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# RIVULET FLOW OF LIQUID ON THE OUTER SURFACE OF AN INCLINED CYLINDER

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**Introduction.** Falling liquid films are wide spread in nature and are often used in technical applications. In the literature, most studies are devoted to homogeneous liquid films falling on a vertical cylinder or an inclined surface [1, 2]. In condensers and heat exchangers, horizontal tubes are often employed as well. In this case, the thickness of the film varies strongly over the perimeter of the tube but remains uniform along its generatrix. At present, condensers and heat exchangers with weakly inclined tubes are considered promising and are already in use. Such equipment is highly effective, because the condensate is collected on the lower generatrix of the tube, and a dropwise-condensation regime is realized on the remaining heat-exchange surface. Systematic studies of similar processes are not yet reported in the literature.

In the present study, we deal with an experimental study of the specific features of flow of a viscous liquid on the external surface of an inclined cylinder in jet irrigation.

**Experimental Equipment.** The experiment is shown schematically in Fig. 1. The working section is a glass tube with outer diameter $D = 19$ mm and 1 m long. The dimensions of the tube are characteristic of heat-exchange equipment. The liquid is fed to the working section as a jet issuing from a convergent nozzle with diameter $d = 1$–$3$ mm. The nozzle-to-cylinder surface distance $\delta$ was varied from 0 to 10 mm, and the angle of inclination of the cylinder $\alpha$ was varied from 2 to 15°.

The basic form of motion on an inclined cylinder is rivulet flow along the lower generatrix. In the literature, such a flow is called a rivulet. It is well known that the motion of a rivulet is mainly affected by the contact angle (wettability) and its hysteresis [3]. The latter effect leads to the unpredictable snakelike motion of the rivulet. This makes it impossible to obtain unambiguous flow characteristics. The basic result of the present study is the formation of rivulets with strictly constant parameters, and this enabled us to study the hydrodynamics of rivulet flow in detail. For this purpose, the glass tube was polished by grinding powders, and, as the working liquid, we used ethanol. As a result, a rivulet of constant width with zero contact angle was formed.

At a temperature of 20°C, the working liquid had the following physical characteristics: density 805 kg/m$^3$, kinematic viscosity $\nu = 1.49 \cdot 10^{-6}$ m$^2$/sec, and kinematic coefficient of surface tension $29.9 \cdot 10^{-6}$ m$^3$/sec. The liquid rate $Q$ was varied within the range 0.045–4.0 mliters/sec. The characteristic range of variation of the Reynolds number Re, which was defined as $\mathrm{Re} = Q/(b\nu)$, amounted to 3.8–270 for $\alpha = 10°$. Here $b$ is the width of the rivulet (Fig. 1).

During the experiment, the flow patterns were video- and photorecorded, the wave characteristics and the rivulet thicknesses were measured, and the magnitudes of liquid ejection were determined. The local thickness of the rivulet $h$, which was defined as the maximum thickness of the liquid layer in the transverse cross section of the rivulet (Fig. 1), was measured by the shadow method [1]. Its essence lies in registration of the shadow cast by the liquid layer exposed to light from the side. To convert the displacements of the shadow to an electric signal, we used a photodiode. The signal was then processed on a PC. The thickness of the smooth rivulet also served as a clock-type indicator with scale factor 0.01 mm.

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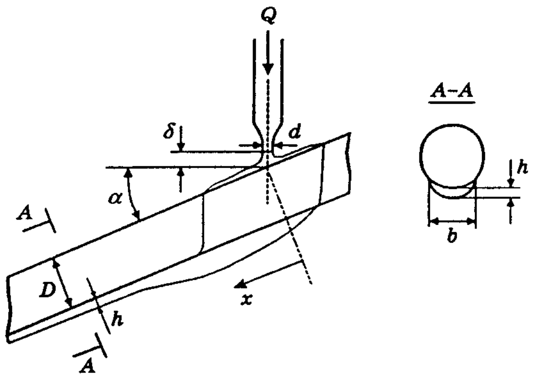

