HEAT EXCHANGE FOR BOILING IN A HORIZONTAL TUBULAR BUNCH UNDER DEVELOPED THERMAL PSEUDOFLUIDIZATION CONDITIONS

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The results of an experimental investigation of the boiling of water and aqueous solutions in a horizontal tubular bunch in a dispersed layer of solid particles are analyzed and generalized. An analytical solution of the problem of the distribution of the mean vapor content over the height of the layer is obtained which is in agreement with experimental data.

In [1] experimental data on heat exchange for boiling under conditions when channels are formed in a dispersed layer of solid particles are generalized. The experimental data for the second practically important relation of the group of states of a disperse system — for states of the developed thermal pseudofluidization are analyzed and generalized. Under these conditions, due to the action of the vapor phase circulation occurs, i.e., stable regions of raising and lowering motion of the disperse system. The more intense motion of the particles under these conditions compared with the channel-formation conditions, enables the deposition of scum on the heating surface to be prevented [2].

The experimental conditions in a horizontal tubular bunch and some data are considered in [2]. The tubular bunch ($d_t = 10$ mm, $i = 1$-5) in a dispersed layer of particles ensured fairly uniform generation of the vapor phase in the volume of the lifting zone of the layer, since the distance between the tubes of the bunch was considerably less than the height of the dispersed layer H, while the height of the tubular bunch was approximately equal to the height of the layer. Experiments were carried out with layers of alumosilicate particles with an optimum diameter $d_{opt} = 2.77$ mm, from the point of view of heat exchange, which was chosen on the basis of the data given in [1]. The realization of a certain hydrodynamic mode under the conditions studied was determined by the relation d_T, H, H_l, $w \equiv Q/\rho_v rS = f(q_i$, p, F_b/S, the kind of liquid). Experiments showed that when organizing the boiling process in a horizontal bunch, consisting of three or more series in height, as q_i increases it becomes possible to change from the dispersed layer into the mobile state at reduced vapor speeds $w = w_{of} \approx 0.3$ m/sec. Transition to the pseudofluidization state as q_i increases was observed only when the static height of the liquid level in the apparatus H_l exceeded the static height of the particle layer H. Otherwise, no pseudofluidization of the dispersed layer occurred even if the dynamic liquid level exceeded H when q_i was increased.

When there is a further increase in $w \geqslant w_{oc} \approx 1.4$ m/sec and when $H_l \geqslant H$ the dispersed layer arrives in the state of developed circulation thermal pseudofluidization. Under these conditions at the center of the apparatus lifting motion of the three-component dispersed system occurred, and in the region of the walls lowering motion of the dense layer of particles flooded with liquid. A similar behavior of the transition to developed pseudofluidization was obtained in [3, 4], where for a gas—liquid—solid particle system different states of mobility of the particles were observed.

Previously [1] in experiments on individual heated surfaces a characteristic value of the thermal flux density q* was observed for which transition occurs to structures with lifting motion of the components of the dispersed system in constantly acting vapor channels, and lowering motion in the flooded layer outside the channels. Under boiling conditions in a tubular bunch with $\bar{q} = \bar{q}(w_{oc})$ a transition occurs to a structure with lifting motion of the

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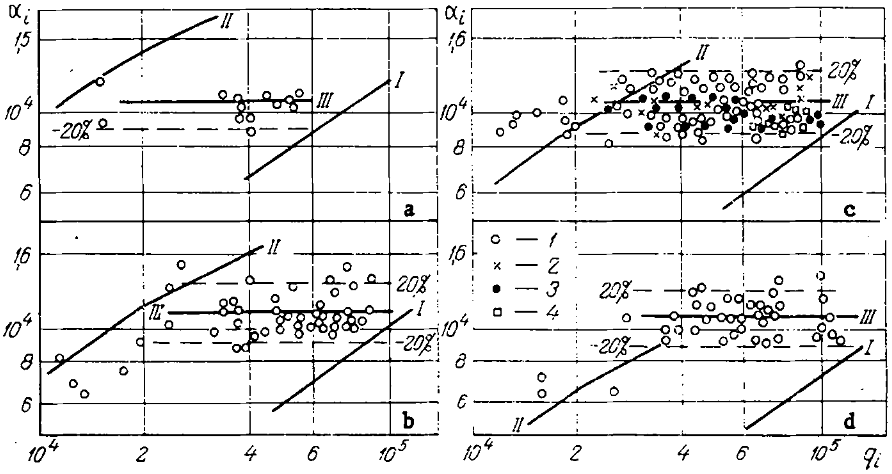

