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SURFACE FACTOR IN INCOMPRESSIBLE LIQUID FILM FLOW

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The results of investigation of the influence of a solid surface on the film flow of a viscous incompressible liquid in a gravitational field are analyzed. Using the dimensional method, a generalized similarity criterion for a film flow has been obtained. The laboratory facility and the method for investigating the film flow for various types of packing elements are described.

Film flows of a viscous incompressible liquid in a gravitational field are generated in film apparatus and packed columns. The parameters characterizing the hydrodynamic processes in incompressible liquid film flows and, accordingly, influencing the heat-and-mass exchange processes largely depend on their influence on the physicochemical properties and structure of the solid surface of the substrate on which the liquid flow occurs. By the substrate structure we mean both roughness and the form of its surface — shaped, porous, perforated, punched, wattled, and cloth materials. Exact calculation and creation on its basis of an effective design of a packed unit for optimum film flow conditions excluding critical phenomena in it are impossible without knowing and taking into account the mechanism of interaction of the spraying liquid film flow with the substrate surface. The aim of the present paper is to investigate the influence of the substrate on the character of the film flow at a different liquid load and determine the surface factor E_{surf} permitting quantitative account of this interaction. The viscous liquid flow in films on the surface in the presence of a free surface largely depends on the surface phenomena arising at the interfaces of the phases participating in the process, and the larger the specific surface of the liquid, the stronger this dependence. The film flow under consideration is due to gravity. Because the flow is connected with the substrate, it slows down, causing a decrease in its velocity, which promotes its spreading on the substrate surface. The flows connected to the substrate are due to the adhesion forces on the one hand, and, on the other hand, to the presence of a hydrodynamical resistance to the flow of the substrate surface structural elements. At dynamic equilibrium, gravity is balanced by the forces of resistance to the film flow. Moreover, the surface tension force of the spraying liquid counteracts the formation of a new surface and seeks to roll up the film flow into a jet, causing deformation of the liquid. The viscous forces, on the contrary, counteract the film flow deformation. The process of liquid film flow considered by us proceeds under isobaric conditions.

The determination of the degree of interaction of these forces presents insurmountable difficulties because of the uncertainty of the factors influencing them. These difficulties are connected with the estimation of the surface activity of the substrate. Therefore, to determine the degree of influence of the substrate surface on the hydrodynamics of a film flow running down by it in a gravitational field, we used the hydraulic simulation technique of [1]. It is very difficult, in our opinion, to obtain similarity criteria by reducing the system of equations and uniqueness conditions to a dimensionless form because of the lack of sufficient data for a mathematical description of the process under consideration. Therefore, to solve this problem, we use the dimensional method. The task is to determine the degree of deformation of the film (plane) flow running on a particular substrate. In our earlier studies [2], we estimated the degree of deformation of the film flow, manifested as its rolling-up into a jet, by the relation between the plane flow width in the initial cross-section b_0 and the flow length l from the initial cross-section to the node of its rolling-up into a jet and revealed the dependence of the obtained simplex on the surface properties and the linear water concentration. Let us replace this dimensionless parameter by the quantity tan α (see Fig. 1). We determine the value of the angle α form the relation $0.5b/l = \tan(\alpha/2)$, where $\alpha/2$ is the angle of tilt of the side boundary of the film flow to