Fig. 1

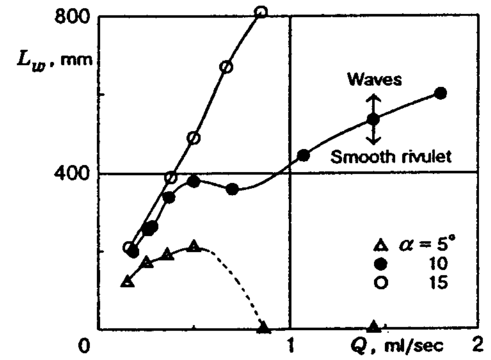

Fig. 2

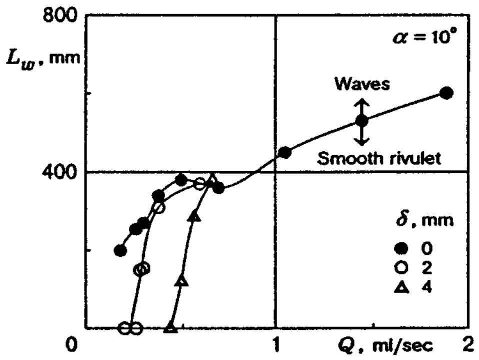

Fig. 3

**Experimental Results.** In impinging the jet on an inclined cylinder, one can distinguish three main flow zones: a zone of freely falling jet, a zone of continuous liquid film, and a zone of rivulet flow (or rivulet). In this study, we focused on the rivulet as the basic form of liquid motion on the inclined surface. In the range of angles of inclination $\alpha$ of the cylinder that we studied, the continuous-film zone is as small as a few centimeters.

As in the case of falling liquid films [1], the rivulet flow is unstable. This instability leads to nonlinear surface waves with a complex structure. The wave formation is mainly affected by the initial conditions, in particular, by the distance $\delta$ between the nozzle and the tube surface. For small $Q$ and at definite values of $\delta$, we observed a self-oscillating regime of jet outflow and jet breakdown into drops. In both cases, the wave formation begins directly in the irrigation zone, and the wave characteristics are defined by the frequency of the initial perturbations. Similar wave regimes are equivalent to the waves described by Alekseenko, Nakoryakov, and Pokusaev [1, 2].

At fairly large flow rates $Q$ and small $\delta$ (0–1 mm) there are no perturbations in the irrigation zone. In this case, waves appear owing to the natural instability of the flow and were first observed at a certain distance $L_w$ from the point of irrigation. We call them natural waves. Figure 2 shows the coordinate of the point of wave formation versus the rate $Q$ at various angles of inclination of the cylinder. Here $\delta = 0$, i.e., the initial perturbations are absent. For large angles of inclination of the flow ($\alpha \geqslant 15°$), the length of the smooth zone increases with increasing flow rate, whereas at small angles ($\alpha \leqslant 5°$) a local maximum of $L_w$ is reached as $Q$ increases. The $L_w$ value then decreases and becomes equal to zero at the critical value of $Q$. In the latter case, the entire surface of the rivulet is wavy.

Figure 3 shows the effect of the distance between the nozzle and the cylinder surface on the coordinate of the wave-formation point. As expected, the increase in $\delta$ in the region of small flow rates $Q$ gives rise to

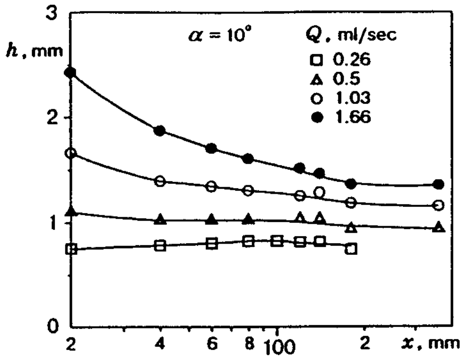

Fig. 4

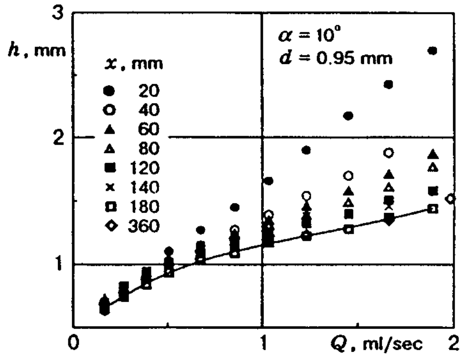

Fig. 5

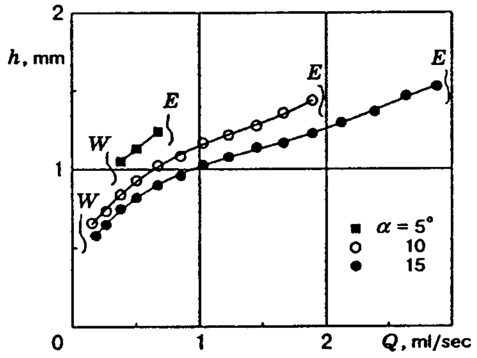

Fig. 6

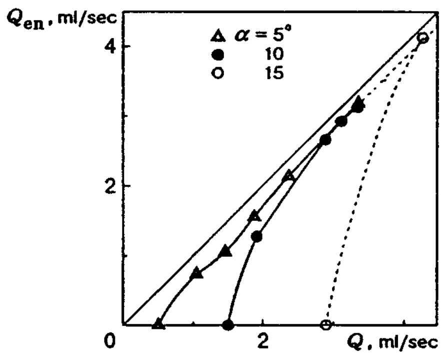

Fig. 7

the occurrence of initial perturbations and to a sharp decrease in the smooth zone. The data presented are indicative of the more complicated regularities of wave formation in rivulets compared with homogeneous films [1].

