

EXPERIMENTAL STUDY OF THE EFFECT OF CONDENSATION
ON THE TRANSITION INTO THE TURBULENT MODE OF FLOW
IN A DESCENDING FILM OF LIQUID WITH AN ASSOCIATED
GAS STREAM FLOWING AROUND IT

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The results of an experimental investigation into the transition of a descending film of water into the turbulent mode of flow are presented, the film being accompanied by a stream of gas, either of the condensing variety (water vapor) or of the noncondensing kind (air).

In order to calculate the heat and mass transfer taking place in various film-type devices, it is essential to know the limits of stability of the several possible modes of flow of a descending film of liquid: strictly laminar, laminar-wave motion, or turbulent. The results of some experimental investigations into the hydrodynamics of a descending film in contact with stationary air were presented in [1]. The Reynolds numbers corresponding to transition from the strictly laminar to laminar-wave motion or from the latter to turbulent flow were determined. Other published data [2, 3] indicate that, when a descending film is acted upon by a counterflow of noncondensing gas, the limits of stability of the strictly laminar and laminar-wave forms of flow are greatly reduced. However, as yet the transition to turbulent flow in descending films with a flow of associated gas passing around them has never been studied. Also of special interest from the point of view of condensation devices are the limits of stability of the various modes of flow of a descending film during the condensation of moving vapor.

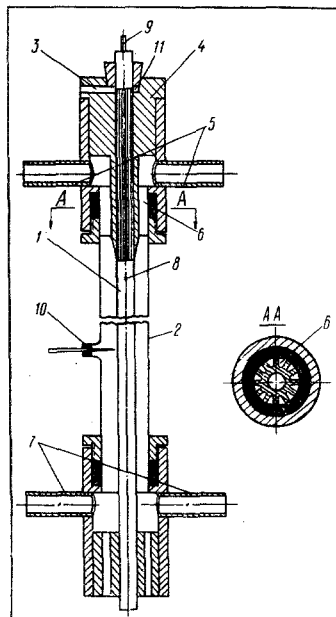


Fig. 1. Arrangement of the principal parts of the experimental apparatus.

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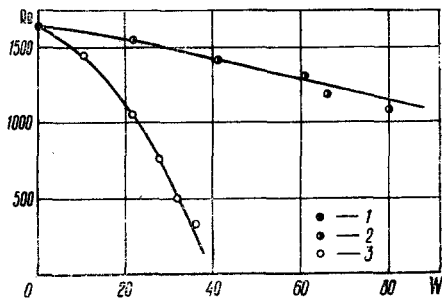


Fig. 2. Dependence of the transitional Reynolds number on the rate of gas flow (W , m/sec): 1) without any gas phase flowing around it; 2) gas flow and condensation; 3) gas flow without condensation.

We accordingly set up a special experimental apparatus to study the transition to turbulent flow in descending water films with flows of both noncondensing gas (air) and condensing water vapor passing around them. We shall now describe the experimental apparatus and the method of conducting the experiments and also set out the results of this investigation.

A descending water film was created on the outer surface of a vertical aluminum tube 1 (external diameter 10 mm, length of the part covered with the film 250 mm). A flow of distilled water regulated from outside with a valve passed through the channel 3 into the annular groove 11 encompassing the tube 1. Then the distilled water passed into the gap between the tube 1 and the bushing 4. The gap in question comprised a set of parallel capillary channels milled on the outer surface of the tube 1 and ensured the creation of a descending film uniform over the tube perimeter. Air or water vapor passed through the side tubes 5 into the unit. Passing through longitudinal parallel channels 6 (channel depth 5 mm, maximum width 4 mm,

length 50 mm), in which any possible eddying was eliminated, the gas flow passed into an annular gap between the film flowing down the tube 1 and the glass tube 2, with an internal diameter of 22 mm. The gas flow was led out through the side tubes 7. In the upper part of the tube 1 was an aperture 8 with a diameter of 0.1 mm for feeding an extremely fine jet of coloring liquid into the film through the capillary 9. On passing water vapor into the apparatus the tube 1 was cooled by passing tap-water through it; the moving vapor then condensed on the surface of the film, accompanied by specific thermal fluxes of the order of $2 \cdot 10^5$ W/m². When the moving vapor was being condensed, the glass tube 2 was heated from the outside in order to prevent blocking.

Under this apparatus we measured the flow of liquid in the descending film (by weighing), the flow rate of injected air (with a double diaphragm), the flow rate of injected vapor (by weighing after complete condensation in an auxiliary condenser), and the temperature of the injected distilled water. The uniformity of the descending film around the tube perimeter was verified by measuring the film thickness on different sides of the tube in the same horizontal section, using the electric probe 10. The Reynolds number of the film was determined from the equation

$$Re = 4V/\nu. \quad (1)$$

The transition from laminar-wave flow to turbulent flow was studied by visual observation of the state of the fine jet of injected coloring liquid. For low rates of flow of the liquid in the film this jet suffered no dispersion and was clearly visible along the whole length of the tube. On increasing the rate of flow a condition developed in which the jet started becoming diffuse in the lower part of the tube. On further increasing the rate of flow the boundary of the diffuse region approached the aperture 8. All this suggested that the point at which the colored jet became diffuse corresponded to the point of transition into the turbulent mode of flow in the film of descending liquid.

In order to verify the method we first made some experiments with a stationary gas phase (without injecting air or vapor). In these experiments we obtained stably reproducible Reynolds numbers corresponding to the transition into the turbulent form of flow in the film. This value of the Reynolds number according to our experimental results equalled 1600 (error no greater than $\pm 8\%$), in good agreement with earlier data [1].* Subsequently we started experiments involving the injection of air and waver vapor (with condensation on the film).

Figure 2 shows the transitional Reynolds numbers as a function of the velocities of the air flow and the condensing vapor. The curves refer to a cross section at 150 mm from the beginning of the film.

We see from the curves presented that with increasing rate of gas flow the stability of the laminar-wave motion of the descending film decreases, and this leads to a fall in the Reynolds number corresponding to the transition into the turbulent mode of flow. However, the extent to which the stability is reduced

*In [1] the Reynolds number was determined from the equation $Re = V/\nu$. The value of the transitional Reynolds number established in these experiments was 400, which on referring the determination to Eq. (1) gives 1600.

with increasing velocity of the gas phase is substantially affected by the condensation process. We see from the curves that, whereas in the presence of an air flow ("dry" flow) at a velocity of 36 m/sec the transitional Reynolds number falls to 320, in the case of the condensation of vapor moving at 42 m/sec it only falls to 1450. Even for the maximum velocities of the vapor (up to 80 m/sec) the transitional Reynolds number does not fall as far as 1000. It should be noted that these results (for the condensation of moving vapor) agree satisfactorily with experiments on heat transfer [4] in which the transition to the turbulent form of flow in a condensate film is reflected by a change in the heat-transfer law.

As a whole the results obtained indicate considerable differences in the hydrodynamic interactions between the gas phase and the liquid film for the two cases in question: "dry" flow, and flow with condensation. The condensation process not only greatly alters the laws of interphase friction, as indicated in [5, 6], but also largely determines the character of the flow in the film of condensate.

NOTATION

- Re is the Reynolds number;
V is the volume flow of liquid in the film per unit length of the tube perimeter;
 ν is the kinematic viscosity of the liquid;
W is the velocity of the gas and vapor flows.

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