HYDRAULIC RESISTANCE OF A NONCIRCULATING DYNAMIC TWO-PHASE LAYER

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The results of an experimental study of the hydraulic resistance in a developed bubbling (foam) process are presented. Similarity equations are obtained which agree with the experimental data with an accuracy of ±15%.

One of the urgent problems which arise in the creation of efficient heat-exchange devices, created as a result of the application of the organized flow of two-phase streams, is the working out of methods of calculating the heat- and mass-exchange processes, which can be intensified through the provision of the optimum physicochemical conditions and also, to a greater extent, through the provision of favorable hydraulic conditions. These conditions are determined by the hydrodynamic state of the interacting phases and are limited by the increase in hydraulic resistance of the two-phase stream, i.e., by the energy expenditures on providing for the operation of the apparatus, and by the reduction of the efficiency of the contact part of the apparatus owing to the entrainment of the liquid phase which develops with increased gas-stream velocities and in the absence of special separation devices.

The results of a study of the hydraulic resistance of a noncirculating dynamic two-phase layer are examined in the present article. This study is a continuation and an integral part of studies performed earlier [1, 2] on the laws of convective heat exchange in a froth bed.

Despite the prolonged and considerable interest displayed by investigators in the dynamic two-phase layer, there is presently an absence of universal functions enabling one to determine the hydraulic resistance in a sufficiently wide range of initial parameters. Individual studies on this question are presented in [3-5] and in a number of other works of native and foreign authors. Only graphic or empirical functions obtained for the concrete problem are given in them, however.

The laws of hydraulic resistance were studied by the authors of the present article with a developed bubbling (froth) process ($W_0'' = 0.5$-3.0 m/sec) in a wide range of variation in the size of the initial liquid layer ($h_0 = 5$-250 mm). The gas phase in all the tests was air, while the liquid phase was water and aqueous solutions of glycerin ($C_m = 40, 60, 80, 97\%$), ethyl alcohol ($C_m = 10$-95%), and sodium oleate ($C_m = 0.003$-0.025%).

The experiments were conducted in a Plexiglas column with a cross section of 50 × 80 mm^2 and a height of 1 m. The froth was produced on dual gas-distributing grids of Duralumin 2 mm thick with openings arranged in rows (Table 1). The rims of the openings were rounded on both sides. To assure the full exposure of the openings of the main (lower) grid the diameter of the openings of the upper grid was 0.5-1 mm larger.

Special experiments on the study of the hydraulic resistance showed the admissibility of this structural design of the grid. The operating procedure was as follows: first the ventilator was turned on, then the openings of the main grid were covered by shifting the upper grid and the liquid was added, which made it possible to establish exactly the size of the initial liquid layer, after which the upper grid was returned to the initial position and the required flow rate of air was established, measured from the readings of an inclined micromanometer using the manometric total-pressure and static-pressure tubes. Then the total

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TABLE 1. Parameters of Gas-Distributing Grids

Grid number	d_0, mm	m, mm	s_0, %	n, openings
1	1	4	5,77	294
2	2	7	6,05	77
3	3	10 (11)	6,00	34
4	4	14 (16)	5,97	19
5	5	16 (20)	5,88	12
6	6	25 (20)	5,95	8 (6 mm), 1 (4 mm)

Note. 1. In column m the spacing of the openings along the length of the row is given in parentheses. 2. An additional opening with d_0 = 4 mm was drilled in grid No. 6 to assure that s_0 = idem.

resistance of the froth apparatus was measured with a U-shaped manometer and the height and temperature of the froth were measured. The height of the initial liquid layer as a determining factor was verified after each measurement and was established before a new measurement. For the uniform distribution of air near the grid a bundle of thin-walled tubes 4 mm in diameter and 120 mm long (l/d = 30), which filled the cross section of the column, was mounted below the grid at a distance of 200 mm.

