ture factor; T, temperature; $\bar{\alpha}$, α, mean and local heat-transfer coefficients; ξ, hydraulic-resistance coefficient. Indices: e, equivalent; 0, at the entrance; w, mean wall value; f, mean for a flow; f-e, front-end; ex, external; in, internal, L, laminar; T, turbulent; st, straight; I, II, first and second types of channels.

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BREAKDOWN OF STABILITY OF HEAT- AND MASS-TRANSFER PROCESSES IN CERTAIN GAS—LIQUID SYSTEMS

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Using the critical equation for the limiting regimes of a gas—liquid system with independent flow rate of the gaseous phase, experimental results on the stability of a two-phase mixture are generalized to thermosiphons.

The simultaneous motion of liquid and gas in equipment for different purposes is characterized by an interaction at the boundary of the phases. The characteristics of this interaction, the conditions of exchange of different regimes of motion, the patterns of the flow regimes, etc. have been investigated in [1-4]. In a large number of gas—liquid systems used in practice, it is possible to single out systems with independent flow rate of the gaseous phase and a dynamic two-phase layer [4]. Such systems are encountered in various types of bubbling equipment. Along with the horizontal positioning of the gas-permeable distributor surface (Fig. 1a), systems with vertical surface of the blowing may also by used (Fig. 1b). Closed two-phase thermosiphons with lateral heat supply are a particular case of such systems. The characteristics of the transfer processes in such systems may be significantly different from those in the systems shown in Fig. 1a; this is due to the change in the direction of motion of the phases in relation to the surface of the blowing. At the same time, some useful results may be obtained from the investigation of these processes for individual positions and also from the analysis of well-known experimental results.

We consider a dynamic gas—liquid system in a gravitational field and consisting of two characteristic regions with discrete gaseous and liquid phases, respectively. In order to describe such a system we must set up a system of differential equations describing the transfer processes in the above two regions. The corresponding system of dimensionless groups can be found either directly from this system of equations or from a joint analysis of critical equations obtained for the description of the processes in separate regions of the two-phase flow (the dynamic two-phase layer and the gas flow with liquid drops). In [5], the system of dimensionless groups describing the process of fractionalization and the removal of liquid—drop moisture from the dynamic two-phase layer is derived from the equations of the motion of the vapor—liquid flow, the fractionation of the liquid, the motion of the drop in the vertical flow, and the Laplace and Clausius—Clapeyron equations describing self-evaporation of the

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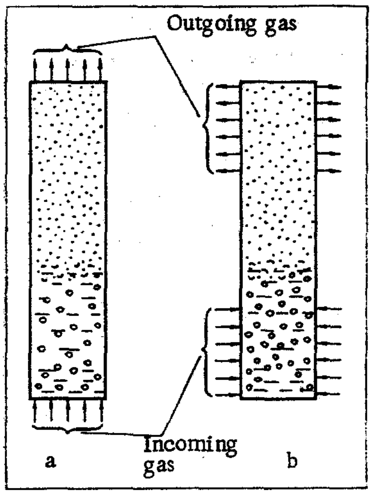

Fig. 1. Schematic diagram of gas—liquid systems with independent flow rate of the gaseous phase.

drop during its motion. The critical system describing the transfer processes in the two-phase layer itself is derived in [4]. A joint analysis of these critical systems for the case of the limiting regime of motion of the two-phase flow leads to the following equation:

$$\frac{W''_{0\,\mathrm{cr}}\sqrt{\rho''}}{\sqrt[4]{\sigma g(\rho'-\rho'')}}=f\left(\frac{g\delta^3}{\nu'^2}\cdot\frac{\rho'-\rho''}{\rho'};\ \frac{\sigma}{(\rho'-\rho'')gl^2};\ \frac{H}{\delta};\ \frac{\Delta p\delta}{\sigma};\ \frac{\mu'}{\mu''};\ \frac{\rho'}{\rho''};\ \frac{l_1}{l}\right)$$

or

$$K=f(\mathrm{Ar},\ \mathrm{We},\ \mathrm{We}_1,\ K_{\Delta p},\ \bar{\mu},\ \bar{\rho},\ \bar{l})\,. \tag{1}$$

Equation (1) describes the limiting regimes of operation of the gas—liquid system under consideration in the general form. As is well known, the nature of the critical phenomena in such systems may be different: removal of the liquid from the solid wall by the blown gas, attainment of the state of saturation of the dynamic two-phase layer, or breakdown of the bubble layer in the case of a steep increase in the drop removal. The onset of one or the other type of critical phenomenon depends on the region of variation of the decisive criteria as well as on the boundary conditions at the segments of supply and removal of the gaseous phase.