Fig. 1. Heat transfer during boiling in a horizontal tubular bunch in a dispersed layer of particles of alumosilicate with d_T = 2.77 mm, and i = 1-5 (q_i, W/m²; α_i, W/m²•deg): I) boiling curve when there is no dispersed layer; II) boiling curve under channel-formation conditions, calculation as in [1]; III) boiling curve under circulation thermal pseudofluidization conditions; a, b, c, d) p = 0.12, 0.20, 0.31, and 0.48 bar; 1) water, 2) a solution of NaCl (11%), 3) a solution of NaCl (20%), 4) seawater (11%).

components of the dispersed system in the central zone of the apparatus and a lowering motion of the liquid and particles in the region close to the walls. It should be noted that the values of the quantity $\bar{q}(w_{oc})$ and q* are approximately equal. This is obviously due to the qualitatively similar nature of the variation of the system structure — a transition to circulation motion of the system components.

It can be assumed that the intensity of the heat transfer during boiling under circulation heat pseudofluidization conditions is determined by the joint occurrence of heat transfer with evaporation of liquid films and vapor cavities formed on the heating surface, and convective heat transfer with a pseudofluidization layer on the parts of the heated surface free from vapor cavities

$$\bar{q} = \left(c\,\frac{\lambda_l \xi_f}{\bar{\delta}} + \bar{\alpha}_{\text{conv}}\xi_{\text{conv}}\right)(\bar{T}_w - T_s - \Delta T_{\text{cd}} - \Delta T_{\text{hd}}). \qquad (1)$$

A qualitative analysis of the factors in (1) confirms that unlike the conditions for which the convective component is negligibly small [1], the quantities ζ_f, ζ_{conv}, $\bar{\alpha}_{\text{conv}}$, ΔT_{hd} when $w \geqslant w_{oc}$ make a considerable contribution to the resulting heat-transfer process.

Thus, under conditions of developed circulation pseudofluidization the average porosity of the dispersed layer increases as w(q, p) increases, leading to an increase in the characteristic dimensions of the pore space in the region close to the walls d_{por}. An increase in d_{por}, according to [1], gives rise to an increase in the effective value of the liquid film close to the wall $\bar{\delta}$ (q = idem) and to a reduction in the contribution of the evaporative component to the total thermal flux. By analogy with [5-7] it can be assumed that this change in $d_{\text{por}}[m(w)]$ is responsible for the nonmonotonic nature of the curve of α_{conv} against w(q, p). In addition, an increase in the intensity of the motion of the particles as w increases may lead to disturbances of the vapor—liquid structure close to the walls and thereby to a reduction in ζ_f and an increase in ζ_{conv}. The resulting dependence of the heat exchange due to the simultaneous action of these factors has a complex form, determined by the change in the values of $\bar{\delta}$, α_{conv}, ζ_{conv} as $\bar{q}$ increases from the values characteristic for channel-formation conditions to values characteristic for boiling conditions in a free volume.

