# FLOW OF A LIQUID FILM ALONG A VERTICAL SURFACE

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Results are shown of a study, by the photographic method, concerning the flow of a water film along a vertical glass plate by wave and by turbulent motion.

The most important experimental and theoretical studies concerning the flow of liquid films have been surveyed and analyzed in [1, 2].

In view of the complexity of the actual pattern, especially at high values of the Reynolds number, the basic method of studying a film flow is by experiment.

Modern experimental techniques for studying the characteristics of film flow (these techniques are described thoroughly in [3]) include the widely used photographic methods, which obviate the need for special measuring probes inserted into the stream and inevitably distorting the flow pattern. Just as important is the fact that photographic methods yield a general qualitative estimate of the liquid flow characteristics, which is absolutely necessary for the understanding of its physical nature.

The flow of a liquid film along a vertical glass plate was studied photographically and the results will be shown here. The test apparatus was set up according to the schematic diagram in Fig. 1. Water was raised from reservoir 1 to the discharge tank 3 by means of a pump 2 and then let run down through a channel onto a vertical plate of polished mirror-quality glass. The water rate was checked by a rotameter 5. The wet plate surface was illuminated from a light source 6. The optical inhomogeneity of the dropping film, owing to the wavy structure of its free surface, projected a shadow onto a dull screen on the obverse side of the glass plate. Pictures of this shadow were taken with camera 8.

For photographing we used as the light source a pulse-type electron tube giving light flashes of approximately $2 \cdot 10^{-4}$ sec duration. For kinematography we used a 500 W reflector-type phototube. The active height of the glass plate was 1.9 m. The water stream was 0.25 m wide in all tests.

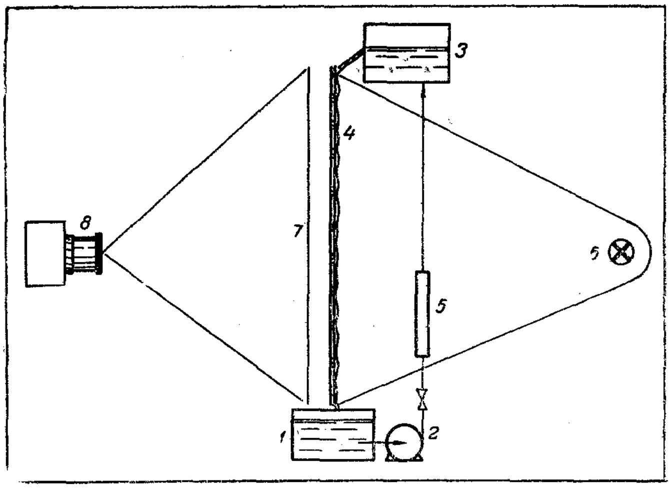


Fig. 1. Schematic diagram of the test apparatus.

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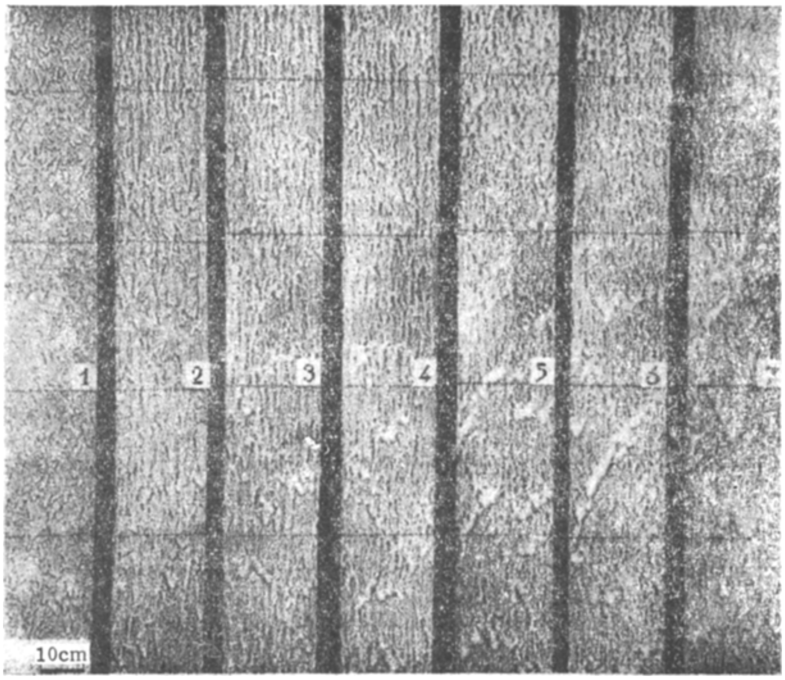

