JET FLOW BETWEEN TWO PARALLEL PLATES

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Fluid flow in the narrow gap between two parallel surfaces is the simplest physical model of processes in porous media. Such a flow is encountered, e.g., in the cracks of reservoir rock for obtaining geothermal energy [1]. The simplest model for such a flow is the radial flow from a source [2]. However, in practical cases axisymmetric radial flow is, as a rule, an extreme idealization. In the majority of cases unsymmetric jet flow between parallel surfaces is the most probable flow condition. The initial segment of the jet near the source or the sink is of the greatest interest because it determines the hydrodynamic resistance of the system. A systematic study of this problem is not found in the literature. The objective of this paper is to study the general nature of the jet flow in the narrow gap and to obtain the basic hydrodynamic characteristics in the transition and turbulent regions of the flow.

Experiments were conducted in the setup whose schematic diagram is shown in Fig. 1. Two parallel flat plates 1, 2 made of 24-mm-thick Plexiglas formed a gap whose width could be varied with the insert 3. The insert had the shape shown in Fig. 1b, which ensured the jet efflux from the nozzle clamped between the plates. Vitoshinskii profile was used for the nozzle contour. The fluid input and output were carried out through connectors 4, 5 located at the top and bottom ends of the plates. Circular rubber gasket was placed in the groove of the plate 2 and the plates were uniformly pressed together.

Twelve electrochemical friction transducers [3] with circular electrodes of 0.1-mm diameter, separated by a distance of 20 mm from each other, were embedded along the axis of the plate 1 for measurements. The plate with the transducers was grounded along the plane so that the flow remained undisturbed during measurements. The transducer signals were amplified by multichannel wide band dc amplifiers. The signal output from amplifiers were recorded by integrating and rms voltmeters; in certain cases a number of signals were simultaneously recorded in the recorder MR 021 of the firm "Schlumberger" (with frequency modulation).

Flow visualization with optically sensitive fluid was initially carried out at different flow conditions using the technique described in [4]. Characteristic pictures of the flow field are shown in Fig. 2. Reynolds numbers defined as $Re = u2h/\nu$ (u is the mean flow velocity in the nozzle, ν is the kinematic viscosity) equal 1250 and 6000 (Fig. 2a and b, respectively). In the laminar region the jet (Fig. 2a) leaving the nozzle is characterized by a small expansion angle. Initial flow instability in the form of fluctuations in the jet at a certain distance from the entrance occurs with an increase in velocity. In the turbulent flow (Fig. 2b) the expansion angle increases sharply.

Wall shear stress distribution τ_w along the jet axis was measured for different values of nozzle width b and the distance between plates h. Characteristic distributions of τ_w in the turbulent boundary region of the flow are shown in Fig. 3 for h = 1.5 mm, b = 3.5 mm, x is the distance from the nozzle section measured along the axis, point 1 is for Re = 9530; 2 is for Re = 13,620; and 3 is for Re = 19,050. Shear stress distributions $\tau_w(x)$ have qualitatively identical form for different values of b and h. For small x there is a rapid increase initially in τ_w associated with turbulence of the jet, then τ_w attains a maximum after which it drops rapidly along the length. The distance across which the turbulent jet extends increases with jet width and decreases with a decrease in the distance between the plates, which is quite natural, since the initial momentum of the jet increases with an increase in b and with a decrease in the distance between plates there is an increase in energy dissipation due to friction.

