\right). \tag{1}$$

Equation (1) suggests that in the accelerated motion of a body in a stream of liquid or gas the relative acceleration $\dot{U}/U$ plays the same role as does the velocity gradient U'. The position of the line of boundary-layer separation should depend on the magnitude and sign of the relative acceleration.

We have experimentally investigated a nonstationary boundary layer for a sphere moving with acceleration in a stream of liquid.

Experimental Procedure. Our studies were carried out in a hydrodynamic apparatus, with a 40 × 40 mm Plexiglass channel as the working part (Fig. 1). The apparatus includes a supply tank 1, a collector tank 2, a pump 3 for pumping water from one tank to the other and maintaining a pressure differential, a throttle 4, a distributor half-ring 5 to reduce perturbations in the inlet part of the tube, a mercury thermometer 6 for monitoring the water temperature, and, finally, the working part 7 of the channel in which the experiment was performed.

In the working part of the channel we mounted a device (Fig. 2) which can be used to accelerate the streamlined body at a particular time. The device has the following design. The streamlined body 1 is attached to the end of a steel tube 2 of diameter ~1 mm. Water with dissolved molecules capable of fluorescing under strong illumination is carried to the forward point of the streamlined body 1 by this tube, which lies along the axis of the body. This allows the boundary layer and the wake to be made visible. The tube with the body in-

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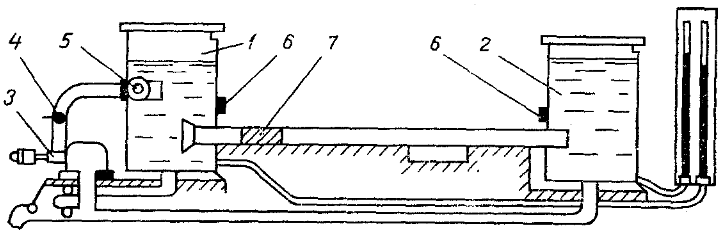

Fig. 1. Hydrodynamic apparatus.

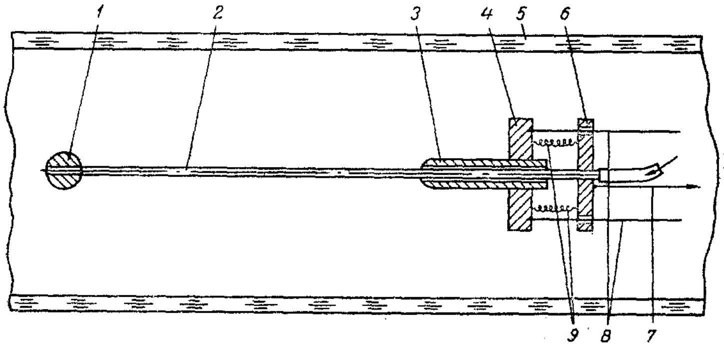

Fig. 2. Device for setting a body in a flowing stream into accelerated motion.

serted in it in turn passes through a guide tube 3, which is firmly mounted in a support 4. The support is attached on either side to the walls of the channel 5. The fastener 6 is firmly fastened to the tube 2, on which the streamlined body is mounted, and guide string 7 pulls fastener 6 along with the body under study backward along guide rod 8, without allowing the streamlined body to rotate around its axis, while springs 9 stretch. At a given time the string breaks and compressing springs cause the streamlined body to move with acceleration.

Method of Visualizing the Boundary Layer. For visualization we used fluorescing impurities, a small amount ($<0.01\%$) of which had been previously dissolved in water and were fed through tube 2 to the forward point of the streamlined body, whereupon the onrushing stream carried them along the boundary layer. The fluorescing impurities were excited by strong laser light and gave off a bright green emission. This method of visualization ensures a well contrasted bright picture of the flow around the body and makes it possible to study the dynamic processes of boundary-layer separation. The exposure for photographing the streamline flow was $\sim 10^{-3}$ sec.

Among the advantages of the visualization method used is the fact that the impurity in the water is present in such a small amount as not to alter the density of the water and the viscosity, i.e., it introduces no perturbations into the stream.