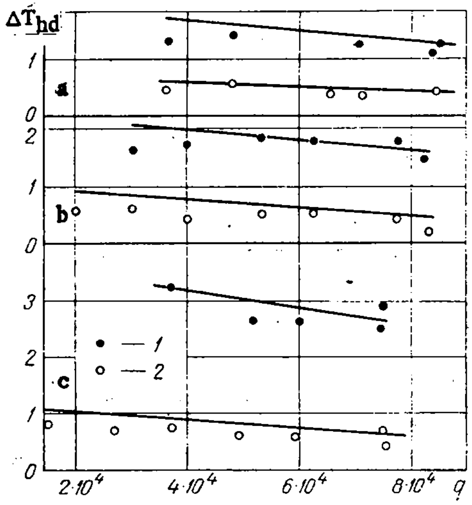

Fig. 2

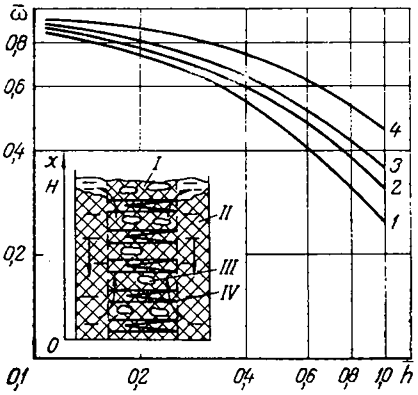

Fig. 3

Fig. 2. Effect of thermal load on the change in ΔT_{hd} over the height of the dispersed layer (q, W/m^2; ΔT_{hd}, degrees): a, b, c) p = 0.31, 0.20, and 0.12 bar; 1, 2) i = 1, 4. The curves are calculated using (17), (3), and (4).

Fig. 3. Average vapor content of the dispersed layer under thermal pseudofluidization conditions (calculated from (17)): 1, 2, 3) Fr = 1, H/L = 1; 0.3; 0; 4) Fr = 10, H/L = 0; I) raising zone; II) lowering zone; III) vapor bubble; IV) element of the tubular bunch.

The experimental data obtained (Fig. 1) corresponds to conditions in which the reduction in ζ_f/δ as $\bar{q}$ increases is obviously compensated by an increase in the values of $\bar{\alpha}_{conv}$, ζ_{conv}. This may explain why α has been found to be independent of p (Fig. 1): a reduction in ζ_f/δ (q = idem) when p is reduced is compensated by an increase in $\bar{\alpha}_{conv}$ due to the increase of the characteristic velocity of motion of the vapor w as p decreases due to the reduction in ρ_v. The intensity of the heat transfer under these conditions (taking into account the experimental data on ΔT_{hd} (Fig. 2)), as in [1], is independent of the height of the dispersed layer over the heated surface (Fig. 1). The experimental data on heat transfer in the conditions investigated is described, with a spread of ±20%, by the relation

$$q_i = 1.1\,[\bar{T}_w - T_s\,(p) - \Delta T_{cd} - \Delta T_{hd_i}], \tag{2}$$

which holds for the following conditions: p = 0.1-0.5 bar, $\bar{q} = \bar{q}(w_{oc}) - 10^5\ W/m^2$, i = 1-5, liquid — water, a solution of NaCl (0-20%), seawater (11%), and material of the heated surface — copper.

The quantity $\Delta T_{hd} \equiv T_s(p + \Delta p_{hd}) - T_s(p)$ under circulation thermal pseudofluidization conditions can reach values comparable with ΔT (Fig. 2). Experiments confirm (Fig. 1) that it is necessary to take it into account for the correct calculation of the heat transfer. Hence, when using Eq. (2) or relations of a similar form, it is necessary to determine the value of $\Delta T_{hd}(\Delta p_{hd})$ by a method which is independent of direct measurements (by which Fig. 1 was constructed). To do this we write

$$\Delta p_{hd} = [1 - \bar{\omega}\,(H - x)]\,g\rho\,(H - x), \tag{3}$$

where

$$\rho = m_{lp}\rho_l + (1 - m_{lp})\,\rho_{\text{т}}. \tag{4}$$

Direct calculation of T_{hd} using (3) and (4) is difficult because of the lack of data on w(x) — the distribution of the mean vapor content over the height of the dispersed layer.

We will calculate w(x) in the lifting zone of the dispersed layer (Fig. 3) with the following assumptions:

1) The dispersed layer in the lifting zone is in the pseudofluidization state with a porosity $m_{ep} \simeq m_0$. This assumption is based on the data in [9] which shows that m_{ep} depends only slightly on the reduced velocity of the bubbling gas;

2) the vapor bubbles bubbling through a layer with velocity $\omega(x)$ carry away an additional mass of the layer of volume $w(x)/2$; the remaining mass of the liquid-particle system moves with the velocity of the beginning of pseudofluidization w^*;

3) the quantities q and F_b are continuous functions of the coordinates in the central zone of the layer of volume SH, and constant in the horizontal cross sections of the layer.