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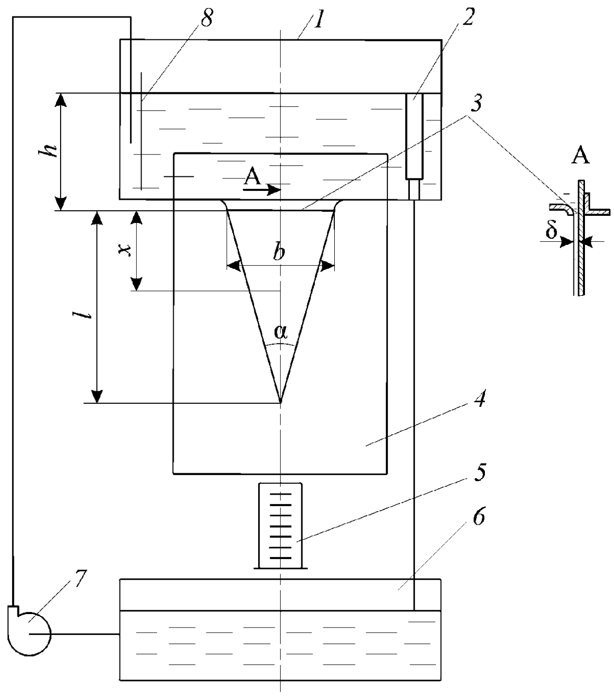

Fig. 1. Laboratory facility for investigating film flow.

its longitudinal axis. This relation can be given as a first-order derivative, which permits taking into account the change in the flow width b as a function of its length. Using the Buckingham similarity theorem (π-theorem) to solve the problem formulated, we determine all variables influencing the liquid flow, whose values are given or determined in the course of the experiment. In the first approximation, the variables determining the influence of the environment on the film flow (vacuum liquid outflow condition) are ignored. Proceeding from this, we include in the physical equation only nine parameters, and it will be of the form

$$f(b_0, l, \delta_0, \Gamma_v, h_0, \rho, g, \nu, \sigma) = 0 .$$

Each variable quantity included in the equation is expressed, in accordance with the dimensional formula, in terms of three basic units of measurement: length, mass, time. According to the π-theorem, $9 - 3 = 6$ dimensionless π-terms, which will define the function

$$f(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6) = 0$$

will be obtained.

Each π-term consists of four variables. On these, three variables are dimension-independent and the fourth one is determined in terms of the dimensions of the first three variables. As dimension- independent variables, we take b_0, Γ_v, and ρ. Write the sought dimensionless π-terms in the form of exponential equations expressed in terms of dimensions, from which we determine the content of each π-term:

$$\pi_1 = \frac{b_0}{l}\,; \quad \pi_2 = \frac{b_0}{\delta_0}\,; \quad \pi_3 = \frac{b_0}{h_0}\,; \quad \pi_4 = \frac{\Gamma_v}{\nu} = \mathrm{Re_f}\,; \quad \pi_5 = \frac{\rho\Gamma_v^2}{b_0\sigma} = \mathrm{We_f}\,; \quad \pi_6 = \frac{\Gamma_v^2}{b_0^3 g} = \mathrm{Fr_f}\,.$$

The last three dimensionless complexes are the Reynolds, Weber, and Froude similarity criteria for the film liquid flow ignoring the influence of the substrate surface on the film flow. In this case, the criterial equation will take on the form

$$f\left(\frac{b_0}{l}, \frac{b_0}{\delta_0}, \frac{b_0}{h_0}, \mathrm{Re_f}, \mathrm{We_f}, \mathrm{Fr_f}\right) = 0 .$$