The fluorescing impurities to make the flows visible were excited optically by a blue laser whose beam was transformed into an "optical knife" upon passing through a cylindrical lens. This flat beam induced luminescence in a given plane of the streamlined body and adjacent regions, including the wake. Still photographs and movies were taken of the streamlining.

Study of the Boundary Layer of a Sphere. In the initial state the sphere was set up at the extreme right position and hence the springs were stretched. In this case a stream of water flows past a motionless sphere (Fig. 3a). The point of laminar boundary-layer separation corresponds to the angle $\varphi = 83.5°$.

The guide string 7 (see Fig. 2) then breaks and the sphere moves with acceleration under the force of the springs 9 against the oncoming stream (Fig. 3c-d). Figure 3b records the instant when the sphere receives a slight thrust counter to the stream. The point of boundary-layer separation is observed to be displaced backward substantially, i.e., even a slight forward thrust causes a considerable displacement of the line of boundary-layer separation and the wake behind the sphere becomes narrower.

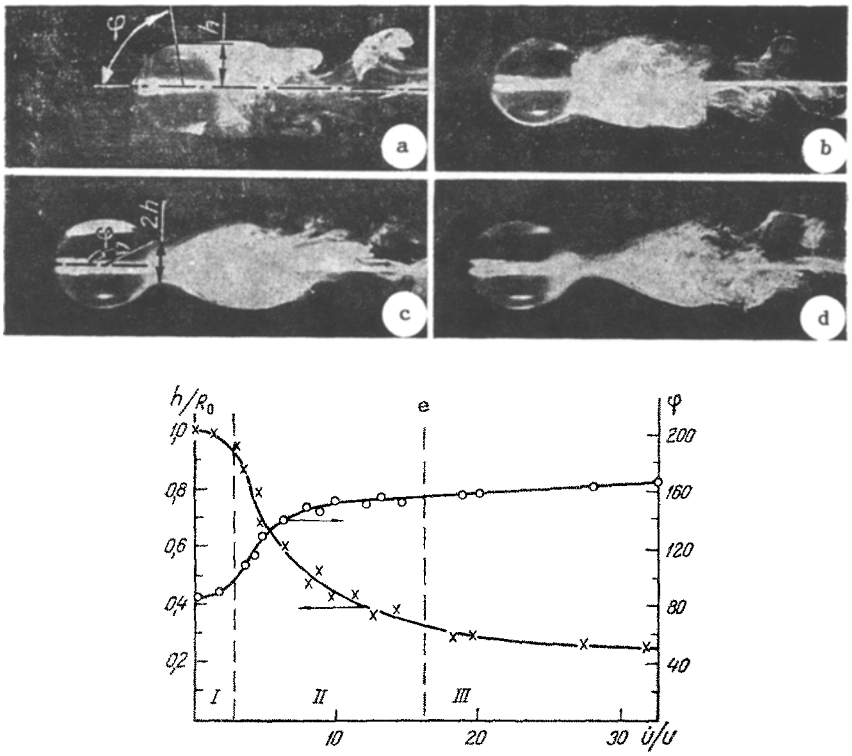

Fig. 3. Flow past a sphere slowing down in a stream.

Figure 3c shows the instant when the sphere moves with acceleration $\dot{U}$ = 7.2 m/$\sec^2$, having a velocity U = 0.6 m/sec (with allowance for the velocity of the oncoming stream); in this case the relative acceleration $\dot{U}/U = 12.0 \sec^{-1}$, which is several times smaller than the average value $U' \sim U(\pi R_0/2)^{-1} = 38.1 \sec^{-1}$. Under these conditions of motion the point of boundary-layer separation is near the angular coordinate $\varphi = 158°$ and the wake narrows down greatly to a thickness 2h = 0.4 D.

Figure 3d records an instant of virtually unseparated flow past a sphere moving with velocity U = 0.3 m/sec and acceleration U = 13.0 m/$\sec^2$. The relative acceleration $\dot{U}/U$ = 43.3 $\sec^{-1}$ substantially exceeds the average $U' = 19.1 \sec^{-1}$. Under these conditions of motion the point of boundary-layer separation is closer to the rear stagnation point and the corresponding coordinate is $\varphi = 165°$. The wake has a very small thickness, 2h = 0.26 D.