Characteristic oscillograms of the diffusive current in the transducers at different points along the jet length are shown in Fig. 4, where Re = 11,600, for the fully developed

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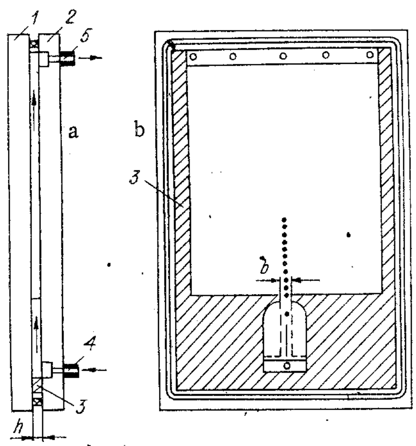


Fig. 1

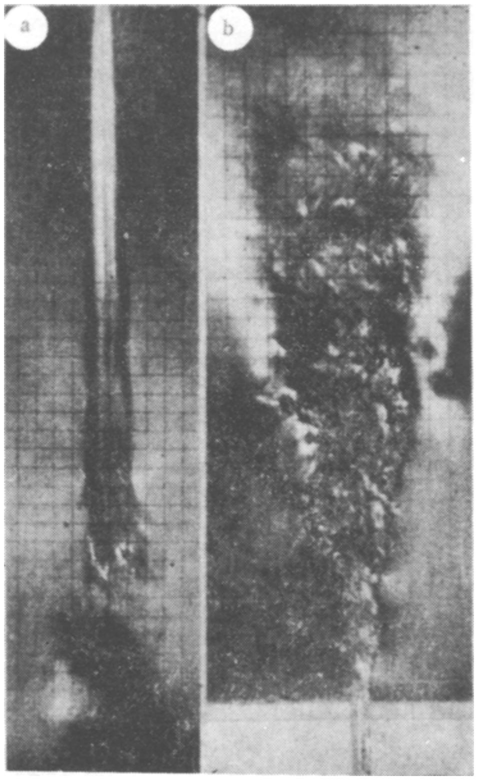


Fig. 2

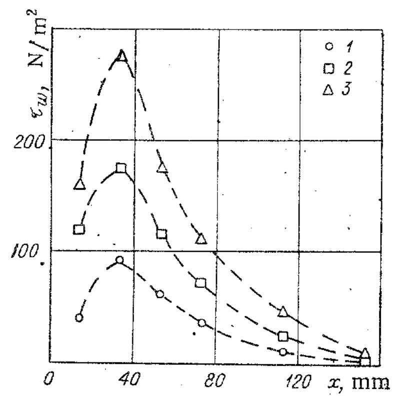


Fig. 3

turbulent flow. The coordinate x for 1: 15, for 2: 35, for 3: 55, for 4: 75, and for 5: 115 mm. With an increase in x there is at first an increase in the intensity of shear stress fluctuations followed by a rapid reduction when the fluctuations have much lower frequencies and at a certain distance from the entrance relaminarization takes place which is indicated by a straight line signal from the transducer. The output spectrum in turbulent flow is continuous and is qualitatively similar to the spectrum of turbulent fluctuations in the tube.

In studying the transition region steps were taken to eliminate possible periodic disturbances. Experiments were conducted in the evening, all the instrumentation located in the adjacent rooms (motor, fans) except the measuring equipment were switched off. The fluid was pumped into the upper chamber and then the pump motor was switched off, and during the experiment the fluid flowed from the upper chamber through the test section. Constant mass flow was maintained manually by regulators, the flow rate was measured with the rotameter RS-3 or RS-5. It was possible to maintain flow rate within an accuracy of ±2% manually (the variation in flow rate did not exceed ±1.5 divisions of the rotameter).

Experiments were conducted with "natural" transition and the initiation of turbulence was determined by uncontrolled initial disturbances which are unavoidably present in the