As is known, for weakly inclined flows of viscous liquid layers, there is a rather large initial region in which the hydrodynamic stabilization of flow occurs. The velocity field and the thickness of the layer change as well. In this work, we have studied the development of the thickness of the rivulet by which we mean its maximum value $h$ in the transverse cross section (see Fig. 1). Figure 4 shows examples of the smooth-rivulet thickness distributions along the longitudinal coordinate $x$ for various flow rates $Q$. Clearly, in the range of flow rates that we considered, the length of the initial section does not exceed 180–200 mm. The $h$ values versus $Q$ are given in Fig. 5 (the curve corresponds to steady-state flow).

A distinguishing feature of rivulets on the lower side of an inclined cylinder is flow separation from the interface surface. For each angle $\alpha$, there is a critical rate value starting from which the liquid is ejected. Two types of separation — droplet separation and jet separation — were discovered. The first type is observed at the crests of big waves, while the second appears in the irrigation region. Figure 6 shows the data on the thickness of the rivulet in the steady-state region as a function of $Q$. The experimental points split at the angle $\alpha$. For each empirical curve, the limit $E$ relative to the flow rate $Q$ beyond which an intense drop ejection begins is indicated. The boundary of the onset of wave formation $W$ is indicated on the left.

The intensity of ejection (flow rate) $Q_{\rm en}$ depends on the initial flow rate $Q$ and on the angle of inclination $\alpha$ (Fig. 7). However, for large values of the initial flow rate ($Q > 2$, 2.8, and 4.2 ml/sec for $\alpha = 5$, 10, and 15°), the intensity of separation is directly proportional to the rate $Q$ and does not depend on $\alpha$. This implies a constant flow rate in steady-state rivulet flow. The value of the flow rate $(Q - Q_{\rm en})$ equals approximately 0.25 ml/sec.

One more important flow parameter is the width of the rivulet, i.e., the region of the wetted surface of

