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BRIEF COMMUNICATIONS

Conditions for Foam Flow and Breaking

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The continuous removal of the foam formed during flotation from a liquid surface is a challenging engineering problem, which has to be solved to ensure stable flotation and high quality of the separated product.

Foam transport by mechanical and vacuum pumps is inexpedient because of high energy consumption. Moreover, since the gas content of foams is high, then, in their pumping, the flow continuity is disturbed and the pump operation becomes unstable. According to experimental data [1], the operation of centrifugal pumps transporting a yeast suspension is stable only when the gas content is ≤0.2. Therefore, it is better to remove foam by gravity. The geometric parameters of foam ducts should be calculated with regard for the rheological properties of foams.

Let us consider foam flow in an inclined channel (Fig. 1). In a steady flow, the driving force is the gravitational force (its projection onto the x axis). The flow is impeded by the frictional force, which is defined as the difference between the tangential stresses acting on the upper and lower faces of a foam volume element $dxdydz$:

$$F_{\mathrm{fr}} = \frac{\partial \tau_{xy}}{\partial y} dxdydz.$$

The force-balance equation taking into account the foam directions is

$$\rho g \sin\alpha - \frac{\partial \tau_{xy}}{\partial y} = 0. \qquad (1)$$

Integration of Eq. (1) with respect to y from 0 to δ (δ is the flowing foam layer thickness), with allowance made for the fact that $\tau_{xy} = 0$ on the free surface and $\tau_{xy} = \tau_w$ at the bottom, gives the following expression for τ_w:

$$\tau_w = \rho g \delta \sin\alpha. \qquad (2)$$

The condition for the onset of foam flow is, obviously,

$$\tau \geq \tau_0. \qquad (3)$$

The slope of the channel at which the foam starts to flow, α_{fl}, is then

$$\alpha_{\mathrm{fl}} \geq \arcsin\frac{\tau_0}{\rho g \delta}. \qquad (4)$$

In foam transport, it is expedient to perform partial (or complete) foam breaking (degassing). In the case under consideration, mechanical foam breaking commences when the shear stress τ in the near-wall zone exceeds the breaking shear stress τ_{br} for the given foam. The slope at which the foam in the near-wall zone is broken, α_{br}, is

$$\alpha_{\mathrm{br}} \geq \arcsin\frac{\tau_{\mathrm{br}}}{\rho g \delta}. \qquad (5)$$

Expressions (4) and (5) enable one to assess the feasibility of gravity transport and mechanical breaking of foams under actual conditions with regard for the rheological properties of foams.

The proposed mathematical model of the flow and breaking of foams was tested experimentally for goodness of fit.

We studied two types of foams, namely, yeast foams produced by concentrating nutrient yeast and foams that form in sewage aeration and contain synthetic surfactants.

Yeast foams are characterized by low foam ratios β and by high static and dynamic strengths due to the presence of protein macromolecules, which strengthen liquid films [2, 3]. The foams were studied by rotational viscometry with a REOTEST-2 instrument. We examined yeast foams after one and two flotation steps. These foams were characterized by the yeast concen-

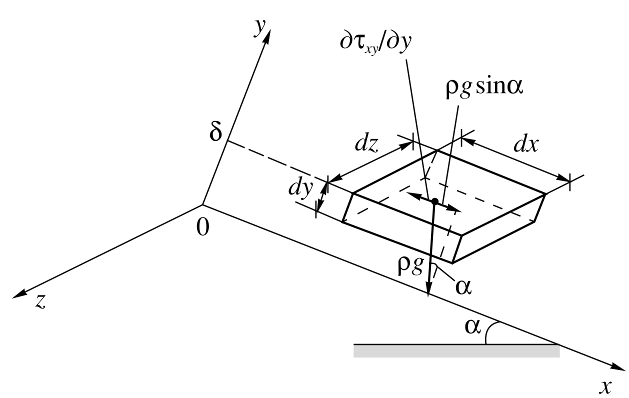

Fig. 1. To the calculations on the foam flow along an inclined chute.