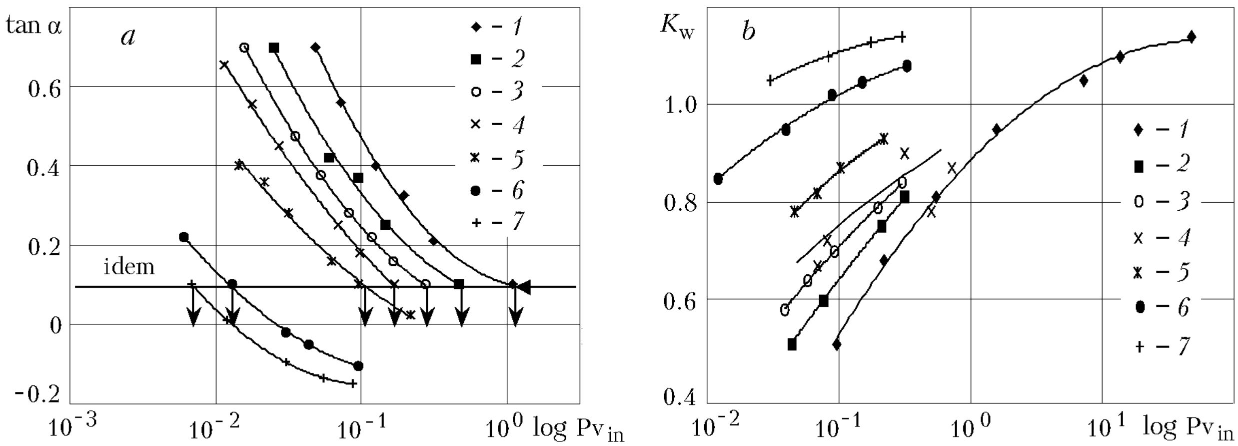

Fig. 2. Dependence of tan α and K_w at b_0/x = 1 (a and b, respectively) on Pv_{in} for film flows of water on different types of substrates (see Table 1).

TABLE 1

Position number in Fig. 2	Material or substrate structure	Pv_{in}	F_{surf}	θ	ϑ	K_σ	K_w
1	Air	1.096	1	114	0.297	1	—
2	Polypropylene (smooth film)	0.467	2.35	92	0.482	1.62	1.45
3	Stainless steel, polished sheet	0.270	4.06	47	0.84	2.83	1.43
4	Fabric from polypropylene bands (sacking)	0.170	6.45	92	0.482	1.62	3.98
5	Window glass (used)	0.095	11.53	4	0.999	3.37	3.42
6	Porous oxidized steel sheet coating	0.013	84.31	24	0.957	3.22	26.18
7	Wood (plywood)	0.007	156.57	29	0.937	3.16	49.55

Consider the conditions for using the functional relation of the equation obtained to determine the influence of the substrate on the degree of deformation of the film flow, reflected by the term π_1, of all the other terms of the equation, which we reduce to the generalized complex parameter of the film flow. Denote this independent generalized parameter of the film flow as Pv_{in}. In accordance with the definition that any combination of similarity criteria is also a similarity criterion [3], using summation of the surface forces [4], we form an independent generalized complex parameter of the film flow

$$Pv_{in} = \frac{We_f\, Re_f}{(We_f + Re_f)\ Fr_f\, \pi_2 \pi_3}\,.$$

Let us introduce into the expression obtained the content of each similarity criterion, and, simplifying it, we obtain

$$Pv_{in} = \frac{\rho g b_0 \delta_0 h_0}{b_0 \sigma - \rho \Gamma_v \nu} = \frac{\rho g V}{b_0 \sigma - \Gamma_m \nu} = \frac{g m}{b_0 \sigma - \Gamma_m \nu} = \frac{F_g}{F_{\Sigma\sigma}}\,.$$

The negative sign in the denominator shows that the viscous forces counteract the surface tension forces of the liquid upon film flow deformation. Thus, the independent generalized complex parameter of the film flow is the ratio of gravity to the sum of the surface forces acting on the film flow.

For experimental studies of the film flow, we choose a physical model based on the simplex $\pi_1 = b_0/l$ expressed in terms of tan α and determine its functional dependence on the complex parameter of the film flow Pv_{in}:

$\tan\alpha = f(Pv_{in})$. Provided $\tan\alpha$ = idem, the change in the value of Pv_{in} that takes place when the liquid flows on the surfaces of various types of substrates will make it possible to determine the degree of influence of these surfaces on the film flow of the liquid under investigation.