Comparing Figs. 3a-d, we can see that in the case of accelerated motion of a sphere in a stream of liquid the line of boundary-layer separation is displaced considerably toward the rear stagnation point and, hence, the wake behind a body moving with acceleration becomes substantially narrower than behind a body with a steady-state stream flowing past it (Fig. 3a). In situations when the relative acceleration $\dot{U}/U$ decreases to less than U' as the velocity increases the line of separation again gradually shifts upward to its steady-state position, while the wake behind the sphere also gradually expands.

On the basis of an analysis of motion pictures of the flow past a sphere moving with acceleration in a stream, we plotted the position of the point of boundary-layer separation against the relative acceleration (Fig. 3e). The position of the point of boundary-layer separation is characterized by the angle φ and the distance h from the horizontal axis (we make a dimensionless quantity by dividing it by the sphere radius R_0). We can easily see that the width of the wake is 2h and is uniquely related to the angle φ. Three characteristic segments can be distinguished in the graphs in Fig. 3e. Segment 1 is characterized by small values of the relative acceleration and the angles φ are close to the values obtained when a sphere moved without acceleration: this angle is $\varphi = 83.5°$ in the case of a laminar boundary layer ($Re_D < 10^5$). Segment 1 is characterized by a maximum wake width. This case of streamline flow occurs when the acceleration $\dot{U}$ is small (close to zero) of when the acceleration is substantialy but the velocity U is high enough so that the relative acceleration $\dot{U}/U$ is small (much smaller than U').

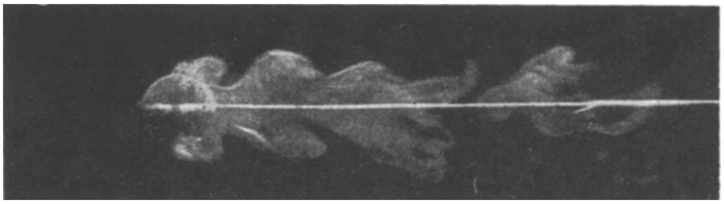

Fig. 4. Flow past a sphere slowing down in a stream.

Segment II of the graph corresponds to the average value of $\dot{U}/U$. It is characterized by an increased role by the relative acceleration in flow past the sphere. The line of boundary-layer separation gradually shifts to the rear stagnation point; angle φ gradually increases and the thickness of the wake consequently decreases. We should point out that on this segment the experimental points have a large scatter, which is attributed to the transient flow conditions of the boundary layer.

Segment III corresponds to large values of the relative acceleration. In this case streamline flow past the sphere can be assumed to be virtually without separation since the line of boundary-layer separation is shifted far to the rear, to the rear stagnation point, the wake becomes narrow and tends to a thickness of 0.26D, while $\varphi \to 165°$. This mode can be observed most clearly at low velocities U, when even a small acceleration $\dot{U}$ give a large value for $\dot{U}/U$, exceeding the velocity gradient U'. Such a mode can be obtained at high velocities as well, but then the acceleration should also be large so that the relative acceleration would exceed U'.

These studies were carried out at different stream velocities (the velocity reached 5 m/sec). We used spheres of different diameters, ranging from 0.5 to 1.0 cm. The Reynolds number over the diameter of the spheres varied from 0.1 to $5 \cdot 10^4$, i.e., we studied a laminar boundary layer, although the external stream was both laminar and turbulent. With all of these conditions we observed the described shift of the line of boundary-layer separation.

We also experimentally studied the nonstationary boundary layer in the case when the sphere slows down in the stream. The line of boundary-layer separation was observed to shift forward, to the forward stagnation point, while the wake became wider (Fig. 4).

Using a resistance strain gauge placed in the device (Fig. 2) for accelerating the streamlined body, we measured the hydrodynamic drag of that body. The hydrodynamic drag of the sphere was transmitted by rod 2 to the resistance strain gauge, functioning in a bending mode. We determined experimentally that when the sphere moves with acceleration in the direction counter to the stream the drag decreases by 30-40% in comparison with the case of steady-state streamline flow at the same velocities.