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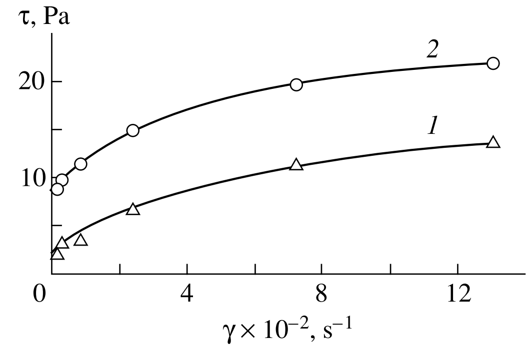

Fig. 2. τ versus γ for the yeast foam flow after the (*1*) first and (*2*) second flotation steps.

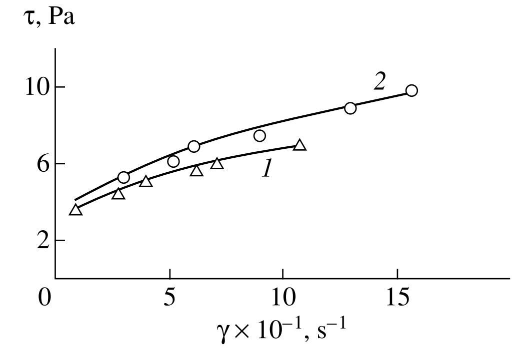

Fig. 3. τ versus γ for the flow of the foam produced from (*1*) 1 and (*2*) 3% PO-12 solutions.

trations C_1 = 90–120 kg/m^3 and C_2 = 330–380 kg/m^3 and by the foam ratios β_1 = 6.0–7.1 and β_2 = 3.9–4.5, respectively.

Foams were also obtained from 1 and 3% solutions of the PO-12 surfactant, and their β values varied in the ranges 290–360 and 340–470, respectively. Because of the high β values and low strengths of these foams, their rheological properties were determined by capillary viscometry, specifically, by measuring the foam flow rate Q and the pressure difference ΔP produced by the foam across the horizontal segment L of a measuring column (a glass tube 40 mm i.d.) [4].

The shear rate and the shear stress were calculated by the formulas

$$\gamma = \frac{4Q}{\pi R^3}, \tag{6}$$

$$\tau = \frac{\Delta pR}{2L}. \tag{7}$$

To reduce the measurement error caused by the foam collapse and boundary slip, the foam structure was monitored during the rheological investigations and the volumetric concentrations of the gas and liquid phases were maintained at a constant. In addition, the experiments were performed at low shear rates (18.8–156.4 s^{-1}), which also helped to retain the initial structure of high-ratio foam.

The maximum allowable values of the flow rate and the shear rate of the foams under examination were governed by the stability of their flow in the measuring column. Flow rates and shear rates exceeding their maximum allowable values brought about foam collapse: in the measuring column, air cavities emerged, which made the foam discontinuous.

Figures 2 and 3 present the foam flow curves. The initial shear stress τ_0 was found by extrapolating the curves to the τ axis. For the yeast foams at C_1 = 90–120 kg/m^3, we have τ_0 = 2.0 Pa; at C_2 = 330–380 kg/m^3, τ_0 = 8.0 Pa. For the foams produced from the 1 and 3% PO-12 solutions, τ_0 is 2.0 and 3.0 Pa, respectively.

The foam strength was characterized by the breaking shear stress τ_{br} determined according to a published procedure [5]. We measured the average weight $\bar{m}$ of foam drops separating from a vertical cylindrical foam duct and the diameter of the foam cylinder at the point of rupture, whereupon the axial foam strength was computed:

$$\tau_{ax} = \bar{m}g/F.$$

It has been shown [4, 6] that $\tau_{br} = 0.5\tau_{ax}$.

This method was used to determine the strength of the foams obtained from the 1 and 3% PO-12 solutions.