The dependence of the hydraulic resistance of the froth bed on the diameter of the openings of the grid and its relative clear cross section was not examined, since the effect of these geometrical factors on the hydrodynamics of a two-phase layer is described in [7] and our experiments repeated these relationships. The same conclusion also pertains to the effect of the transverse dimensions of the bubble column.

It is known [3, 7] that the hydraulic resistance of a froth bed depends to a considerable degree on the height h_0 of the initial liquid layer. An analysis of the functions presented in [1, 2] allows one to also bring out a number of other influencing factors, including the dimensionless complexes K and Re*.

The latter can be justified as follows. Processes in a dynamic two-phase layer, just as in any gas–liquid system, are determined by the interaction of the forces of inertia, gravity, surface tension, and friction.

The complex K can be represented in the form

$$K = (Fr'')^{1/2}\left(\frac{1}{We}\right)^{1/4}\left(\frac{\rho''}{\rho' - \rho''}\right)^{1/2} \tag{1}$$

and can be considered as a measure of the interaction of the dynamic pressure light phase with the surface tension at the interface and with the force of gravity. Here the friction at the interface is determined by the product of the hydraulic resistance coefficient ξ_n times the dynamic head, while

$$\xi_n \sim (Re'')^n (Re^*)^n, \tag{2}$$

where even under turbulent conditions $\xi_n \sim (Re'')^{-0.25}$.

In the case of a dynamic two-phase layer one should expect a considerably smaller effect of the hydraulic resistance coefficient on the process under study.

As the scale of the linear dimensions of the freely developing formations for the process under consideration we take

$$l_0 = \sqrt{\frac{\sigma}{g(\rho' - \rho'')}}. \tag{3}$$

Thus, by introducing K and Re* as the determining similarity criteria and l_0 as the scale of the linear dimensions we can take into account the main influencing factors. As a result, the functional dependence of the determination of the hydraulic resistance of a froth bed has the form

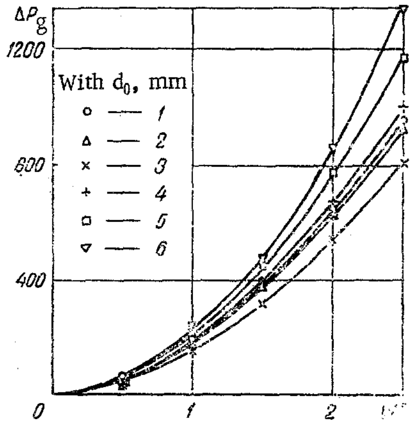

Fig. 1

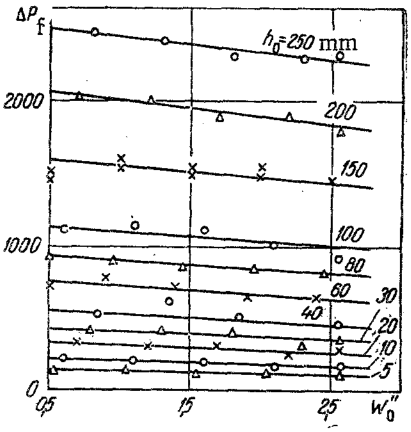

Fig. 2

Fig. 1. Dependence $\Delta P_g = f(W_o'', d_o)$ of hydraulic resistance of a "dry" grid. The numbers of the grids are given in Table 1. ΔP_g, N/m^2; W_o'', m/sec.

Fig. 2. Dependence $\Delta P_f = f(W_o'', h_o)$ of hydraulic resistance of the froth bed for the gas–liquid system of air–water.

$$Eu^* = f\left(Re^*, K, \frac{h_0}{l_0}\right). \tag{4}$$

In the course of the experiments the resistance of the froth bed was determined from the formula

$$\Delta P_f = \Delta P - \Delta P_g. \tag{5}$$

Dependences of the hydraulic resistance of the "dry" grids on the air velocity in the column are presented in Fig. 1. It is seen from the figure that grid No. 3 has the minimum resistance. The latter can be explained by the fact that for thin grids with relatively large diameters of the openings (d_o = 3-6 mm) local resistances, determined by the degree of uniformity of the distribution of openings over the grid surface, rather than fractional resistance have the main influence. Therefore, grid No. 6 with the lowest degree of uniformity of the distribution of openings has the maximum resistance.