The experiment was performed on the laboratory facility shown in Fig. 1. The facility consists of a pressure tank 1 with a regulated drain 2 providing, in the course of the experiment, a constant given level of the liquid in the 0.02–0.2 m range. The liquid is pumped into the pressure tank through a perforated screen 8 from a water tank 6 by a pump 7. A separable element of the flat substrate in question 4 is fastened to the bracket of the pressure tank bottom. Between the flat element of the substrate and the pressure tank bottom a slit 3 of certain dimensions is made, and it can be varied in the course of the experiment. In the case of the liquid flow into the air space, the substrate element is not mounted, and a conoidal slit of proper dimensions is made. The liquid flowing out of the slit forms a film flow with certain parameters that runs either into the air space or on the substrate being investigated. The value of the liquid flow rate needed to calculate the hydrodynamic parameters of the flow in its initial cross-section is determined by means of a measuring cylinder 5 and a timing device. The geometric parameters of the film flow in the air space and on the substrate surface were determined by a measuring instrument.

The method for experimental studies of the film flow involves a set of sequentially performed experiments in which the values of the variables entering into the independent generalized similarity criterion for the film flow Pv_{in} were varied, with the physical parameters of the liquid under investigation (in our case — water) being constant (ρ = 998 kg/m^3, $\nu = 0.96\cdot10^{-6}$ m^2/sec, $\sigma = 72.4\cdot10^{-3}$ N/m). As a result, film flows with different given hydrodynamic parameters and a different degree of dispersion were generated. In considering the running of these flows in the air space or on the surface of the substrate under investigation, a different degree of deformation of the flow was observed. The degree of deformation was determined by the change in the angle α of the film flow rolling-up into a jet.

The experimental study conducted has made it possible to plot graphs of $\tan\alpha = f(Pv_{in})$ for the water flow on different substrates (Fig. 2a).

Analysis of the data obtained shows that when the film flow is running in the air space or on any of the investigated substrates, with decreasing Pv_{in} the rolling-up angle α of the film flow increases, and the liquid spreading kinetics thereby is parabolic. The change in the angle α is due to the increase in the hydraulic losses on the substrate surface, which are proportional to the squared flow velocity. A decrease in the mechanical energy of the flow leads to a decrease in the Pv_{in} values and an increase in the rolling-up angle α. In the cases of the liquid film flow on different types of substrates, there is a shift of the corresponding curve towards smaller values of Pv_{in} at the same values of $\tan\alpha$. The sudden change in the Pv_{in} values relative to the curve for the film flow into the air is due to the increased activity of the investigated substrate surface. There is a sharp increase in the forces counteracting the flow on the substrate surface at the same values of mechanical energy of the liquid flow.

Consider the change in the Pv_{in} value at one and the same value of $\tan\alpha$ = idem. It should be noted that as the values of $\tan\alpha$ = idem increase, there is an increase in Pv_{in}. The reason for this is the appearance of superimposed side jets of the flow, and the larger the angle α, the higher the power of these jets and the stronger their influence on the investigated process. At $\alpha = 0$ the streamlines are parallel to one another, the film flow is not rolled up, and no side jets are formed. Therefore, we take the least possible (according to the experimental results) values of $\tan\alpha = 0.1$ = idem. In this case, the value of the angle of tilt of the side jet to the flow axis $\alpha/2$ will be less than 3^{o}. The maximum value of the independent generalized complex parameter of the film flow takes place in the case of its running into the air space where the influence of the substrate is practically absent (we neglect the work of the flow drag due to air). We conditionally take this value of Pv_{in12} as the base one and denote it by Pv_{in12}. The ratio of the Pv_{in12} value at $\tan\alpha = 0.1$ = idem to the Pv_{in} value for the flow of the same liquid on the substrate reflects the change in the value of the force of resistance on the surface of the investigated substrate to the liquid flow. We shall call this ratio the surface factor

$$F_{surf} = Pv_{in12}/Pv_{in} .$$

The values of the surface factor for different substrates with a film flow of water on them are given in Table 1 and Fig. 2.

