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FLOW BENEATH AN INCLINED PLATE, ESTABLISHED IN AN AGGREGATIVELY UNSTABLE SYSTEM

V. I. Chizhov and M. V. Demura UDC 628.16.066.7

The flow of a film under a plate is investigated. An expression is obtained for determining the angle of inclination of the plate, for large values of which the flow of the film transforms into wave motion.

Gravitational separation of aggregatively unstable systems, represented by highly concentrated finely dispersed particles, in the space between the inclined elements (plates, pipes) proceeds more vigorously than settling in an infinite space. Many workers have shown that under static and dynamic conditions the maximum rate of the sedimentation process for suspensions with concentrations 10-50 kg/m^3 is observed for plates positioned at an angle of 30-40° to the horizontal [1, 2]. It was assumed that the basic factor that influences the increase in the sedimentation rate of suspensions is the smallest height of the sediment determined along the vertical from the upper plate to the lower plate. However, as experience has shown, separation of an aggregatively unstable system in the space between inclined plates is accompanied by the formation of a film flow of the clarified liquid under the upper plate, which must have an effect on the sedimentation rate. We studied the flow that forms on an experimental setup which consisted of a collection of flat glass tubes closed at one end ($l = 0.5$ and 1.0 m; $b = 0.15$ m; $h = 0.023$, 0.033, and 0.053 m), a device for recording the changes in the velocity of motion of the film, including a MT-54M microthermistor sensor and a plotting device, and a system for photographing different aspects of the flow. The modeling medium was chosen as an unflocculated suspension of kaolin with a density of $\rho_s = 1010$-1015 kg/m^3. The investigations were carried out under static conditions using the following technique. The flat glass tubes were filled with carefully mixed modeling medium and they were placed successively at different angles to the horizontal. The sedimentation process in the inclined tube was accompanied by the formation of a film flow of the clear liquid beneath the upper plate. A coloring liquid was introduced into the effective cross section of the moving film in order to make visual observations and a microthermistor sensor was also inserted in order to record changes in the velocity of motion of the film.

When the angle of inclination of the tube was varied from 20 to 80°, visual analysis of the motion of the colored liquid revealed the presence of two regimes in the flow of the film: laminar and turbulent; analysis of the trace on the plotter in juxtaposition to the motion of the colored stream indicated the presence of three regimes: stable laminar, laminar with the formation of waves, and turbulent. As an example, Fig. 1 shows the stable laminar regime (a) and the regime with clearly manifested turbulence (b). Figure 2 shows typical chromograms of the three flow regimes of the thin clarified liquid film. When the tubes are placed at an angle to the horizontal less than 30°, the colored stream and the trace on the plotter have an identical character: a smooth line without perturbations. At an angle of inclination approximately equal to 40°, the flow of the colored stream shows the continued presence of laminar film motion, while simultaneously the chromogram reveals pulsations in the velocity and waves are visually observed, i.e. the motion of the film, while remaining laminar, acquires a wave character. When the tubes are placed at an angle exceeding 50° to the horizontal, the flow of the film is clearly turbulent, the streamlike nature of the colored liquid is destroyed, and eddies and large-scale vortex zones appear (Fig. 1b). On the chromogram in Fig. 2c, velocities of motion of the film differing by factors of 2-3 and more are distinguished. The film thickness was determined by measuring

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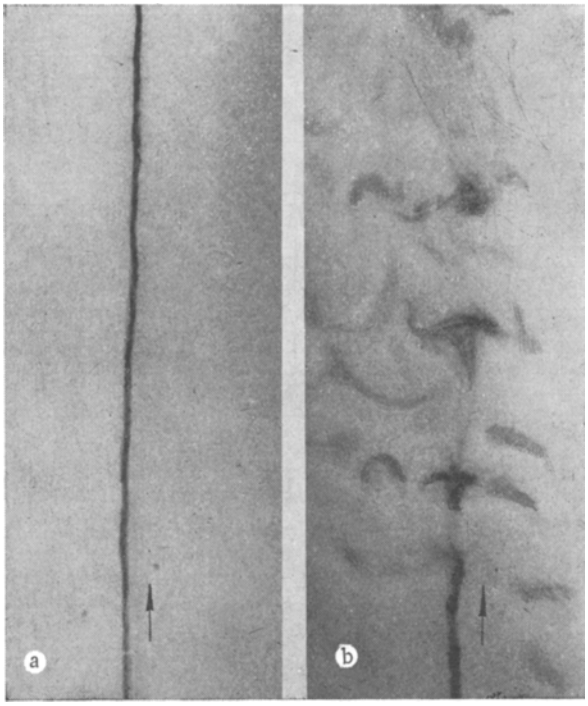