Fig. 2. Photographs showing the film flow of water at various values of the Reynolds number: Re = 382 (1), 1400 (2), 2400 (3), 2650 (4), 4300 (5), 4620 (6), 6900 (7).

Both wavy and turbulent flow of the film were studied with the Reynolds ranging from 175 to 10,000.

Unlike the conventional photographic test methods [4, 5], this shadow method allows one to see and, therefore, also to photograph the flow pattern across the entire plane of the glass.

The photographs in Figs. 2 and 3 show how a typical stream structure changes as the Reynolds number is increased. A general concept of the flow pattern covering the entire plane of the film can be inferred from Fig. 2. The upper edge of the picture frame refers to a distance of 0.2 m from the distributor.

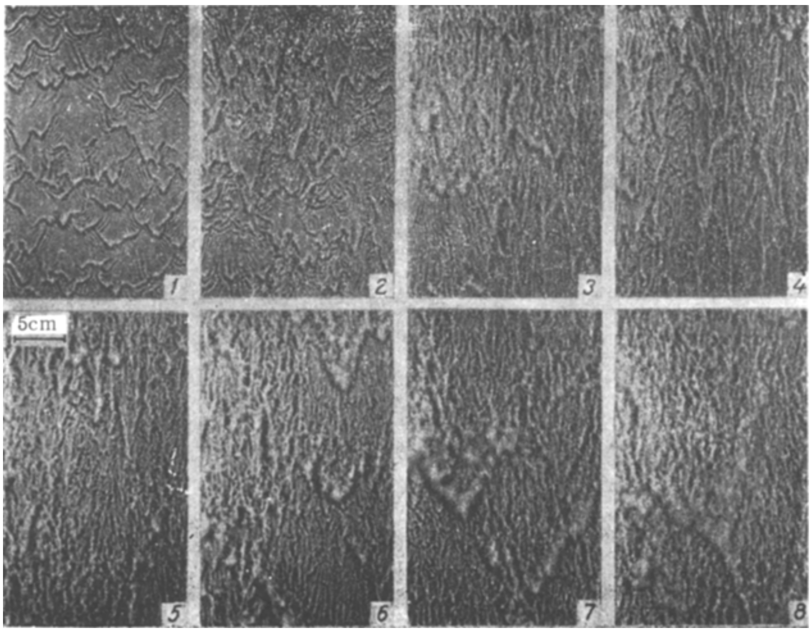

Fig. 3. Flow characteristics of a water film at a distance of 1.2 m from the distributor, at various values of the Reynolds number: Re = 175 (1), 330 (2), 2200 (3), 2300 (4), 2800 (5), 3500 (6), 5300 (7), 6900 (8).

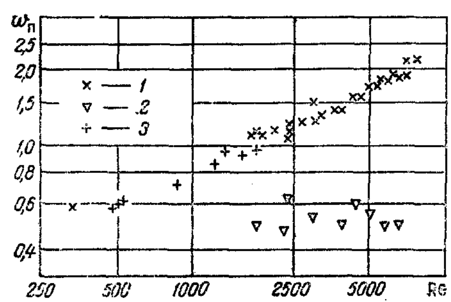


Fig. 4. Velocity of wave propagation (m/sec), as a function of the Reynolds number: velocity of large waves (1), velocity of waves in the "lower" layer (2), data of [7] (3).

The most characteristic segments in the stable flow region were photographed at a distance of 1.2 m from the distributor and are shown in Fig. 3.

At a Reynolds number Re = 178 already (Fig. 3; 1) the entire film surface is uniformly covered with a wave mesh. As the Reynolds number increases, the wave pattern evolves into a merger and collapse of individual waves (Fig. 2: 1), a gradual elongation of the waves (Fig. 2: 2 and Fig. 3: 2), and a stronger interference between the waves. The liquid at the wave crests begins to move intensely, the crests begin to swell and "break" (lower region in Fig. 2; 2), and ripples begin to appear on the surface of the large elongated waves.