The strength of the yeast foams was measured under plant conditions. A cylindrical foam duct was attached not to a foam generator but to an industrial plant for concentrating the nutrient yeast suspensions. The table presents the measured results. As one can see, the strength of the yeast foams is 2–3 times higher than that of the foams prepared from the PO-12 solutions. This finding is explained by the presence of yeast cells, which glue liquid films and prevent their rupture. As the yeast concentration increases, the foam strength grows.

Foam strength characteristics

Foam	$F \times 10^4$, m^2	$\bar{m} \times 10^4$, kg	τ_{ax}, Pa	τ_{br}, Pa
Foam produced from a 1% PO-12 solution	0.87	1.3	14.66	7.33
Foam produced from a 3% PO-12 solution	0.87	1.8	20.30	10.15
Yeast foam after the first flotation step	1.15	3.2	27.30	13.65
Yeast foam after the second flotation step	1.15	5.3	45.21	22.60

Rheological investigations corroborated the above results: with a rising shear rate, the flow curves of the studied foams asymptotically approach the values of the breaking shear stresses for these foams. The shear stresses do not rise further because of foam collapse.

Investigation of the flow and breaking of the foams was continued on a setup whose schematic is given in Fig. 4.

A foam prepared from the PO-12 solutions in a bubble-type foam generator *1* was transported by gravity along an open chute *2*. The chute was attached to the upper part of the foam generator with a horizontal hinge *3*, which permitted the chute to be rotated about the horizontal axis. The angle α was fixed with rods *4*. The necessary foam ratio (and, therefore, the rheological properties of the foam) was ensured by controlling the air flow rate with a rotameter *5*. Foam stabilization and a longer induction period preceding syneresis were achieved by raising the concentrations of the foaming agent (PO-12 solutions) and the solid phase (yeast) [7, 8]. The induction period of the foams under investigation (40–60 s) is longer than the time of their flow along the chute (3–8 s). Therefore, the formation of a liquid layer between the foam and the solid surface and the foam slip along the chute are ruled out.

The generated foam was fed to the chute inlet, and at a certain minimum value of α_{fl}, the foam started to flow by gravity. The foam layer thickness δ was measured at the distance $l = 4a$ (a is the chute width) from the chute inlet (at the steady-flow segment) and at the chute outlet.

Note that, at small α (for the yeast foams, $\alpha_{fl} < 15°$; for the foams obtained from the PO-12 solutions, $\alpha_{fl} < 30°$), the foam flow is discontinuous. At the foam-generator outlet, the foam layer thickness is increased and the foam structure is changed; after the onset of syneresis and the accumulation of the liquid phase on the solid surface, the foam flow becomes discontinuous and portions of the foam slide down.

Thus, the continuous foam flow along the chute commences when the gravitational force exceeds the initial shear stress of the foam (Eq. (3)) rather than as a result of syneresis.

We studied the effect of syneresis on yeast foam breaking. Experiments were carried out on the setup described above. Foam was supplied to the chute immediately from an industrial fermenter. The static stability of the foam was preliminarily estimated (as the foam column half-breaking time [8]). The breaking times of the foams with the yeast concentrations $C_1 = 90–120$ kg/m^3 and $C_2 = 330–380$ kg/m^3 were 16 and 28 h, respectively. Apparently, the rate of dynamic breaking of the yeast foams is several orders of magnitude higher than the rate of their static breaking. In view of this, the influence of the latter was ignored. For determining α_{br}, the flowing foam layer thickness δ at the inlet and the outlet of the chute were compared.

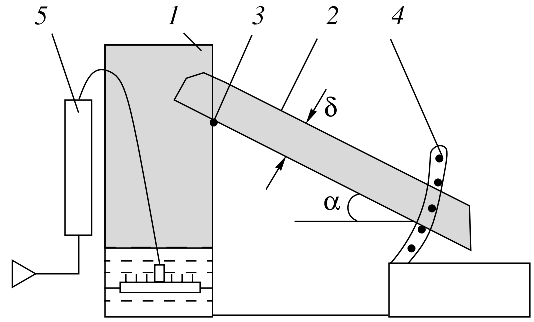

Fig. 4. Schematic of the experimental setup.