Fig. 1. Photograph of flow beneath a plate (dark regions indicate the flow of colored liquid): a) pure laminar flow ($\alpha > 30°$, $\rho_S = 1010$ kg/m^3); b) turbulent flow ($\alpha > 50°$, $\rho_S = 1010$ kg/m^3).

directly from the visible phase separation boundary through the lateral walls. In the presence of the laminar motion and the laminar wave regime, the average film thickness was found to lie in the range $\delta = 1.5 \cdot 10^{-3}$–$2.0 \cdot 10^{-3}$ m.

The motion of the pure liquid film proceeds from the lower part of the tube to the upper part due to the difference in the densities of the film and the suspension. For the conditions of the laminar regime, the tangential stresses and the pressure gradient on the phase separation surface are small and the equation of equilibrium for an elementary film volume is written in the form

$$(\delta - y)(\rho_s - \rho_o) g \sin\alpha = \mu \frac{\partial V}{\partial y}. \qquad (1)$$

The boundary conditions for Eq. (1) are $V = 0$ for $y = 0$ and $\partial V/\partial y = 0$ for $y = \delta$. After transformations and integration of (1), we obtain the average velocity of motion of the film

$$V_{av} = \frac{(\rho_s - \rho_o) g \delta^2 \sin\alpha}{3\mu}. \qquad (2)$$

The destruction of stability of the laminar motion of the film is related to the appearance of perturbations of a different character. Among these perturbations, gravitational and continuous waves are manifested most strongly. The appearance of continuous waves is related with the concentration dependence of the flow velocity of the film. The concentration in this case is the corresponding density of the phases of the suspension and the pure liquid. For constant phase density, continuous waves carry the appropriate value of the film thickness in the direction of motion. The velocity of propagation of continuous waves is greater than the average velocity of motion of the film by approximately a factor of 3 [3-5] and, taking into account (2), can be represented by the equation

$$V_c = \frac{(\rho_s - \rho_o) g \delta^2 \sin\alpha}{\mu}. \qquad (3)$$

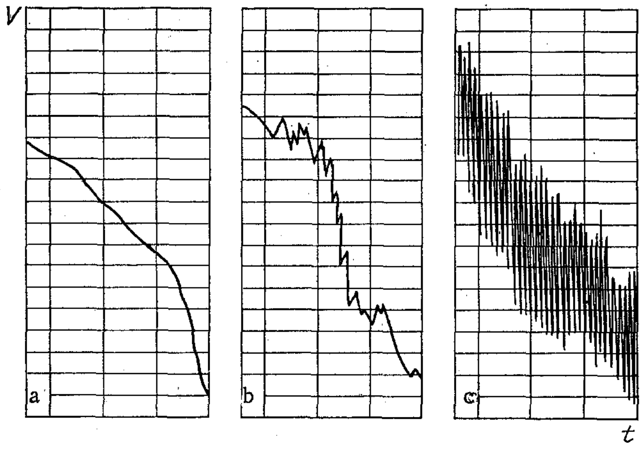

Fig. 2. Characteristic chromograms showing the flow velocity of films underneath a plate: a) pure laminar flow ($\alpha < 30°$, $\rho_s = 1010$ kg/m^3); b) laminar flow with wave formation ($\alpha \approx 40°$, $\rho_s = 1010$ kg/m^3); c) turbulent flow ($\alpha > 50°$, $\rho_s = 1010$ kg/m^3).

