RANGE OF EXISTENCE OF CONTINUOUS FILM FLOW

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The problem of finding the range of existence of a continuous film is analyzed for the case of a wave mechanism for the flow.

A problem which arises in the development of improved equipment for large power systems is that of the film flow of a liquid. For example, the choice of the optimum range of working conditions for the separation equipment in steam generators and turbines for an atomic cycle depends on the determination of the upper stability boundary of the flow, i.e., the point at which drops break away from the surface of the film, as well as the lower boundary, corresponding to the existence of a continuous liquid layer. Many problems arise from the motion of a film in the flowing part of wet-steam turbine stages, where a liquid film on the wall can rupture and pull away from the wall, forming bands which generate intense showers of drops. These drops pose an erosion hazard to the blades and greatly reduce the efficiency of the turbine stages.

Apparently the first attempt to determine the conditions for the rupture of the film in an isothermal flow was undertaken by Hartley and Murgatroyd [1]. They formulated stability conditions in terms of the force and energy. The force condition is based on the assumption that in the static state the surface-tension force of the meniscus formed upon the rupture of film balances the force due to the liquid pressure on the meniscus. This latter force arises in the conversion of the kinetic energy of the moving layer into pressure (Fig. 1a):

$$P_\sigma = P_{v'} \tag{1a}$$

or

$$\sigma(1-\cos\theta) = \int_0^\delta \frac{\rho'}{2}\,[v'(y)]^2\,dy. \tag{1b}$$

The energy condition is determined from the condition that the film reaching the wall through cross section AB (Fig. 1b) ultimately reaches a constant width T and a thickness δ such that the sum of the kinetic and surface energies of the flux is minimized:

$$E_{\text{kin}} + E_\sigma = T\int_0^\delta \frac{\rho'}{2}\,[v'(y)]^3\,dy + T\sigma v'_{\text{srf}} \equiv \min. \tag{2}$$

In subsequent work [2-4] these conditions were supplemented by an account of the thermocapillary forces, the friction force at the free surface, and the weight; the aerodynamic drag exerted on the end of the film was also taken into account. Since the quantity θ has remained unknown, the force condition has not been tested experimentally. On the other hand, comparison of calculations based on Eq. (2) with the experimental data given in [1] shows that the calculated values of the minimum film thicknesses are several times larger than the experimental values. We believe that the reason for this pronounced discrepancy should be sought in the circumstance that the calculations have been based on a film which retains a smooth surface and a constant thickness up to the point at which the meniscus begins, while in the overwhelming majority of actual flow regimes there is a wavy structure.

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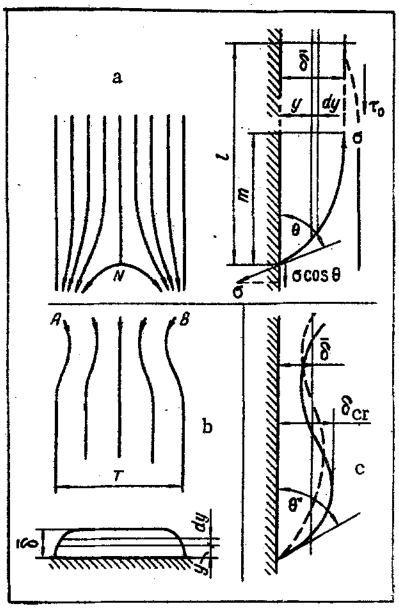

Fig. 1

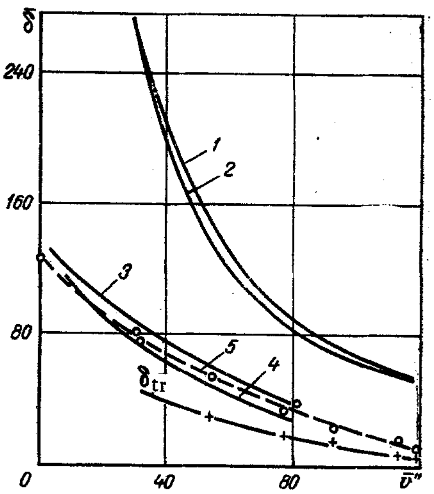

Fig. 2

Fig. 1. Diagrams used in deriving the stability conditions for film flow.

Fig. 2. Comparison of the calculated and experimental values of the average film thickness at the stability boundary ($\bar{\delta}$ and δ_{tr} are given in microns, $\bar{v}''$ is in meters per second).