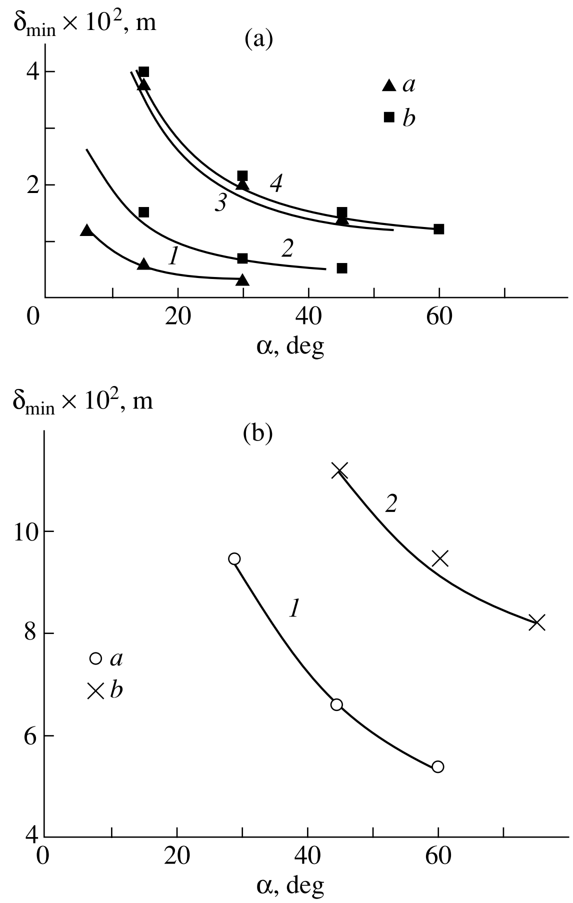

Fig. 5. δ_{min} as a function of α for (*1*, *2*) flowing and (*3*, *4*) breaking foams: (a) yeast foam after the (*a*) first and (*b*) second flotation steps and (b) foam produced from (*a*) 1 and (*b*) 3% PO-12 solutions. Points, experimental data; lines, data calculated by expressions (4) and (5).

When the foam was collapsing ($\alpha > \alpha_{br}$), δ at the outlet of the chute was smaller than at its inlet. Moreover, a liquid film was observed to drain at the chute outlet. We took the decrease in δ at the chute outlet by more than

15% as compared to its inlet value as a criterion of the onset of foam breaking.

Figure 5 plots the minimum thickness δ_{min} of the foam layer that begins to flow and collapses in the chute as a function of α. The increase in the layer thickness was ensured by varying the foam flow rate. The calculated and observed data agree satisfactorily. Note that the foams produced from the PO-12 solutions did not collapse when flowing along the chute with $\alpha = 30°$–$75°$ because of insufficient shear stresses (high foam ratios and low foam densities). A further rise in the layer height (>100 mm) changed the foam properties (the foam density and the foam ratio) because of syneresis.

Thus, the gravity transport of foams along open channels is possible only for foams that have low foam ratios.

NOTATION

C_1, C_2—yeast concentrations in the foam after the first and second flotation steps, respectively, kg/m^3;

F—rupture section area, m^2;

g—acceleration of gravity, m/s^2;

L—measuring-column length, m;

$\bar{m}$—average drop weight, kg;

ΔP—pressure difference across the measuring column, Pa;

Q—foam flow rate, m^3/s;

R—measuring-column radius, m;

α—slope of the channel, deg;

β—foam ratio;

γ—shear rate, s^{-1};

δ—foam layer thickness, m;

ρ—foam density, kg/m^3;

τ—shear stress, Pa;

τ_0, τ_{br}—initial and breaking shear stresses, respectively, Pa;

τ_{ax}—axial strength, Pa.

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