Our studies show that in the case of flow past a sphere positive relative acceleration (the acceleration of motion counter to the stream) is conductive to flow of liquid inside the boundary layer without separation; the line of boundary-layer separation shifts backward to the rear stagnation point and the hydrodynamic drag decreases.

Where the sphere slows down in the stream (negative relative acceleration), conversely, the line of boundary-layer separation is displaced to the forward stagnation point and the wake becomes wider, i.e., deceleration in the stream facilitates boundary-layer separation.

NOTATION

Re, Reynolds number; ν, kinematic viscosity; δ, thickness of the boundary layer; U, stream velocity at the boundary with the boundary layer, cm/sec; U', velocity gradient ($U' = \partial U/\partial x$); x, coordinate along the arc of the streamlined body; $\dot{U} = \partial U/\partial t$, derivative of the velocity with respect to time (acceleration); $\dot{U}/U$, relative acceleration, $\sec^{-1}$; φ, angular coordinate of the point of boundary-layer separation, measured from the leading edge of the streamlined body, deg; R_0, radius of the sphere, cm; D, sphere diameter; $Re_D = U/D\, \nu^{-1}$, Reynolds number along the diameter of the sphere; h, distance of the point of boundary-layer separation from the horizontal axis; 2h, thickness of the weak; and $2h/D = h/R_0$, dimensionless thickness of the wake.

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ACCELERATION OF SOLID PARTICLES IN A CHANNEL

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On the basis of an anlaysis of the distribution of the parameter of a two-phase flow emerging from a channel we obtain a criterial relation for the velocity disequilibrium of the phases.

A very important factor to be considered when designing experimental setups for studying the processes responsible for the formation of the structure of two-phase (gas—solid particles) jets is that of the magnitudes and fields of velocities of the discrete phase at the exist from the accelerating device, whether it be a supersonic jet or a tube with one cross-sectional shape or other. When choosing the design elements of the setup, we must know the length and cross-sectional size of the accelerating device in order to obtain the desirbed particle velocity.

Our main goal is to obtain a criterial (dimensionless) relation that determines the efficiency of the acceleration of solid particles by the gas flow and the effect that the particle properties and determining geometrical parameters of the accelerating device have on it.

A typical element of a setup for obtaining two-phase flows usually is an accelerating part, constituting a fairly long tube with one cross-sectional shape or other. In the case of supersonic velocities of the carrier phase a nozzle with a flaring conical part is placed at the end of the tube. The critical cross section of the nozzle is usually slightly smaller than the cross section of the tube since a considerable narrowing of the cross section causes particles to accumulate in front of it and then periodically to be ejected into the flow and also induces rather intensive transverse displacements of particles, leading to poorer particle acceleration.

Gas flows with different Mach numbers are obtained by varying the inlet cross section of a nozzle with a constant critical cross section.

To prevent erosion from changing the size of the critical cross section, a cylindrical band is made in it to maintain a constant Mach number. Particles are usually introduced into the initial part of the tube.

An experimental setup, based on this scheme, was used for our studies, whose results are discussed here. The setup was described in detail in [1]. In the experiments we used particles of standard electrocorundum (GOST 3647-80), whose fractions had an average particle size d_s = 16, 23, 32, 44, 88, and 109 μm and a strictly determined particle size distribution function. The particles were irregularly shaped fragments. The specific weight of the particle material was $\gamma_p = 3800$ kg/m³. The concentration K (kg particles/kg gas) did not exceed 0.3 and, according to our data and the data of [2], this ensured a mode of "single" particles. Cold air was used as the carrier phase.

Particles were introduced from a batcher in the vertical direction in cross section II of the horizontal accelerating portion III at a distance X from the inlet cross section (see Fig. 2). In the experiment we measured the distribution of the carrier-phase velocity U, the discrete-phase velocity U_s, and the ("smeared") discrete-phase density ρ_s (mass of the discrete phase per unit volume). The discrete-phase velocity U_s was measured with a laser Doppler velocity meter and the density was measured with a laser concentration meter; the design of these instruments, the measuring procedure, and the data processing were described in detail in [3].

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