In its physical essence, the surface factor F_{surf} is a quantity determining the degree of influence on the film flow of the forces that arise under the action on it of the substrate surface. The nature of these forces is dual. As mentioned above, among them are forces caused by the surface phenomena at interfaces (intermolecular interaction) and mechanical forces of hydraulic resistance causing an additional deformation of the flow. Proceeding from this, we represent the surface factor as the product of the coefficient of influence of surface forces K_σ by the coefficient of influence of mechanical resistance forces K_{mech}

$$F_{surf} = K_\sigma K_{mech} .$$

The influence of the surface forces reflected by the coefficient K_σ appears as the flow energy loss due to the formation of a new free surface, which is counteracted by the liquid surface tension forces at interfaces and the forces determined by the liquid adhesion to the substrate surface. As a result of adhesion, the lower layer of the liquid flow sticks to the substrate surface and the drag forces are transferred to the liquid volume through its viscosity.

The surface tension of the liquid at its boundary with air is known, and the surface tension of the liquid at the liquid–solid interface is more difficult to determine, since this is connected with the unknown quantity — the surface tension of the solid. The substrate surface forces do the work of spreading expressed by the spreading coefficient [5] which is the difference between the work of adhesion and cohesion

$$W_{sp} = W_a - W_c = \sigma_{31} - (\sigma + \sigma_{23}) .$$

Let us replace the difference $\sigma_{31} - \sigma_{23}$ by the expression from Young's law [6]

$$\sigma_{31} - \sigma_{23} = \sigma \cos \theta .$$

The wetting angle θ is a specific quantity for a given concrete combination of solid and liquid surfaces. It depends not only and not as much on the physical characteristic of the substrate material as on the state of this surface and the conditions under which the contacting phases interact, namely, the degree of its oxidation and impurity, surface roughness and deformation, and the temperature and composition of the ambient gas. Therefore, the wetting angle should be determined by experiment for the real surface of a solid body, taking into account the above conditions, by the known methods [5].

The value of the appearing coefficient will take the form

$$W_{sp} = \sigma \cos \theta - \sigma = \sigma (\cos \theta - 1) .$$

With allowance for the work of spreading the surface tension on the surface of the film liquid flow facing the substrate will be equal to

$$\sigma_{23} = \sigma + \sigma (\cos \theta - 1) = \sigma \cos \theta .$$

Determine the arithmetic mean value of the surface tension of the film liquid flow running down by the substrate:

$$\sigma_{mean} = (\sigma + \sigma \cos \theta)/2 = \sigma (1 + \cos \theta)/2 = \sigma\vartheta .$$

The quantity of the work of adhesion is also related to the sticking coefficient ϑ that takes into account the possibility of slipping of the liquid wall layer relative to the substrate surface. In this case, the losses due to the work of the viscous forces decrease. Proceeding from the foregoing, the sum of surface forces in the formula of the generalized similarity criterion for the film flow with allowance for the influence of the substrate will be of the form

$$F_{\Sigma\sigma} = b_0\sigma\vartheta - \Gamma_m \nu\vartheta = (b_0\sigma - \Gamma_m \nu)\, \vartheta ,$$

whereas for the flow into the air space the sum of the surface forces is equal to

$$F_{\Sigma\sigma_{12}} = (b_0\sigma - \Gamma_m\, \nu)\, \vartheta_{12} ,$$

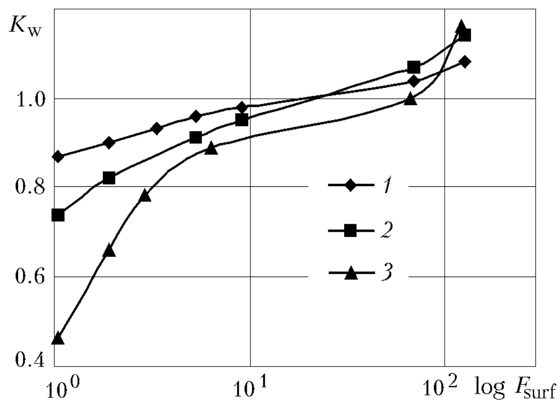

Fig. 3. Dependence of $K_w = f(F_{surf})$ at $Pv_{in} = 0.3$ and various values of b_0/x: 1) $b_0/x = 2$; 2) 1; 3) 0.5.

where ϑ_{12} is the sticking coefficient of the liquid at the air-liquid interface.