It can be seen in Fig. 2 that an increase of the Reynolds number lengthens the zone of flow stabilization. A drastic lengthening of this zone occurs approximately when Re = 2,000-2,500.

The wave structure begins to change at Re = 1500, when the elongated waves collapse and a "two-layer" flow mode sets in (Fig. 2: 3, 4 and Fig. 3: 3, 4, 5). The "lower" layer of liquid, adjoining the wall, has a smooth free surface covered with a mesh of ripples. The "upper" layer of liquid consists of discrete large waves moving very fast along the surface of the "lower" layer while perturbing and turbulizing it. The build up of large waves ceases approximately when Re = 3,500.

As the Reynolds number increases further, the velocity of the large waves becomes higher and the "lower" film gradually acquires a microporous turbulent structure.

While in Fig. 2; 5, 6 and Fig. 3: 6, 7 one can still observe discrete areas of a smooth surface, in Fig. 2: 7 and Fig. 3: 8 the entire surface of the "lower" layer is already covered with ripples. The turbulence is fully developed when the Reynolds number has reached the range Re = 8,000-10,000 (no photographs of this conditions are shown here). Large waves become already indistinguishable on the film surface and the latter becomes uniformly porous.

The development of turbulence during the film flow of a liquid is in many aspects analogous to the development of turbulence during the flow of a liquid through pipes. Recent studies concerning the development of turbulence [6] have shown that laminar and turbulent flow modes may appear staggered in one section at the same Reynolds number. The reason for this staggering of modes is that turbulence originates within descrete regions of the stream in the form of "locks" covering the entire pipe section. A somewhat similar pattern is observed in the film flow of a liquid. These so-called locks appear now in the form of staggered turbulent waves.

In this kind of flow, as in a pipe flow, the energy required for developing turbulence is drawn from the main stream, whose shape becomes unique during the film flow of a liquid on account of surface tension acting on the free surface.

The excellent picture obtained by the shadow method has made it possible to measure the propagation velocity of large as well as small waves in the "lower" layer. The results of these measurements are given in Fig. 4. For comparison, on the same diagram are also shown the data obtained by D. West and R. Cole [7], who measured the surface velocity of a water film by photographing fine nonwettable luminous particles sprayed on the film surface. As can be seen here, our velocity measurements made for large waves agree closely with the values obtained by those authors. The velocity of waves in the "lower" layer is on the average 0.5 m/sec and does not depend on the Reynolds number. Assuming for the "lower" layer a ratio of surface velocity to mean velocity equal to 1.5 [8], and using the equation for the mean flow velocity

$$w = \frac{g\,\delta^2}{3\nu},$$

we find that the mean thickness of the "lower" layer is 0.32 mm. This agrees with the findings by H. Brauer [8], who has shown that, when the Reynolds number Re > 1600, the minimum film thickness at the wave valleys is 0.3 mm and does not depend on the Reynolds number.

Knowing the film thickness and its mean flow velocity, we can now determine the Reynolds number for the "lower" layer ($Re = 4\delta w/\nu$) and find that here Re = 400. This indicates that the flow in the "lower" layer is laminar.

Thus, the peculiar characteristics of turbulence developing in the film flow of a liquid is that a large portion of the film remains in a laminar state. The turbulent portion of the film, which corresponds to the main stream in a pipe flow, exists as discrete turbulent waves which form a continuous layer of liquid only when the Reynolds number reaches the 8,000-10,000 range.

## NOTATION

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| $Re = 4\Gamma/\nu = 4w\delta/\nu$ | is the Reynolds number for a film of liquid; |
| $\Gamma$ | is the water spray density, $m^2/sec$; |
| $\nu$ | is the kinematic viscosity, $m^2/sec$; |
| $w$ | is the mean velocity of film, m/sec; |
| $w_s$ | is the velocity at the film surface, m/sec; |
| $\delta$ | is the mean film thickness, m; |
| $g$ | is the acceleration of free fall, $m/sec^2$. |

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