The Weber number We_1 includes the vertical dimension of the gaseous space and affects the removal at small values of H [5]; therefore, it can be dropped from Eq. (1). Then we have

$$K=f(\mathrm{Ar},\ \mathrm{We},\ K_{\Delta p},\ \bar{\mu},\ \bar{\rho},\ \bar{l})\,. \tag{2}$$

The dimensionless criterion $K_{\Delta p}$ contains the quantity Δp, which does not occur in the condition of uniqueness; therefore, it must be transformed suitable. For this purpose we make use of the relationship

$$\Delta p\equiv E\,\frac{\Delta\rho''}{\rho''}\,, \tag{3}$$

where $E=\rho''(\partial p/\partial\rho'')$ is the modulus of compressibility. Then the criterion $K_{\Delta p}$ can be written in the following form:

$$K_{\Delta p}\equiv\frac{E\delta}{\sigma}\,. \tag{4}$$

Complex (4) represents the compressibility criterion in the most general form and can be used for the analysis of experimental data on the motion of not only two-phase mixtures, but also nonmiscible two-component mixtures (liquid—liquid) in a single system of coordinates. In particular, for an ideal gas [4, 6] we have

$$\frac{\partial p}{\partial\rho''}\sim\frac{p}{\rho''}\,. \tag{5}$$

Then the compressibility criterion takes the form of the pressure criterion [4]:

$$K_p \equiv \frac{p\delta}{\sigma}. \quad (6)$$

Let us investigate some particular cases of Eq. (2). For the case of the system shown in Fig. 1a and low-viscosity liquids, the regime of pressing back of the liquid is described by the following formula:

$$K = 7\left(\frac{\rho''}{p}\right)^{1/4}\left[\frac{g\sigma}{\rho'-\rho''}\right]^{1/8}. \quad (7)$$

The stability criterion lies in the range 0.05-0.2 in a wide range of investigations. A sudden breakdown of the bubbling regime associated with the removal of small drops (ω = 100%) occurs for the stability criterion [2] having the value

$$K = 0.8 \div 0,9. \quad (8)$$

A complete breakdown of the bubbling layer (regime of flooding in bubbling columns) occurs when the velocity of the gas flow becomes equal to the terminal velocity of the large liquid drops. The recommendations on the terminal velocity of drops available in the literature [8, 9] permit one to compute the corresponding value of the stability criterion. The following formula is given in [8]:

$$W_{\text{term}} = \sqrt{\frac{4g(\rho'-\rho'')d_{\text{d}}}{3\zeta\rho''}}. \quad (9)$$

For the region where the quadratic drag law holds, the value ζ = 0.44 is recommended. For a spherical drop the characteristic size is $\delta = V/\Omega = {}^2/_3 d_{\text{d}}$. Taking $\delta = \sqrt{\sigma/g(\rho' - \rho'')}$, we obtain the value of the stability criterion from Eq. (9):

$$K = 2.13. \quad (10)$$

At the same time, the following equation is given in [9]:

$$W_{\text{term}} = \sqrt{2,2gd_{\text{d}}\frac{\rho'}{\rho''}}. \quad (11)$$

It is easy to show that even in this case the stability criterion has the value

$$K = 1.81. \quad (12)$$

It should be noted that Eqs. (9) and (11) are derived for normal atmospheric conditions and, therefore, they do not take into consideration the entire set of possible conditions described by Eq. (2).