The total energy of the elementary volume of the bubbled layer will be equal to the sum of the kinetic and potential energies in the gravitational field and of the surface tension. The total energy of the bubbled layer of height H

$$E = \int_0^H (dE_{\text{kin}} + dE_{\text{pot}} + dE_{\text{st}}). \tag{5}$$

we will seek $\omega(x)$ in the class of smooth functions $\{\omega(0) = 0, \ \omega(H) = 1\}$ assuming that it reaches a minimum of the functional (5) when

$$\int_0^H [1 - \omega(x)]\, dx = H_0. \tag{6}$$

Taking this assumption into account we will write

$$dE_{\text{kin}} = \frac{\rho w(x)^2}{2} \frac{\omega(x)}{2} dx + \frac{\rho w^{*2}}{2} \left[1 - \frac{3\omega(x)}{2}\right] dx. \tag{7}$$

From the law of conservation of mass for the vapor phase

$$d[\rho_V \omega(x) w(x)] = \frac{q(x) F_b(x)}{rSH} dx, \tag{8}$$

neglecting the dependence of ρ_v on $\Delta p(x)$ we have

$$w(x) = \frac{F_b}{r\rho_V SH\omega(x)} \int_0^x q(x)\, dx, \tag{9}$$

and from (8) and (9)

$$dE_{\text{kin}} = \left\{ \frac{\rho}{4\omega} \left[\frac{F_b}{r\rho\, SH} \int_0^x q(x)\, dx \right]^2 + \frac{\rho w^{*2}}{2} \left[1 - \frac{3\omega(x)}{2}\right]\right\} dx. \tag{10}$$

The remaining terms in (5) have the form

$$dE_{\text{pot}} = \rho g x [1 - \omega(x)]\, dx, \tag{11}$$

$$dE_{\text{st}} = 4\pi R^2{}_b\, \sigma n dx = \frac{3\sigma}{R_b} \omega(x)\, dx. \tag{12}$$

The function $q(x)$ and (9) can be represented in the form

$$q(x) \simeq \alpha \left\{ \bar{T}_W - T_s - \Delta T_{cd} - \frac{\partial T}{\partial p} [1 - \omega(x)] g\rho (H - x) \right\} \simeq$$

$$\simeq \alpha \left\{ \bar{T}_W - \Delta T_{cd} - T_s \left[1 - \frac{v_V - v_l}{r} (1 - \omega) g\rho (H - x) \right] \right\}. \tag{13}$$

The solution of problem (5) and (6) in general form, taking (10)-(13) into account, is extremely complex. The weak dependence of ΔT_{hd} on q observed experimentally (Fig. 2) enables us to assume that $\omega(x)$ depends only slightly on q and, consequently, is only slightly sensitive to the specific form of $q(x)$ for a fairly wide class of monotonically increasing $q(x)$, which takes the value $q(H) = \alpha[T_w - T_s(p) - \Delta T_{cd}]$.

We will solve (5) and (6) assuming $q(x)$ to be linear:

$$q(x) = q_0\left(1 - \frac{H-x}{L}\right), \tag{14}$$

where L has the physical meaning the depth of the layer at which $q = 0$ due to $\Delta T(x = H) = \Delta T_{hd}$, while $q_0 \equiv q(T_{hd} = 0)$. Then (5) and (6) take the form

$$E(w) = \int\limits_0^H \left\{ \frac{\rho w_0^2}{4\omega(x)} \left[\frac{x}{H} - \frac{x}{L} + \frac{x^2}{LH} \right]^2 + \frac{\rho w^{*2}}{2} \left[1 - \frac{3\omega(x)}{2} \right] + \rho g x [1 - \omega(x)] + \frac{3\sigma}{R_b} \omega(x) \right\} dx,$$

$$\int\limits_0^H [1 - \omega(x)]\, dx = H_0, \quad \omega(0) = 0, \quad \omega(H) = 1. \tag{15}$$

After using the Lagrange multiplier rule and varying ω [10], the solution (15) reduces to the solution of a two-point boundary-value problem for the algebraic equation

$$\omega(\bar{h}) = \left[1 - \bar{h}\left(1 + \frac{H}{L}\right) + \frac{H}{L}\bar{h}^2 \right] \Big/ \sqrt{1 + \frac{4\bar{h}}{\mathrm{Fr}}}, \tag{16}$$

where $h \equiv H - x$; $\bar{h} \equiv h/H$; $\mathrm{Fr} \equiv w_0^2/gH$; $w_0 \equiv w(H)$ for $q = q_0$. Since two-point boundary-value problems for algebraic equations have no solutions in general form, the fact that a solution (16) exists for problem (15) may serve as a confirmation of the justification for formulating problem (15).