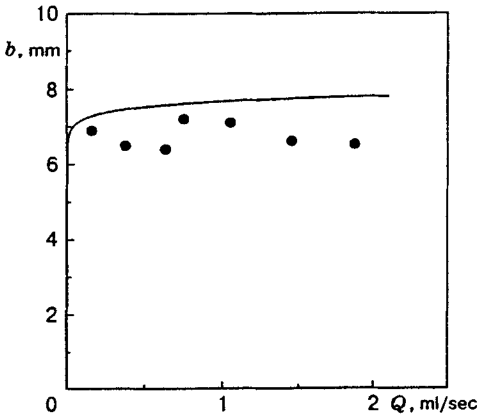

Fig. 8

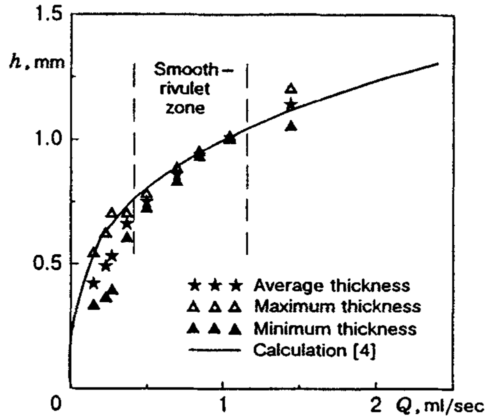

Fig. 9

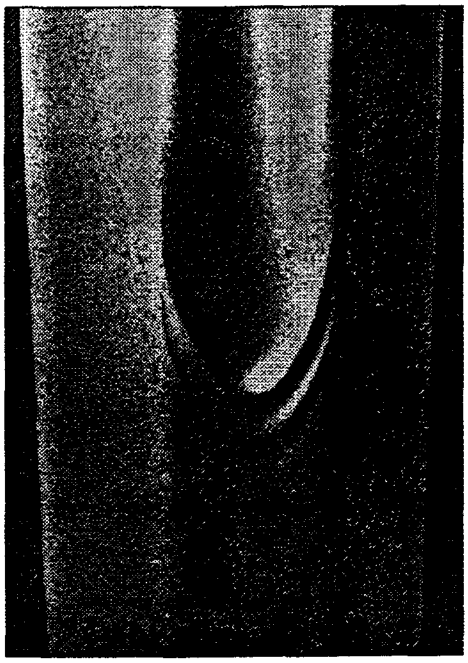

Fig. 10

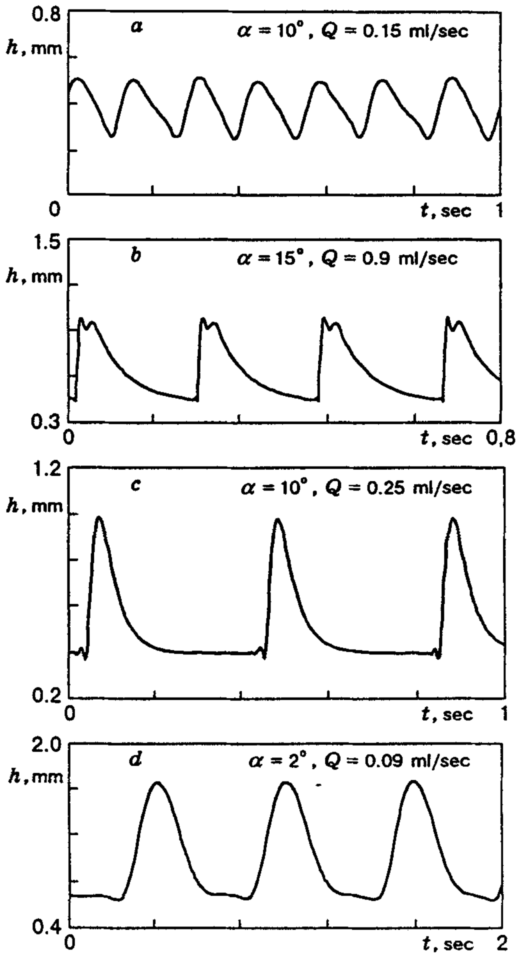

Fig. 11

the cylinder. It turned out that in the range of parameters under study, the rivulet width $b$ does not depend on the flow rate. Figure 8 illustrates the data on the width of the rivulet for $\alpha = 10°$ and $x = 260$ mm (points refer to the experimental results of the present study, and the curve refers to the calculation of [4]). The constancy of the rivulet width is in agreement with the predictions of the single theoretical investigation [4] and is of paramount value for analysis of heat-transfer processes in heat exchangers with inclined tubes.

In Fig. 9, the dependences of $h$ on $Q$, obtained in [4] and in our study ($\alpha = 10°$ and $x = 180$ mm), are compared. The experimental data for both smooth and wavy flows were used. On the whole, the agreement is satisfactory. The systematic deviation of the experimental points from the theoretical curve at very small flow rates needs, however, to be explained. Note that the calculated dependence $h(Q)$ is strongly different from the cubic Nusselt law for a plane film [1] because of the strongly nonuniform thickness of the liquid layer over the circumference of the cylinder.

It follows from the experiment that the wavy regime is a typical rivulet regime. Unlike film flows, rivulet flows are always three-dimensional, as is seen from the photograph in Fig. 10 (bottom view). However, the fairly small width of the rivulet leads to the coincidence of the transverse dimension of the wave with the width of the liquid flow and, hence, quite determined waves are realized, which are comprehensively described by experiment.

Figure 11 shows the most typical oscillograms of the surface waves in the rivulet. Clearly, there are periodic waves, which are almost sinusoidal, and soliton-like waves. It is noteworthy that the wave profiles in Fig. 11a and c are completely identical to the waves on the vertically falling liquid film. The other two types of waves are new in comparison with the plane film.

The wave regime in Fig. 11d is a sequence of almost axisymmetric drops moving slowly over the lower side of the weakly inclined cylinder. The main mechanism of formation of such waves is likely to be associated with the Rayleigh–Taylor instability.

The wave regime in Fig. 11b is typical of the higher angles of inclination ($\alpha \geqslant 15°$) and of the larger flow rates. A specific feature of this regime is the presence of two humps and a very smooth tail. These waves are shaped like the Burger triangles observed in the plane film at very small flow rates [1].

Thus, we have studied experimentally the rivulet flow along the lower side of an inclined cylinder upon jet supply of a liquid. It has been shown that in the range of parameters considered, the magnitude of the wetted surface of the cylinder is constant and is not dependent on the flow rate. The data on the thickness of the rivulet, the wave characteristics, and on the amount of liquid ejected due to drop separation from the free surface have been given. New types of waves have been discovered.

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