HEAT TRANSFER IN THE DISPERSE FILM-BOILING MODE OF CRYOGENIC LIQUIDS

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The structural form of the dependence is obtained and results of generalizing test data on heat transfer in broad ranges of the change in uniqueness conditions are presented on the basis of a modified Reynolds flow model.

At this time it has been solidly established that the intensity of the heat transfer of two-phase nonequilibrium flows from the wall of a steam generator in the disperse film-boiling mode (DFBM) is higher than in the flow of single-phase steam at the same Reynolds numbers [1-5]. Meanwhile, different views exist about the mechanism of the intensifying influence of the discrete liquid phase on the heat transfer from the wall, in which connection different methods are proposed for extending the test data [1-5] which do not have adequate generality (we have in mind results of investigations based on a separate description of the phases, where homogeneous equilibrium models of two-phase flows are not considered). Critical remarks apropos of the treatment of the transport process mechanism in DFBM, proposed by the authors of [1, 2], for instance, have been expressed earlier in [6-8].

A comparative analysis of the conservation equations in the two-dimensional formulation for one-phase gas and vapor with drops permits the conclusion that the presence of evaporating drops specifies the following: deformation of the vapor velocity field because of the presence of mass sources whose intensity is proportional to the rate of vapor generation per unit volume and varies along both the radius and the length; increase in the turbulent transfer near the wall because of intensive vapor generation in, namely, the near-wall region; and deformation of the vapor temperature field both for the reasons noted and because of the presence of heat sinks whose intensity is proportional to the degree of underheating of the liquid phase, the rate of vapor generation, and the degree of its overheating. It is hence evident that the tendencies noted should appear the more strongly, the higher the drop concentration in the near-wall flow region.

The known model of a Reynolds flow modified in application to two-phase flows with phase transitions in the stream was used to obtain a structural form of the dependence extending the heat-transfer test data in DFBM in a one-dimensional description.

Let us consider a two-phase flow control volume with film boiling bounded by the surfaces Q—S (Fig. 1). The control volume intersects the Reynolds streams g_v and g_l reflecting the convective vapor and liquid phase transport in the wall direction. In the reverse direction the control volume intersects the same streams but with other enthalpies, where $g_l = g'_l + g''_l$ in which g''_l is the part of the stream g_l corresponding to the convective transfer of the vapor phase being formed in the control volume because of a phase transition. In conformity with the Reynolds hypothesis, the heat-balance equation for the control volume Q—S is

$$q_w = g_v i_{vw} + g'_l i_{ls} + g''_l i_v - g_l i_l - g_v i_v =$$

$$= g_v (i_{vw} - i_v) \left[1 + \frac{g'_l}{g_v} \cdot \frac{i_l - i_{ls}}{i_{vw} - i_v} + \frac{g''_l}{g_v} \cdot \frac{r + i_v - i_{vs}}{i_{vw} - i_v} \right]. \quad (1)$$

Here $g = w \cdot \mathrm{St} = \alpha/c_p = kw$ [kg/m^2 · sec] according to the Reynolds flow model [9]. Inserting dimensionless enthalpy heads into (1), we obtain

$$\frac{\mathrm{Nu}}{\mathrm{Nu}_0} = 1 + k_2 \frac{w_l}{w_{v0}} \cdot \frac{\theta_l}{\theta_w} + k_1 \frac{w_v}{w_{v0}} \cdot \frac{1 + \theta_\delta}{\theta_w}. \quad (2)$$

For streams without phase transitions $g''_l = 0$ and (2) simplifies:

$$\frac{\mathrm{Nu}}{\mathrm{Nu}_0} = 1 + \frac{c_l}{c_{pv}} \frac{1 - x}{x} \left(k \frac{\varphi}{1 - \varphi} \cdot \frac{T_w - T_l}{T_w - T_v} \right), \quad (3)$$

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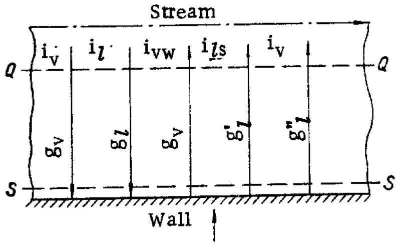

Fig. 1. Reynolds model diagram for a two-phase flow.

where the member in the parentheses is found experimentally as a function of Re_v, Re_δ, and δ/d [10].