The mean vapor content of the bubbling layer of depth h can be represented as

$$\bar{\omega}(\bar{h}) = \frac{1}{\bar{h}} \int\limits_0^{\bar{h}} \omega(\tilde{h})\, d\tilde{h} = \frac{1}{\bar{h}} \left\{ \mathrm{Fr} \frac{\sqrt{1 + \frac{4\bar{h}}{\mathrm{Fr}}} - 1}{2} - \mathrm{Fr}^2 \left(1 + \frac{H}{L}\right) \frac{\left(\frac{2\bar{h}}{\mathrm{Fr}} - 1\right)\sqrt{1 + \frac{4\bar{h}}{\mathrm{Fr}}} + 1}{12} \right.$$

$$\left. + \mathrm{Fr}^3 \frac{H}{L} \frac{\left(\frac{48}{\mathrm{Fr}^2}\bar{h}^2 - \frac{16}{\mathrm{Fr}}\bar{h} + 8\right)\sqrt{1 + \frac{4\bar{h}}{\mathrm{Fr}}} - 8}{480} \right\}. \tag{17}$$

Figure 3 shows the relationship (17).

Tubular bunches of industrial apparatus, as a rule, are heated by condensed vapor or by circulating liquid in which case boundary conditions close to T = const are realized. The thermal flux Q over the whole surface of the tubular bunch under circulation heat pseudofluidization conditions can be calculated as follows. From (2) we find $q_0(x = H)$, i.e., q for $\Delta T_{hd} = 0$. By specifying $(H/L)_0 = 0$ we find w_0 from (9), $\omega_0(\bar{h})$ from (17), and $\Delta T_{hd}(x)$ from (3) and (4). After this we find $q_0(x)$ and $Q_0 = F_b \int_0^s q_0(x)dx$. From the function $q_0(x)$ obtained we find the accurate value of $(H/L)_1$, for which we find $q_1(x)$, etc. The functions obtained by this process converge extremely rapidly and a satisfactory degree of agreement is reached after the first step. As an example, Fig. 2 compares the experimental and theoretical values of ΔT_{hd}. The good agreement between these values over the whole range of p, q, and h investigated confirms the applicability of this model of the motion of the components and phases and shows that expressions (17), (3), and (4) are fairly accurate.

NOTATION

T, temperature; q, heat-flux density; Q, heat flux; r, specific heat of vaporization; H, height of the layer; S, area of transverse cross section of the lifting zone of the layer; F, area; d, linear dimension; w, reduced vapor velocity; p, pressure; c, a coefficient of proportionality in the first term of Eq. (3); g, acceleration due to gravity; E, energy; R_b, radius of a bubble; n, number of bubbles; L, characteristic depth of the layer; m, porosity; x, height coordinate; $\overline{h} \equiv (H - x)/H$, $Fr \equiv w_o^2/gH$, $w_o \equiv w(H)$ for $q \equiv q(\Delta T_{hd} = 0)$; v, specific volume; ρ, density; λ, thermal conductivity; α, heat-transfer coefficient; $\overline{\delta}$, average thickness of the liquid film; ζ, fraction of the heating surface; and ω, volume vapor content. The indices represent the following: T, material of the particles; l, liquid; v, vapor; s, saturation; w, wall; cd, concentrational depression; hd, hydrodynamic depression; i, number of a bundle row along the height; of, origin of fluidization; oc, origin of circulation; conv, convective; f, film; por, porous; lp, liquid–particle system; a bar, the mean; kin, kinetic; pot, potential; st, surface tension; and o, initial.

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