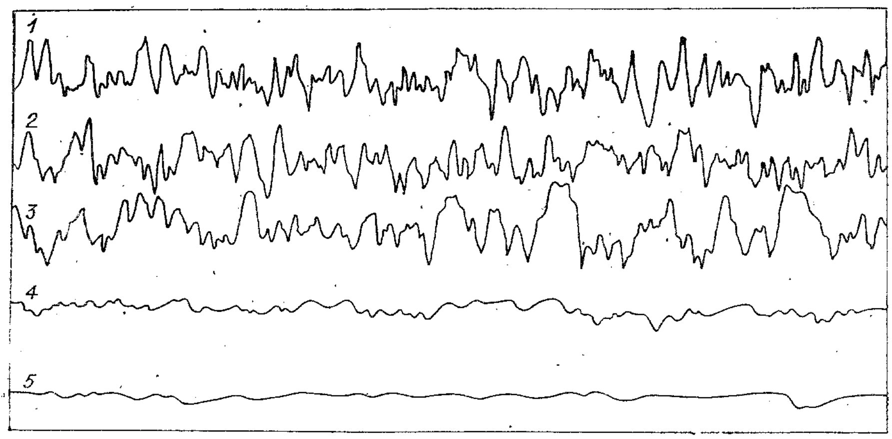
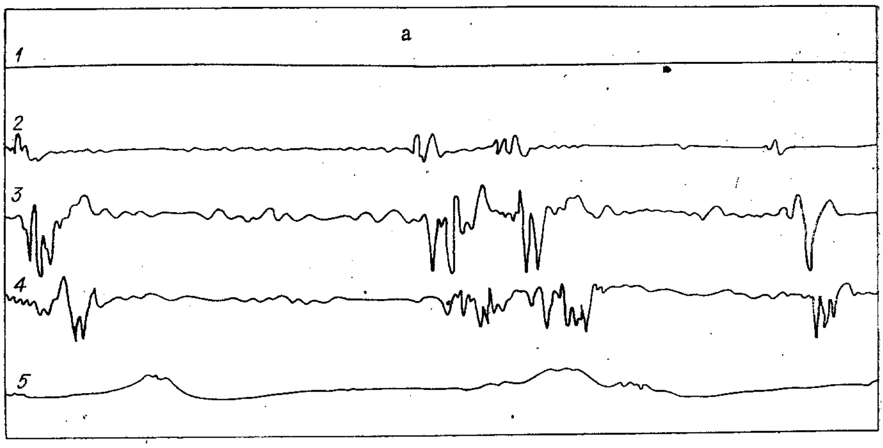


Fig. 4



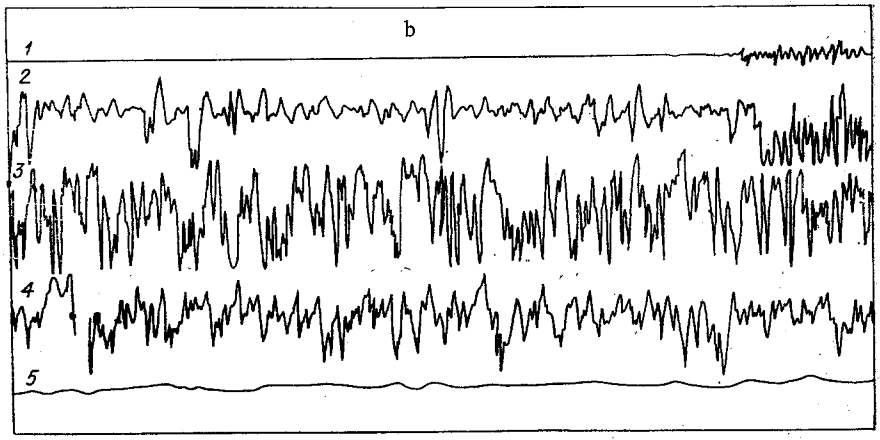


Fig. 5

hydrodynamic line. In principle, transition may also be affected by the vibration of the floor due to various sources, since their absence was controlled only in the neighborhood of the experimental setup. Vibration isolation was very difficult since they could be conveyed not only through the foundation on which the experiment was setup but also through the inlet and outlet tubes. Nevertheless, irregular disturbances could not, apparently, contribute significantly to the transition process.