The film of pure liquid with thickness δ resists compression and expansion, which leads to the appearance of gravitational waves. These waves propagate in both directions relative to the motion of the liquid film and in the case of flow inclined to the horizontal at an angle of α, their propagation velocity is determined by the equation

$$V_g = \pm (\delta g \cos \alpha)^{0.5} . \tag{4}$$

Continuous and gravitational waves interact with one another effecting the stability of the film motion. The film motion becomes unstable when the condition $V_c > V_{av} + V_g$ is satisfied [4-6], or, taking into account (2)-(4),

$$\frac{(\rho_s - \rho_o) g\delta^2 \sin \alpha}{\mu} > \frac{(\rho_s - \rho_o) g\delta^2 \sin \alpha}{3\mu} + (\delta g \cos \alpha)^{0.5} . \tag{5}$$

Solution of (5) for α gives the angle of inclination for large values of which the flow will be unstable:

$$\alpha = \arccos \frac{(1 + 4A^2)^{0.5} - 1}{2A} , \tag{6}$$

where $A = 4\delta^3 g(\rho_s - \rho_o)/9\mu^2$ is dimensionless.

A graphical representation of Eq. (6) is given in Fig. 3 in the form of α as a function of $\rho_s - \rho_o$ and allows for given density of the phases a determination of the angle of inclination of the plates corresponding to the transition (for a large angle) from laminar flow to wave flow.

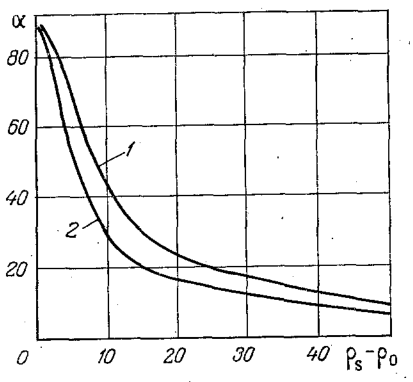

Fig. 3. Effect of phase densities on the angle of inclination of plates, determining the boundary for stable film flow of pure liquid: 1) $\delta = 1.5 \cdot 10^{-3}$ m; 2) $\delta = 2 \cdot 10^{-3}$ m.

Visual observations show that unstable film motion is manifested in the form of rolls of clarified liquid, the height of which exceeds the film thickness by a factor of 2-3, following one another. Further, part of the suspension is drawn into the zone behind a roll, the stability of the sedimentation is destroyed, which is what leads to the noticeable decrease in the sedimentation rate of suspensions at angles of inclination of the plates exceeding 50° and $\rho_S = 1010\text{-}1015$ kg/m³.

NOTATION

δ, thickness of the film, m; μ, dynamic coefficient of viscosity, N·sec/m²; ρ_S and ρ_0, densities of the suspension and clarified liquid, kg/m³; V_{av}, average velocity of motion of the film, m/sec; V_c and V_g, velocities of propagation of continuous and gravitational waves, m/sec; l and b, length and width of the flat tubes, m; h, distance along the normal between the plates, m; α, angle of inclination of the tubes to the horizontal, deg; A, a dimensionless grouping of constant.

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POSSIBLE MECHANISM FOR THE RETARDATION EFFECT IN THE FLOW OF POLYMERIC LIQUIDS

A. N. Prokunin, B. A. Krasovitskii, and V. D. Sevruk

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The effect is examined theoretically taking into account the influence of both orientational as well as the thermal activation mechanism for viscous flow on the relaxation time and, possibly, irreversible accumulation of ruptures.

It was shown in [1] that in order to stretch melted polyethylene with a constant rate of deformation, a retardation is observed after the flow develops. In the region of retardation, the polymer deforms similarly to an elastic nonlinear body. Then, a flow develops again in the polymer. These facts were established by direct measurement of the reversible and irreversible parts of the deformation. In this case, the tensile forces can have two maxima as a function of time. The secondary increase in the force corresponds to the retardation in the flow, while the secondary drop corresponds to renewed development of the flow. A stationary flow was not achieved in the region of deformations investigated, while the testing time could easily exceed the relaxation time, which is determined by performing a shear experiment in the linear deformation range. We note that the stretching process, possibly, is accompanied by irreversible accumulation of ruptures of macromolecules.

Rheological equations [2], taking into account large elastic deformations and the orientation factor, are used in order to describe partially the effect of a retardation in the flow. The latter is determined by choosing a sharply increasing relaxation time as a

Institute of Problems in Mechanics, Academy of Sciences of the USSR.

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