For streams with a saturated liquid phase ($\theta_l = 0$, $g'_l = g''_l = g_l$)

$$\frac{\mathrm{Nu}}{\mathrm{Nu}_0} = 1 + \frac{g_l}{g_v} \cdot \frac{1+\theta_\delta}{\theta_w}. \tag{4}$$

Assuming that g_l/g_v is proportional to the ratio between the characteristic mass flow rates, we obtain

$$\frac{g_l}{g_v} = k\,\frac{w_v}{w_{v0}} = k\,\frac{q_{ev}V_l F \varphi}{rV_w G x}. \tag{5}$$

The structural dependence (4) can be written in different forms depending on the method of determining the vapor generation intensity. Thus, if

$$q_{ev} = \alpha_\delta (T_v - T_s) = \mathrm{Nu}_\delta \frac{\lambda_v}{\delta}(T_v - T_s)\,\frac{\ln(1+\theta_\delta)}{\theta_\delta}, \tag{6}$$

after simple manipulation of (5) we obtain

$$\frac{g_l}{g_v} = k\,\frac{\mathrm{Nu}_\delta}{\mathrm{Re}_v \mathrm{Pr}_v}\left(\frac{d}{\delta}\right)^2 \ln(1+\theta_\delta) \tag{7}$$

and

$$\frac{\mathrm{Nu}}{\mathrm{Nu}_0} = 1 + k(2 + 0.55\,\mathrm{Re}_\delta^{0.5}\,\mathrm{Pr}_v^{0.33})\left(\frac{d}{\delta}\right)^2 \frac{(1+\theta_\delta)\ln(1+\theta_\delta)}{\mathrm{Re}_v \mathrm{Pr}_v \theta_w}. \tag{8}$$

If the mass-conservation equation for the vapor is used in the form

$$G\,\frac{dx}{dz} = \frac{q_{ev}V_l}{r} \tag{9}$$

to determine $q_{ev}V_l/r$, then the structural form of the dependence (4) will be as follows:

$$\frac{\mathrm{Nu}}{\mathrm{Nu}_0} = 1 + k\frac{\varphi}{x}\,\frac{dx}{d(z/d)} \cdot \frac{1+\theta_\delta}{\theta_w}. \tag{10}$$

Applied to DFBM with its characteristic periodic fractionation of the drops along the length of the vapor generator, the structural form of the generalizing dependences in the form (8) and (10) has an essential disadvantage: Such parameters as Re_δ, δ, dx/dz, and V_l vary by a jump in sections of the vapor generator where drop fractionation occurs, which results in an unjustified spread in the test results [4, 6]. Let us use the energy equation for the vapor,

$$q_w V_w = q_{ev}V_l + Gx\,\frac{di_v}{dz} + G(i_v - i_{vs})\,\frac{dx}{dz}, \tag{11}$$

to express the intensity of vapor generation in terms of the uniqueness conditions and the stream parameters which do not experience strong deformations during drop fractionation. After substituting $q_{ev}V_l$ from (9) into (11) and reducing it to dimensionless form, we obtain

$$\frac{1}{x}\cdot\frac{dx}{d(z/d)} = \frac{q_w \pi d^2}{Grx(1+\theta_\delta)}\left[1 - \frac{Grx}{q_w \pi d^2}\cdot\frac{d\theta_\delta}{d(z/d)}\right] = \frac{\mathrm{Bo}}{x(1+\theta_\delta)}\left[1 - \frac{x}{\mathrm{Bo}}\,\frac{d\theta_\delta}{d(z/d)}\right]. \tag{12}$$

Analysis of the members in the square brackets for different working bodies in broad ranges of variation of the uniqueness conditions showed that they differ slightly from the quantity $(1-x)$ in the region of high moisture content ($\varphi < 0.95$; $x < 0.4$); i.e., $\mathrm{Bo}^{-1}d\theta_\delta/d(z/d) \approx 1$. Hence, substituting (12) into (10), we obtain

$$\frac{\mathrm{Nu}}{\mathrm{Nu}_0} = 1 + k\,\frac{\mathrm{Bo}(1-x)\varphi}{x\theta_w} = 1 + k\,\mathrm{Bo}_q^*. \tag{13}$$