Characteristic signals from electrochemical transducers located at different sections along the jet axis are shown in Fig. 5 as a function of time. Here Re = 4760, the x coordinate for 1: 15; for 2: 35; for 3: 55; for 4: 75; and for 5: 115 mm. In all the cases the electrochemical transducer located in the nozzle (at a distance x = –5 mm from the exit) indicated the absence of fluctuations even at large flow speeds so that the process developed immediately in the jet. The parameter that determines the beginning of transition is Reynolds number based on twice the gap thickness. In this case the critical Reynolds number at which there were sufficiently regular disturbances was close to the corresponding values for the flow in a circular pipe or plane channel. In this connection the present flow appreciably differed from free jet, where instability occurs at considerably lower Reynolds numbers [5].

As seen from Fig. 5, disturbances grow in two possible ways. At low Re, close to the critical value, short duration turbulent "spikes" appear (Fig. 5a). The generation of spikes takes place in the jet and is not the result of fluctuations in the flow rate, since, as a rule, when x = 15 mm, there are no disturbances. With increase in Reynolds number, as in the case of pipe flow, the spikes become longer, with a tendency to come together. It is easy to determine the displacement of the short spikes along the jet from the oscillograms.

Along with the spikes the flow also contains excited segments of appreciable duration (at low Re, from 3 to 10 sec). Excitation exists simultaneously at all sections along x, is continuous in time (within the interval of existence), and with higher frequency than "spikes." To some degree these segments are similar to the growth of disturbances in a free jet [6]. Characteristic excited segment is shown in Fig. 5b.

It is important to mention that it is a characteristic feature of the given flow for segments of undisturbed flow, "spikes," and excited segments (in Fig. 5a, b, these are parts of one and the same flow condition at Re = 4760) to exist at the same flow condition (at a given Reynolds number). The time sequence could be arbitrary but often the spikes appear immediately ahead of excited segments usually followed by undisturbed flow. With an increase in Reynolds number the excited parts appear frequently and finally they combine to form continuous turbulent flow up to a certain section x after which there is a breakdown of turbulence.

The appearance of sufficiently sharply defined "spikes" and excited segments are characteristic at h = 1 mm. When h = 2 mm there is a tendency for a smoother behavior of disturbances with time, which is close to the case of the flow in a free jet. Damping of disturbances along the jet depends both on b and h (similar to the developed turbulent flow) as well as on the type of disturbance. As a rule, "spikes" are propagated farther along x than the region of the disturbed flow.

The value of x at which the excited flow occurs is also not a fixed quantity even for one and the same b and h. As seen from Fig. 5, there are cases when, e.g., x = 15 mm, disturbances are practically absent whereas at x = 35 mm the disturbance is continuous. At the same flow condition excited region exists for certain time even at x = 15 mm. Apparently, the point at which disturbances appear moves randomly along the streamwise direction, the probability of the existence of excited region at a given x falls with a decrease in x, and for some small values of x this probability equals zero for the given flow. Unfortunately, a more detailed investigation of the nature of the movement of the point where disturbances appear along x was not possible because of the large distance between the transducers.

Experiments were also conducted in which the jet was formed from the developed flow in a rectangular channel of cross section 1.5 × 3.5 mm and 150 mm long (the geometry is indicated by dashed lines in Fig. 1). This made it possible, firstly, to evaluate the effect of initial conditions on the development of the flow in the jet, and secondly, to compare transition to turbulence in a rectangular channel and in the jet having free lateral boundaries. Records of the process for this case was compared with records for the jet flow from the nozzle of the same cross section at the same values of flow rates. In the presence of entrance region the initial flow instability is a continuous irregular disturbance whose characteristic frequency is appreciably lower than the flow without the entrance region. The excited regions are not formed in the given case. With an increase in Re, turbulent "spikes" with higher frequency begin to develop from the initial disturbances. These "spikes" are weakly indicated at x = −25 mm (the section is in the rectangular channel) but grow strongly in the jet flow. Higher frequency disturbances appear in the jet where the flow speed drops along the length and these disturbances pass through a considerable distance along x.

As a whole the flow with entrance region is more stable, in particular, with respect to high-frequency disturbances.

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