With a decrease in the diameter of the openings to d_o = 1-2 mm the frictional surface increases considerably with relatively high uniformity of the distribution of openings. At the same time, the resistance of the grid could be affected also by the sharper rims of the openings of small diameters which were difficult to round off.

If the hydraulic resistance of the "dry" grid is related to the velocity W" of the air in the openings, then the resistance ΔP_g can be calculated from the formula

$$\Delta P_g = \xi_g \frac{\rho'' W''^2}{2}. \tag{6}$$

The tests performed with the gas-distributing grid No. 2, for which $\xi_g \simeq 1.0$, are placed at the basis of the generalized experimental material on the hydraulic resistance of a froth bed. The results are treated in the form of graphic functions $\Delta P_f = f(W_o'', h_o)$ for systems of air–water, air–aqueous solutions of ethyl alcohol, and air–aqueous solutions of glycerin.

It should be noted that as the calculated concentrations with ethyl alcohol we took their average values between the initial and final concentrations in the experiments. The mass concentrations of ethyl alcohol and of glycerin in the solutions were determined from the dependence $C_m = f(\rho', t)$, where we measured the densities of the solutions with an accuracy of 0.5 kg/m^3 using a set of densimeters (oreometers). The dependence $\Delta P_f = f(W_o'', h_o)$ for the air–water system is given in Fig. 2 as an example.

For the experiments with water and aqueous solutions of glycerin with K = const and h_o = idem it is found that Eu* depends slightly on Re*; i.e., the hydraulic resistance of

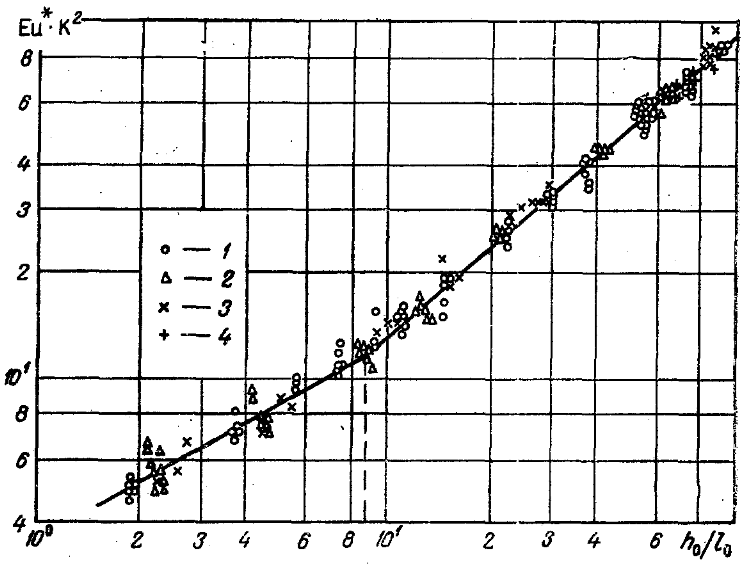

Fig. 3. Correlation of experimental data on the resistance of a froth bed: 1) water; 2) 40, 60, 80, and 97% solutions of glycerin in water; 3) 10-95% solutions of alcohol in water; 4) 0.003-0.025% solutions of sodium oleate in water.

the froth bed is almost independent of the viscosity of the liquid. This agrees with the conclusions of other authors [3, 7]. As a result, we have

$$Eu^* \sim K^{-2}. \tag{7}$$

In Fig. 3 we give a correlation of the experimental data in the form of the dependence

$$Eu^*K^2 = f(h_0/l_0). \tag{8}$$

This dependence is constructed on the basis of the experiments with water (h_0 = 5, 10, 15, 20, 25, 30, 40, 60, 80, 100, 150, and 250 mm) and aqueous solutions of sodium oleate (h_0 = 150 mm), glycerin, and ethyl alcohol (h_0 = 50, 100, and 150 mm).