For obtaining a more general formula, we may use the results of [10, 11] from the investigation of the velocity of the drops of one liquid in another nonmiscible liquid. With the analysis from [4] taken into consideration, the corresponding equation is of the form

$$\text{Re} = 1.3\ \text{Ar}^{1/2}. \quad (13)$$

Equation (13) is transformed to

$$K = 1.3. \quad (14)$$

A similar result is obtained from the data of [2]. Because of the very small compressibility of the liquid ($E \gtrsim 10^{10}$) the value of the stability criterion (K = 1.3) corresponds to very large values of the compressibility criterion in formula (4). Therefore, the above value of K may be regarded as the limiting minimum value for low-viscosity gas–liquid systems in the absence of any additional effect of the geometric factor. Thus, it may be noted that the recommended equations for the terminal velocity of the drops – (9) and (11) – are of a very particular nature and require correction primarily as a function of the pressure of the medium.

Considering the analogy between the critical phenomena in bubbling processes and the processes of boiling of liquid here, we use criterial system (2) for generalizing the experimental data on the critical situations of heat and mass transfer in closed two-phase thermosiphons. In thermosiphons with lateral heat supply, the nature of the processes occurring in them corresponds to the gas–liquid system of Fig. 1b. The experimental equipment and the

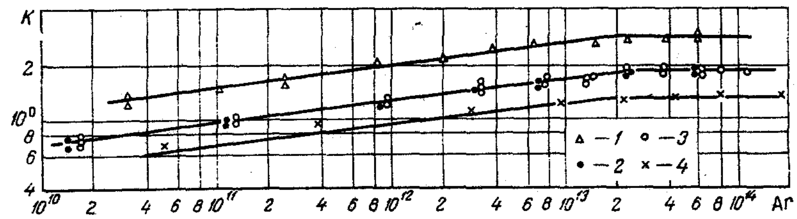

Fig. 2. Dependence of the stability criterion on Archimedes number for different values of K_p: 1) water, $K_p = 0.49 \cdot 10^3$; 2) water, $K_p = 4.27 \cdot 10^3$; 3) Freon-11, $K_p = 6 \cdot 10^3$; 4) Freon-12, $K_p = 8.96 \cdot 10^4$.

procedures for the experiments are described in [12, 13], where some results of the experiments are also given.

In the present work, a generalization for the limiting regimes of operation of thermosiphons in the bubbling regime, i.e., in the presence of excess of the liquid being bubbled by the vapor, is given. The regime in which the breakdown of the stability of operation of the two-phase system was observed was recorded from the steep increase in the temperature of the tube wall in the heated segment (the heat supply in the process q = const). The experiments were conducted with the pressure held constant at a given value in the thermosiphon cavity (this was accomplished by an appropriate manipulation of the heat-removal process in the cooling segment). Thus, under the conditions of the experiment, the possibility of uncontrolled increase of the pressure in the cavity and the resulting transition of the two-phase system into a single-phase system were avoided. In this case, the breakdown of the stability of operation of the thermosiphon was determined only by the dynamic processes in the two-phase system.

The typical cases of breakdown of stability of a two-phase flow, which are known and described above, did not permit us to predetermine the regions of change in the governing criteria in which any type of critical phenomenon is observed. In view of this, criterial system (2) was used for generalizing the experimental data. The height of the heat-supply segment was taken as the control size of the Archimedes number Ar.

The experimental data are shown in Fig. 2 in the form of the dependence K = f(Ar) for different values of K_p in form (6). As is evident from the figure, K is a function of Ar independently of K_p only up to a certain value $Ar = 2 \cdot 10^{13}$. The region of self-similarity of K in relation to the number Ar indicates the lack of dependence of the processes on the state of the two-phase layer with continuous liquid phase.

In Fig. 3 the experimental data are generalized for two characteristic regions of variation of Ar: $Ar > 2 \cdot 10^{13}$ and $Ar < 2 \cdot 10^{13}$. It is obvious that the characteristic dependence of K on K_p is observed in each region for compressible and almost incompressible vapor phases. The values of the stability criterion characterizing the terminal velocity of large drops in gaseous [(10), (12)] and liquid [(14)] media are plotted in Fig. 3a for comparison. Very satisfactory agreement with the results of our investigation may be seen. This comparison also leads to the conclusion that for $Ar \geq 2 \cdot 10^{13}$, the breakdown of stability of the investigated two-phase system occurs as a result of the vapor flow reaching a velocity equal to the terminal velocity of large drops. For $Ar \leq 2 \cdot 10^{13}$, the critical situation in heat and mass transfer occurs apparently due to the saturation of the two-phase layer by the vapor phase and pressing back of the liquid from the heated surface by the vapor. In both cases a sharp increase of the hydraulic drag occurs because of the vapor phase attaining the critical velocity, which leads to an increase of the pressure in the lower part of the heated segment of the thermosiphon and displacement of the liquid phase.