For example, the sticking coefficient of water at the boundary with air $\vartheta_{12} = 0.2966$ because the dynamic wetting angle at the air–water interface $\vartheta_{12} = 114^o$ [5, p. 90]. The relation $F_{\Sigma\sigma_{12}}/F_{\Sigma\sigma} = \vartheta_{12}/\vartheta$ shows the degree of influence of the substrate due to the surface phenomena on the value of the sum of the surface forces. Then the generalized criterion for the film flow with allowance for the surface phenomena Pv_σ will be equal to

$$Pv_\sigma = \frac{mg\vartheta}{(b_0\sigma - \Gamma_m \nu)\,\vartheta_{12}} = \frac{F_g K_\sigma}{F_{\Sigma\sigma}},$$

from which it is seen that $K_\sigma = \vartheta/\vartheta_{12}$.

Having determined the value of K_σ, it is easy to find the value of the coefficient of influence of mechanical forces on the film flow for a given substrate from the surface factor formula $K_{mech} = F_{surf}K_\sigma$.

Thus, according to the proposed method of experimental studies of the film liquid flow, it is possible to determine the surface factor F_{surf} and the coefficient of influence of mechanical forces K_{mech} for various types of substrates. Knowing K_{mech} of the substrate and the values of the wetting angles of any liquid at its boundaries with air and the chosen substrate, it is possible to determine the surface factor and, accordingly, the generalized criterion Pv for the film flow with allowance for the influence of the substrate

$$Pv_f = \frac{We_f\,Re_f F_{surf}}{(Re_f - We_f)\,Fr_f\,\pi_2\pi_3} = \frac{\rho g b_0 \delta_0 h_0 F_{surf}}{b_0\sigma - \Gamma_m\nu} = \frac{mgK_{mech}K_\sigma}{b_0\sigma - \Gamma_m\nu} = \frac{mgK_m\vartheta}{(b_0\sigma - \Gamma_m\nu)\,\vartheta_{12}} =$$

$$= \frac{mgK_{mech}\,(1 + \cos\theta)}{(b_0\sigma - \Gamma_m\nu)\,(1 + \cos\theta_{12})} = \frac{F_g F_{surf}}{F_{\Sigma\sigma}} = Pv_{in}F_{surf}\,.$$

In the course of the experiment, we determined the value of the free surface of the film flow formed on different kinds of substrates (wetted surface) A_w. The ratio of the wetted surface area to the substrate surface area $A = b_0x$ (see Fig. 1) is, as is known, the wetting coefficient of the substrate $K_w = A_w/A$.

The experimental results have shown that the wetting coefficient depends on Pv_{in} and the value of the ratio b_0/x. Figure 2b shows the dependence $K_w = f(Pv_{in})$ at $b_0/x = 1$. From the analysis of the curves obtained it follows that the wettability increases with increasing Pv_{in} and surface factor F_{surf}. Varying these parameters, one can achieve complete wetting ($K_w = 1$) of the packing surface with the spraying liquid. As Pv_{in} is increased, the influence of the properties of the substrate on the value of the wetting coefficient decreases on going to the self-similarity regime at $Pv_{in} = 7$.

In Fig. 3, the dependence of $K_w = f(F_{surf})$ at various values of $b_0 x$ shows that with decreasing ratio b_0/x the wetting coefficient decreases, especially at small values of the surface factor. If $b_0/x < 0.5$, complete wetting of the substrate surface at a given water concentration can be attained only by increasing the surface factor F_{surf}.

CONCLUSIONS

1. This work presents a method for determining the influence of the surface forces on the film flow hydrodynamics with subsequent use of the results obtained to design a high-efficiency structure of packed units of heat-and-mass exchange apparatus.

2. The laboratory facility for investigating the film flow of an incompressible viscous liquid permits determining the degree of influence of the chosen substrate surface on the film flow of the spraying liquid by means of hydraulic modeling. As an independent linear variable, we chose a rigorously determinable quantity — the film flow width in the initial cross-section (extent of the liquid distributor slit) and not the film thickness δ.