As follows from Fig. 3, the dependence $Eu^*K^2 = f(h_0/l_0)$ has a bend in the region of small initial layers (h_0 < 30 mm). This is explained by a change in the structure of the two-phase layer. One would assume that the dependences of Eu* on Re* and K which were established earlier would also change in this case. Therefore, experiments with aqueous solutions of glycerin and ethyl alcohol with h_0 = 5, 10, 20, and 30 mm were also performed. The experiments showed, however, that $Eu^* \sim K^{-2}$ in this case also and Eu* is almost independent of Re*.

Under these conditions the two-phase layer loses stability and an intense interaction develops between the breaking bubbles and the formation of drops. Since the surface of the broken bubbles is many times larger than the surface of the drops which have formed, the effect of the surface forces in the overall energy balance is intensified.

As a result, it is found that

$$Eu^* = 3.5K^{-2}(h_0/l_0)^{0.55} \text{ when } 1.8 \leqslant h_0/l_0 \leqslant 8.7; \tag{9}$$

$$Eu^* = 1.8K^{-2}(h_0/l_0)^{0.85} \text{ when } 8.7 \leqslant h_0/l_0 \leqslant 95. \tag{10}$$

The temperature of the froth bed is taken as the determining temperature and the reduced velocity of the air in the cross section of the column is taken as the determining velocity.

The functions obtained are valid when K = 0.1-0.75.

The deviation of the experimental data from the functions obtained does not exceed ±15% for the most part.

Accordingly, the hydraulic resistance of the froth bed can be represented in the form

$$\Delta P_f = 3{,}5\, h_0^{0,55} (g\rho')^{0,775} \sigma^{0,225}; \tag{11}$$

$$\Delta P_f = 1{,}8\, h_0^{0,85} (g\rho')^{0,925} \sigma^{0,075}. \tag{12}$$

From (11) and (12) one can conclude that the hydraulic resistance of a froth bed in a developed bubbling process is almost unaffected by the force of inertia and that the main influencing factors are the force of gravity and the size of the initial liquid layer. With small initial liquid layers (h_0 < 30 mm) the effect of surface tension increases [Eqs. (9) and (11)].

In the range of initial sizes studied the absolute value of ΔP_f did not exceed 2200-2400 N/m².

NOTATION

$Eu^* = \Delta P_f/\rho'' W_0''^2$, Euler number; $K = W_0'' \sqrt{\rho''} / \sqrt[4]{\sigma g(\rho' - \rho'')}$, similarity criterion characterizing the measure of the interaction of the dynamic pressure of the gas phase with the surface tension at the interface and with the force of gravity; $Re^* = W_0'' l_0/\nu'$, Reynolds number, referred to the kinematic viscosity of the liquid phase; $l_0 = \sqrt{\sigma/g(\rho' - \rho'')}$, characteristic linear dimension, m; W_0'', reduced gas velocity, m/sec; σ, coefficient of surface tension at the interface, N/m; ν', coefficient of kinematic viscosity of liquid phase, m²/sec; g, acceleration of gravity, m/sec²; ρ', ρ'', densities of liquid and gas phases, respectively, kg/m³; ΔP, total resistance of froth apparatus, N/m²; ΔP_f, hydraulic resistance of froth bed, N/m²; ΔP_g, resistance of "dry" grid, N/m²; ξ_g, coefficient of hydraulic resistance of the "dry" grids investigated, which varied in the range of 0.85-1.4; C_m, mass concentration of a component. The indices ' and " pertain to the liquid and gas phases, respectively.

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