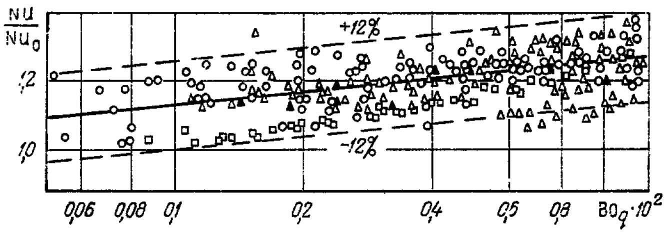

Fig. 2. Heat transfer in vapor generators in the domain $\varphi > 0.95$. See Fig. 3 for the notation.

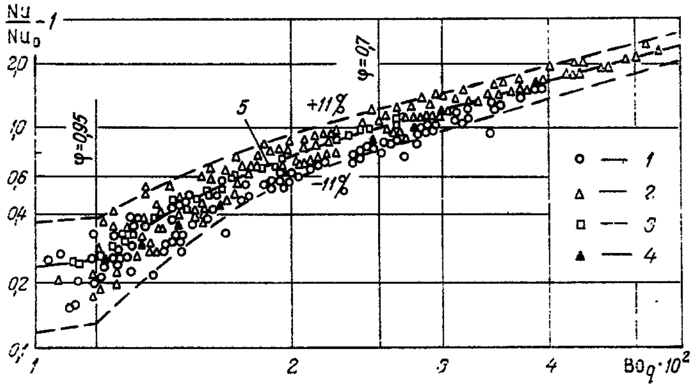

Fig. 3. Heat transfer in vapor generators in the domain $\varphi < 0.95$: 1) hydrogen [4]; 2) nitrogen [3, 4]; 3) argon [4]; 4) nitrogen [1]; 5) by (16). The dashed lines show the interval ±0.11 $(\mathrm{Nu}/\mathrm{Nu}_0)$.

Let us note that according to (13) the intensity of heat transfer is independent of the degree of thermal vapor nonequilibrium (θ_δ) and the drop size; however here x, T_v, φ are the true stream parameters.

The structural form of the dependence to extend heat-transfer test data in the form of (13) is most convenient, since it has been established by the results of the extension that the function $\mathrm{Nu}/\mathrm{Nu}_0(\mathrm{Bo}_q^*)$ is linear only in high moisture content domains. Hence, despite the possibility of transforming the linear equation (13) to the simpler form

$$\frac{\mathrm{Nu}}{\mathrm{Nu}_0} = \left[1 - \frac{k_3(1-x)}{\mathrm{Re}_v^{0,2}\,\mathrm{Pr}_v^{0,6}}\right]^{-1}, \tag{14}$$

the practical utilization of (14) in the whole range of variation of Bo_q^* is not expedient.

Results of extending the test data on the heat transfer of hydrogen, argon, and nitrogen streams in DFBM are presented in Figs. 2 and 3 in the coordinates of Eq. (13). The test data have been obtained in broad ranges of variation of the uniqueness conditions: rise and fall of motion, stationary and nonstationary cooling, channel inner diameter d = 10.4, 12.25, 13.4, 19.5, and 23.6 mm, and vapor generator length L/d = 30–160 [4] for nitrogen; rising motion, stationary cooling, d = 10.4, 13.14, 19.5, and 23.6 mm, L/d = 160–200 [4] for hydrogen; and rising motion, stationary cooling, d = 10.4 mm, and L/d = 160 [4] for argon. The ranges of variation of the modal parameters are $w = 7$–$1000\ \mathrm{kg/m^2 \cdot sec}$; $p/p_{cr} = 0.1$–0.65; $q_w = 10$–$250\ \mathrm{kW/m^2}$; and $T_w = 90$–$1050°\mathrm{K}$. Test results from [1], obtained for stationary cooling of d = 8.2-mm vapor generators by a rising nitrogen stream, are also included in the extension.