In the present paper we adopt the following model for the liquid motion in the meniscus zone (Fig. 1c). In the film there is a wave motion such that waves of small and large amplitude alternately reach the meniscus and are damped at its edge. As a wave approaches the meniscus, there is an increase in the angle θ; as a wave leaves the meniscus or is damped, the contact angle decreases. If the instantaneous value of θ is higher than the limiting value θ^*, the equilibrium in the meniscus zone is disrupted, and the meniscus begins to move downstream. In contrast, when waves affect the edge of the dry region only slightly, the meniscus will begin to move upstream. The problem of the stability of the leading edge thus reduces to the problem of the equilibrium at the instant at which the largest waves are damped. Assuming in a first approximation that the wave velocity is independent of its amplitude, we write the force exerted by the wave on the meniscus as

$$P_c = \int_0^{\delta_{cr}} \frac{\rho'}{2} [c(y)]^2 dy = \frac{\rho'}{2} c^2 \delta_{cr}, \tag{3}$$

where c and δ_{cr} are the phase velocity and thickness of the film, respectively. Denoting the ratio of the pulsed force to the average force as

$$K_r = P_c / P_{v'}, \tag{4}$$

we write equilibrium condition (1a) as

$$P_\sigma = K_r P_{v'}, \tag{5}$$

where $P_{v'}$ is defined above and K_r is a function of the particular regime.

To check Eqs. (1) and (2), we have carried out special experiments on the apparatus described in [5]. Since there are familiar experimental difficulties in measuring the angle θ during the formation of a dry region in film flow, we examined the behavior of large, thick drops of water on the surface of metals of various degrees of purity, making the assumption that the angle θ formed by the leading edge of the drop in the state of unstable equilibrium is approximately equal to the contact angle at the boundary of the dry region in the film during flow over the corresponding surface. The angles were measured from suitably enlarged photographs. To measure the parameters of the film flow, we used a method involving simultaneous multichannel detection with the measurement circuits of [6].

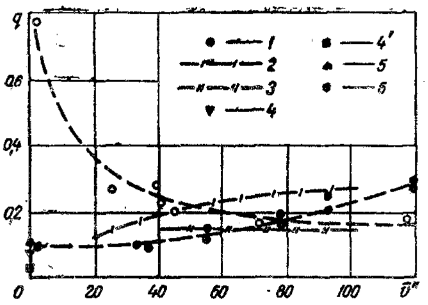

Fig. 3. Dependence of the minimum flow rate in film [q, $cm^3/(cm \cdot sec)$] on the flow direction and on the velocity of the comoving gas flow ($\bar{v}''$, m/sec). 1) From [7]; 2) [11]; 3) [8]; 4) [9] (type 18N10T); 4') [9] (type St. 3); 5) [10]; 6) data of the present study.

The experimental value of the average film thickness corresponding to the stability boundary of comoving and free flow on a vertical wall is shown by dashed curve 5 in Fig. 2. Curve 1 is plotted on the basis of Eq. (1) and the experimental values of the edge angle. Calculations from the force condition taking into account the weight, the surface tension, and the aerodynamic drag yield values of δ which are 15-60% lower than those calculated from Eq. (1). The most important of these additional forces is the tangential stress at the film surface in the vicinity of the meniscus. Since this stress can be determined only extremely crudely [3], however, the values given for the influence of this force should be treated as rough estimates. It follows from Fig. 2 that the experimental values of the film thickness are 2.5-4 times lower than those calculated from Eq. (1). Shown for comparison in Fig. 2 is curve 3, plotted from Eq. (5), in which the coefficient K_r is determined, in accordance with (4), on the basis of the experimental dependence of the local properties of the flow. The discrepancy between the experimental values of $\bar{\delta}$ and those calculated from Eq. (5) does not exceed 15%, so we judge the agreement to be satisfactory.

A distinctive feature of the energy condition is that it is independent of the contact angle, so that at first glance this condition would seem to be more convenient for practical use. By differentiating Eq. (2) with respect to δ, we can find the calculated value of the average film thickness for the corresponding velocity profile. The results of such calculations for the experimental conditions are shown by curve 2 in Fig. 2. There are two reasons for the discrepancy between the experimental and calculated data: Firstly, the film with the equivalent average thickness and with the linear velocity profile adopted in the calculation corresponds to the actual film structure which is formed with the flow rate corresponding to the stability boundary only in the range $\bar{v}'' = 20$-80 m/sec. Secondly, in the form in which it is given, this condition assumes flow with a smooth surface, for which the energetic properties of the film flow are constant over time. The actual structure of film flow is such that we can treat it as an energetically pulsating flow. Large waves moving at a high velocity and incorporating a large mass of moving liquid have a kinetic energy higher than that of the regions of troughs and small waves which follow them. Turning back to Eq. (2), we should write E_{kin} as the sum of the kinetic energy spectra of the translational motion of all parts of the film, and we should write the term E_σ as a function of the surface velocity with a clearly defined nonequilibrium wave motion. To determine the functional dependences of the components of the energy balance on the structural and kinematic parameters of the film flow, we must of course analyze the internal motion of the flow — an extremely complicated problem.