The following computational formulas are obtained from the generalization of the experimental data:

$$K = c\mathrm{Ar}^{0.125} K_p^m \quad \text{for} \quad \mathrm{Ar} \leqslant 2 \cdot 10^{13}, \tag{15}$$

where c = 0.185 and m = −0.17 for $K_p \leq 2 \cdot 10^4$, while $c = 3.5 \cdot 10^{-2}$ and m = 0 for $K_p \geq 2 \cdot 10^4$;

$$K = c_1 K_p^n \quad \text{for} \quad \mathrm{Ar} \geqslant 2 \cdot 10^{13}, \tag{16}$$

where $c_1 = 8.2$, and n = −0.17 for $K_p \leq 4 \cdot 10^4$, while $c_1 = 1.35$ and n = 0 for $K_p \geq 4 \cdot 10^4$. These formulas can be used to determine the limiting regimes of operation of evaporator

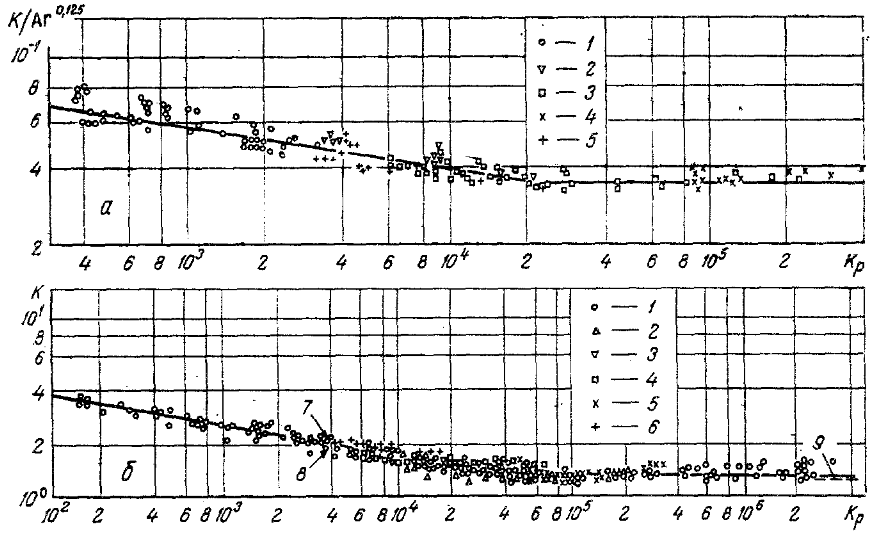

Fig. 3. Generalization of the experimental data on the critical situations of heat and mass transfer in evaporator thermosiphons with lateral heat supply: a) $Ar \leq 2 \cdot 10^{13}$ [1) water; 2) methanol; 3) Freon-11; 4) Freon-12; 5) Freon-13]; b: $Ar \geq 2 \cdot 10^{13}$ [1) water; 2) ethanol; 3) methanol; 4) Freon-11; 5) Freon-12; 6) Freon-113; 7) from data of [8]; 8) [9]; 9) [10], Eq. (14)].

thermosiphons. At the same time, considering the agreement between the obtained results with the known data on the terminal velocity of liquid drops, the obtained relations considerably widen the range of the governing parameters for computing other gas–liquid systems under similar conditions.

NOTATION

Re, Reynolds number; We, Weber number; K, Kutateladze stability criterion; $K_{\Delta p}$, compressibility criterion; K_p, pressure criterion; Ar, Archimedes number; δ, Laplace constant; ω, moisture content; φ, volumetric gas content; ρ', ρ'', densities of liquid and gas; d_d, diameter of liquid drop; W''_{0cr}, reduced critical velocity of vapor; Δp, pressure drop along the height of specific formations (bubbles, drops); σ, surface-tension coefficient; μ, dynamic viscosity; ν, kinematic viscosity; g, acceleration of gravity; H, height of the gas space; l, height of the gas supply segment; E, modulus of compressibility; ξ, drag coefficient; V, drop volume; Ω, cross-sectional area of drop.

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