Processing the test data to obtain the magnitudes of the true phase parameters in the dimensionless complexes of (13) is performed on the basis of solving the system of one-dimensional conservation equations for each phase [4]. The computed values of the true mass vapor content were checked by using direct measurements by the method of a helium diffusion indicator [11]. The degree of thermal nonequilibrium of the stream reached the values $x_e/x = 1 + \theta_\delta = 7.5$ in tests with a saturated liquid phase.

Analysis of the results of extending the test data permits making the following deductions.

1. The proportionality factor k in (13) depends only on the quantity p/p_{cr}: $k \sim (p/p_{cr})^{0.2}$. This dependence is taken satisfactorily into account in the range $0.1 \le p/p_{cr} \le 0.65$ by inserting the quantity $1 - \rho_{vs}/\rho_{ls}$ into the parameter Bo_q^*:

$$\mathrm{Bo}_q = \frac{\mathrm{Bo}_q^*}{1 - \frac{\rho_{vs}}{\rho_{ls}}} = \frac{q_w \pi d^2 (1 - x) \varphi}{Grx\theta_w \left(1 - \frac{\rho_{vs}}{\rho_{ls}}\right)}. \tag{15}$$

2. There is no stratification of the test data in the degree of vapor overheating θ_δ and the drop size, which is explained by the form of the determination of the vapor generation intensity by means of (12). In case (8) is used, the influence of these factors is evident.

3. The construction of test data in the coordinates $\mathrm{Nu}/\mathrm{Nu}_0 = f_1(\mathrm{Bo}) = f_2(x) = f_3(\theta_w)$ shows that, other fixed parameters remaining the same, the influence of each of those listed separately on $\mathrm{Nu}/\mathrm{Nu}_0$ is identical. This agrees with the deduction obtained in the form of (13): The parameters Bo, x, and θ_w should enter into the generalizing dependence in the form of a complex Bo_q.

4. The spread in the test points is half that for an extension of the test data in the form of Eq. (10) proposed in [3, 4].

5. The satisfactory correlation between the test data obtained in broad ranges of variation in the uniqueness conditions for working bodies so diverse in their thermophysical properties as H_2, N_2, and Ar indicates the good foundation for the governing dimensionless parameters used and for the reliability of the one-dimensional models with a separated description of the phases to study the processes in nonequilibrium two-phase streams.

6. Three domains of the parameter Bo_q with different heat-transfer regularities are characteristic for the dependence $\mathrm{Nu}/\mathrm{Nu}_0(\mathrm{Bo}_q)$. It has been established experimentally that the volume heat content $\varphi = 0.95 \pm 0.025$ corresponds to the limiting value $\mathrm{Bo}_q = 0.0119$, while $\varphi = 0.7$ for $\mathrm{Bo}_q = 0.025$; i.e., the domain $\mathrm{Bo}_q < 0.0119$ is close in stream structure to the stream domain of the gas-suspension type, while the domain $0.0119 \le \mathrm{Bo}_q \le 0.025$ is close to fluid streams [10]. Taking account of the deductions obtained from the analysis of the two-dimensional conservation equations, this result premits representation of the specifics of the heat-transfer mechanism in different ranges of variation of the parameter Bo_q as follows.

For $\mathrm{Bo}_q < 0.0119$ the drop concentration in the stream is small, and because of the presence of a temperature field in the vapor (i.e., asymmetry of the vapor efflux from the drop), they are remote from the wall. Under these conditions, any increase in the drop concentration and in the intensity of their evaporation is accompanied by a comparatively slight growth in the heat-transfer intensity $\mathrm{Nu}/\mathrm{Nu}_0$. Meanwhile, the growing role of turbulent heat transfer as compared with molecular transport specifies a diminution in the influence of the temperature factor. Thus, $\mathrm{Nu}/\mathrm{Nu}_0 = 1.25$ for $\mathrm{Bo}_q = 0.0119$, and there is no influence of the temperature factor; hence, the actual increase in the heat transfer as compared to a one-phase gas at $T_w/T_v = 5$, for instance, will be $\mathrm{Nu}/\mathrm{Nu}_0 \approx 3$.

In the range $0.0119 \le \mathrm{Bo}_q \le 0.025$ the drops approach close to the wall where the local vapor generation is a maximum (the maximum phase slip in temperature). This results in a sharp diminution in the thermal resistance of the vapor layers near the wall, i.e., in a growth of heat-transfer intensity. The temperature factor does not influence the heat transfer.