3. The influence of the substrate on the film flow of the liquid running down by gravity is characterized by the surface factor F_{surf} determined in the course of the experiment. It includes both the influence of the surface forces of contacting phases and the immediate mechanical action of the substrate surface structure on the flow.

4. The surface factor F_{surf} depends on the surface wettability by the liquid to a lesser extent than on the surface structure. The surface wettability acquires importance in creating an undisturbed film flow. The surface factor increases considerably at a developed structure of the substrate surface. For example, while for a propylene film with water flowing on it F_{surf} = 2.35 (Fig. 2a, curve 2), for a fabric from propylene bands F_{surf} = 6.45. The value of F_{surf} increases considerably for water flowing on a surface with porous oxidation and on wood (84 and 156, respectively). In this case, besides the considered effects, the influence of capillary impregnation takes place [6]. But if we consider a notch-drawn sheet (NDS) of stainless steel as packings [7], the surface factor for it compared to a smooth sheet of the same steel increases even more markedly due to the highly developed structure of the sheet surface.

5. The generalized criterion of the film flow Pv_f derived in this paper can be used in investigating and estimating the exchange processes in the film flow of an incompressible viscous liquid running down in the gravitational field by the surface of a particular substrate.

6. The proposed method permits determining the real wetting angles in the dynamics of the film flow on a substrate surface with a small roughness (polished surface) when the value of the influence coefficient of mechanical forces K_{mech} is small and equals, as the experiment has shown, $\approx$1.5.

The results of the work can be used to solve problems of selecting materials and calculating the hydrodynamic characteristics of the film flow in designing high-efficiency packed units of heat-and-mass exchange film apparatus.

NOTATION

A, substrate surface area, m^2; Γ_m, mass linear spraying density, kg/(m·sec); Γ_v, volume linear spraying density, m^3/(m·sec); b_0, film flow width in the initial cross-section (extent of the liquid distributor slit), m; F_g, gravity, N; $F_{\Sigma\sigma}$, sum of surface forces, N; F_{surf}, surface factor; Fr_f, Froude film criterion; g, acceleration of gravity, m/sec^2; h_0, film flow pressure in the initial cross-section (at the exit from the liquid distributor slit), m; $h_0 = v_0^2/2g$; K_{mech}, coefficient of mechanical forces; K_w, wetting coefficient; K_σ, coefficient of surface forces; l, film flow length to the node of its rolling-up into a jet, m; m, liquid column mass over the initial cross-section of a plane flow, kg; V, volume of the liquid column over the initial cross-section of a plane flow, m^3; v_0, flow velocity in the initial portion, m/sec; W_a, work of adhesion; W_c, work of cohesion; W_{sp}, work of spreading; x, film flow length on the investigated substrate (packing length), m; α, angle of film flow rolling-up, deg; δ_0, film flow thickness in the initial portion (width of the liquid distributor slit), m; θ, wetting angle, deg; ϑ, sticking coefficient; $\vartheta = (1 + \cos\theta)/2$ [4]; ν, kinematic viscosity, m^2/sec; π, dimensionless complex; ρ, density, kg/m^3; σ, surface tension, N/m; σ_{23}, surface tension at the liquid-solid interface, N/m; σ_{31}, surface tension at the solid–gas interface, N/m; Pv_{in}, independent generalized complex parameter of the film flow; Pv_f, generalized Perlov film criterion; Re_f, Reynolds film criterion; We_f, Weber film criterion. Subscripts: a, adhesion; c, cohesion; mech, mechanical; in, independent; f, film; sp, spreading; w, wetted; mean, mean; g, gravitation; m, mass; v, volume; σ, surface tension; 0, initial area; 12, gas–liquid interface; 23, liquid–solid interface; 31, solid–gas interface; 1, 2, 3, 4, 5, 6, ordinal numbers of π-terms.

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