Let us approach this problem in a different way: We note that the rupture of the liquid film requires a certain time to occur. At any point in the flow, as a potential rupture zone, the stability boundary corresponds to that state in which the kinetic energy pulse of a large wave is capable of balancing the energy expended on stretching the film and is capable of preventing further rupture. If the time interval between the passage of two waves is no longer than the scale time for the rupture of the film, we should replace the term E_{kin} in Eq. (2), determined from the average parameters, by the kinetic energy of a large wave. We introduce the coefficient of the pulsation of the kinetic energy of the translational motion, which is equal to the ratio of the instantaneous peak kinetic energy of the wave to the kinetic energy of a layer of the equivalent average thickness:

$$K_E = E^{\lambda}_{kin}/E_{kin}. \tag{6}$$

For estimates we can use

$$E^{\lambda}_{kin} = \int_0^{\delta_{cr};\ \delta_{cr}-\delta_{tr}} \frac{\rho'}{2}[c(y)]^3\, dy. \tag{7}$$

Here the choice of the upper limit for the integration depends on the flow regime: The more developed the structure of the film flow, the higher the fraction of the energy which is transported in the wavy layer. We have used Eqs. (6) and (7) along with Eq. (2) and the experimental results to calculate the average film thickness; the result is shown by curve 4 in Fig. 2. The calculated values turn out to be quite close to the experimental values, despite the assumptions used in this approach.

The relative positions of curves 3 and 4 correspond to the initial assumptions used in formulating the stability conditions. The energetic condition determines the boundary corresponding to the formation of the rupture zone, while the force condition describes the same boundary for the opposite course of the process. In the latter case the film thickness and the flow rate in the film should be higher; this hysteresis is verified by the experimental results.

The stability conditions can be used in practice if we note the relationship between the local parameters and the parameters of the regime. At present this relationship can be established only for a restricted range of conditions and a restricted range of physical properties of the liquid. We therefore examine the direct relationship between the specific flow rate in film and the parameters of the regime for the stability boundary. We compare the results with the data reported by other investigators. Figure 3 shows the experimental dependences required by Permyakov [7] and Zozulya [8] for horizontal flow and those reported by Potorzhinskaya and Olevskii [9], Norman and McIntyre [10], and Shearer and Nedderman [11] for vertical flow. For the case of free drainage, the data from the present study agree well with the data from [9, 10]; for comoving flow, the nature of the change in the minimum flow rate agrees qualitatively with the data reported by Shearer and Nedderman: The higher the gas velocity, the higher the minimum flow rate. The higher values of q at small values of $\bar{v}''$ for the horizontal flow result from the circumstance that the kinetic energy of the waves in this case is much lower than in the case of vertical flow, in which case the gravitational force is important. At higher velocities $\bar{v}''$ we should apparently assume the minimum flow rate to be independent of the flow orientation.

We see from these experimental results that the increase in E_{kin}^{λ} at $\bar{v}'' > 100$ m/sec slows, because the increase in the wave velocity occurs much more slowly than the decrease in the mass velocity in the waves. At the same time there is an intense increase in the kinetic energy of the equivalent flat layer, because the increase in the average flow velocity $\bar{v}'$ leads the decrease in the thickness $\bar{\delta}$. There is an energetic "smoothing" of the film layer. This smoothing, as we see from the energy condition, leads to a relative increase in the maximum stable thickness or to discharge in the film.

The data from these experiments correspond to flow under conditions such that drops do not break away, as well as to conditions such that there is an intense production of drops. For the dependence shown in Fig. 3, the drops break away in the range $\bar{v}'' = 85$-95 m/sec. It follows from the nature of the curve that this breaking away does not explicitly affect the rupture of the film. However, film rupture can cause drops to break away near the rupture boundary; in flow in which drops are breaking away, the rupture intensifies the drop formation. When dry regions form, the specific flow rate in the remaining part of the film increases, so that the thickness increases there. Drops are more likely to break away from a thick film, so that drops enter the gas core of the flow more rapidly.

NOTATION

E_{kin}, E_{σ}, kinetic energy and surface energy of the liquid layer, respectively; y, coordinate across the film; σ, surface tension of the liquid; ρ', density of liquids; v', film velocity; $\bar{v}''$, average velocity of gas flow; δ, film thickness; $\bar{\delta}$, average film thickness; δ_{cr}, film thickness at crests; δ_{tr}, thickness at troughs; c, phase velocity; θ, edge wetting angle; q, specific flow rate of liquid in film.

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