A further increase in the moisture content ($\varphi < 0.7$) to values corresponding to compact packing of the drops ($\varphi = 0.3$–0.5) is accompanied by stabilization of the law $\mathrm{Nu}/\mathrm{Nu}_0(\mathrm{Bo}_q)$. In contrast to streams with solid particles, in the domain $\varphi < 0.7$, where the dependence $\mathrm{Nu}/\mathrm{Nu}_0(x)$ has a maximum because of the suppression of turbulence in the gas core of the stream, a diminution in the thermal resistance of the near-wall vapor layers remains a governing factor under DFBM conditions, and no maximum in $\mathrm{Nu}/\mathrm{Nu}_0(x)$ is observed.

Test data on the heat transfer of H_2, N_2, and Ar in the whole range of variation of the parameter Bo_q are extended with a not more than ±12% spread by the following dependence:

$$\frac{\mathrm{Nu}}{\mathrm{Nu}_0} = (1 + A\,\mathrm{Bo}_q^n)\left(\frac{T_w}{T_v}\right)^m, \tag{16}$$

where $\mathrm{Nu}_0 = 0.023 \cdot \mathrm{Re}_v^{0.8} \cdot \mathrm{Pr}_v^{0.4}$; $\mathrm{Bo}_q < 0.0119$ and $A = 1$, $n = 0.31$, $m = 0.55\ (\mathrm{Bo}_q - 0.0119)/(\mathrm{Bo}_q + 0.0119)$; for $0.0119 \le \mathrm{Bo}_q \le 0.025$, $A = f_1(\mathrm{Bo}_q)$, $n = f_2(\mathrm{Bo}_q)$, $m = 0$; and $A = 40$, $n = 1$, $m = 0$ for $\mathrm{Bo}_q > 0.025$.

For engineering computations on an electronic computer, it is convenient to represent (16) as a polynomial for $\mathrm{Bo}_q > 0.0119$:

$$\lg\left[10^2\left(\frac{\mathrm{Nu}}{\mathrm{Nu}_0} - 1\right)\right] = \sum_{i=0}^{3} a_i (\lg 10^2 \mathrm{Bo}_q), \tag{17}$$

$a_0 = 1.2273056$; $a_1 = 2.4289615$; $a_2 = -1.9788744$; $a_3 = 0.98484848$.

Formulas (16) and (17) have been obtained in the following ranges of variation of the dimensionless parameters: $x = 0.02\text{–}1.0$; $\varphi = 0.3\text{–}1.0$; $\theta_w = 1.2\text{–}9$; $\rho_{vs}/\rho_{ls} = 0.02\text{–}0.0214$; $T_w/T_v = 1.3\text{–}8$; $Bo_q = 0\text{–}0.065$; $Re_v = (0.5\text{–}50) \cdot 10^4$; $Pr_v = 0.68\text{–}1.6$.

NOTATION

q, heat-flux density; i, enthalpy; w, mass flow rate; c_p, specific heat; x, true mass vapor-content; φ, true volume content; T, temperature; d, inner channel diameter; F, cross-sectional area of channel; V, perimeter; G, mass flow rate of both phases; r, latent heat of evaporation; z, coordinate along the channel axis; p, pressure; ρ, density; u, velocity; α, heat-transfer coefficient; δ, average drop diameter; λ, coefficient of thermal conductivity; μ, dynamic coefficient of viscosity; $St \equiv q_w/\rho u \Delta i$, Stanton number; $Nu \equiv \alpha d/\lambda_v$, Nusselt number for the vapor; $Nu_\delta \equiv \alpha_\delta \delta/\lambda_v$, Nusselt number for the drop; $V_l = 6F(1-\varphi)/\delta$. perimeter of the liquid phase; $\theta = \Delta i/r$, dimensionless enthalpy head; $Re_\delta = \rho_v |u_v - u_l| \delta/\mu_v$, Reynolds number for the drop; Pr_v, Prandtl number for the vapor. Indices: v, vapor; l, liquid; ev, evaporation; w, wall; s, on the saturation line; δ, drop, o, one-phase; cr, critical; e, equilibrium.

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