HEAT AND MASS TRANSFER BETWEEN A BOILING LIQUID AND BUBBLES

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A method is proposed for calculating the flow of a boiling liquid with bubbles through vertical pipes (containers).

The results obtained in [1-13] pertaining to the integral characteristics of the bubble made and to the dynamics of individual bubble buildup can be useful for a more systematic approach to the problem of determining the local characteristics of the bubble mode.

It is essential here that the equations of mixture flow must be considered simultaneously with the equation representing the bubble size-distribution function. For a vertical container (pipe) this latter equation (averaged over the radius, without taking into account the fragmentation and the merger of bubbles) is

$$\varphi_t + (u_1\varphi)_x + (\dot{v}\varphi)_v = n_c P_c \varphi_c;\ \varphi(t,\ 0,\ v) = \frac{n_0 A_0}{u_1}\varphi_0, \tag{1}$$

where φdx denotes the number of bubbles of a size v which are contained in volume A(x)dx. With the aid of the results in [7-9], the flow velocity and the buildup rate of a moving bubble can be written as

$$u_s = av^m;\ \dot{v} = \alpha v^n;\quad \alpha = \sqrt{24}\,(au_s)^{\frac{1}{2}}\,\mathrm{Ja};\ \mathrm{Ja} = \frac{c_p\rho\Delta T}{\rho_1 h_{evap}}. \tag{2}$$

Exponents m and n depend on the bubble dimensions [4, 7, 8]. For a uniformly superheated (or subheated) liquid with ΔT = const, n_c = const and, if $\varphi_c = \delta(v-v_0)$ and $\varphi_0 = \delta(v-v_0)$, then the steady-state distribution $\varphi(x, v)$ is

$$\varphi(x,v) = \frac{n_0A_0}{u_1v_0}K^{1-\frac{n}{c}}\delta(K(\xi^c-1)\mp\eta)(K\xi^c\mp\eta)^{\frac{n}{c}}\xi^{-n} \mp \frac{n_cP_c}{\alpha v_0^n}\theta\left(K(\xi^c-1)\mp\eta\right)\xi^{-n} \pm \frac{n_cP_c}{\alpha v_0^n}\theta(\xi-1)\xi^{-n};$$
$$c = m+n-1;\ K = \frac{av_0^c}{\alpha c x_0};\ \ \xi = \frac{v}{v_0};\ \eta = \frac{x}{x_0};\ \xi,\ \eta > 0;\ P_c = \mathrm{const}. \tag{3}$$

The upper signs correspond to a superheated liquid, the lower signs correspond to a subheated liquid. Exponents m and n in (3) depend on the bubble size as follows [1]:

$$\mathrm{Re} \ll 1;\ u_s = av^{2/3};\ \dot{v} = \alpha v^{5/6}; \tag{4}$$

$$\mathrm{Re} \gg 1;\ u_s = av^{1/6};\ \ \dot{v} = \alpha v^{7/12}; \tag{5}$$

$$\mathrm{Re} > 3\mathrm{Ar}^{1/2};\ u_s = a;\ \dot{v} = \alpha v^{\frac{1}{2}}. \tag{6}$$

The factor ξ^{-n} in (3) indicates that the density distribution decreases as the bubble size v increases. The total quantity of bubbles and the vapor content distribution φ from (3) are (at u_1 = const)

$$n(x) = \int\varphi dv = \frac{n_cP_c}{u_1}x + \frac{n_0A_0}{u_1};\ cA = \int\varphi v dv$$

$$= \frac{n_cP_c}{u_1}\left(v_0x + \frac{\alpha v_0^{\frac{1}{2}}}{2u_1}x^2 + \frac{\alpha^2}{u_1^2}x^3\right) + \frac{n_0A_0}{u_1}\left(v_0 + \frac{\alpha v_0^{-\frac{1}{2}}}{u_1}x + \frac{\alpha^2}{4u_1^2}x^2\right). \tag{7}$$

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According to (7), the vapor content $c \sim x^3$ if the bubble buildup during the flow follows Eq. (6), but $c \sim x$ if there is no bubble buildup and $\alpha = 0$. The average number of bubbles of a size v within the entire volume can be found from Eq. (1) averaged over x:

$$\psi(t, v) = \psi_0\left(v_0\left(\xi^{\frac{1}{2}} - \frac{t}{A}\right)^2\right)\exp\left(-\frac{t}{t_1}\right)\left(\xi^{\frac{1}{2}} - \frac{t}{A}\right)\xi^{-\frac{1}{2}}$$

$$-\frac{S_e n_c}{\alpha v_0^{\frac{1}{2}}}\theta(A(\xi^{\frac{1}{2}} - 1) - t)\exp(D(1-\xi^{\frac{1}{2}}))\xi^{-\frac{1}{2}} + \frac{S_e n_c}{\alpha v_0^{\frac{1}{2}}}\exp(D(1-\xi^{\frac{1}{2}}))\,\theta(\xi - 1)\,\xi^{-\frac{1}{2}};$$

$$A = \frac{2v_0^{\frac{1}{2}}}{\alpha};\quad D = \frac{A}{t_1};\quad t_1 = \frac{x_1}{u_1};\quad \xi = \frac{v}{v_0};\ S_e = P_c x_1 + A_0; \tag{8}$$

$$\psi_0 = (v) = \psi(0, v);\ \psi(t, v) = \int_0^{x_1} \varphi dx.$$

In order to determine the distribution of bubbles, per unit wall area, which emerge in the vapor nuclei and then build up until they separate, it is necessary to solve Eq. (1) for $(u_1\varphi)_x = 0$ with a given size distribution of vapor nuclei and a stationary bubble buildup according to the law in [7] (t_1 denoting the average dwell time of a bubble at the wall). This solution is

$$f(0, R) = f_0(R);\ \dot{R} = \gamma t^{-\frac{1}{2}};\ f(t, R) = f_0(R - 2\gamma t^{\frac{1}{2}})\exp\left(\frac{t}{t_1}\right), \tag{9}$$

with R denoting the bubble radius and $\dot{R}$ denoting the buildup rate of a stationary bubble. Distribution (9) can be used as a constraint for φ_c, φ_0 in the solution of Eqs. (1). Another proposed method of determining the vapor content in a boiling liquid is as follows. By integrating Eq. (1) for φ with respect to vdv, we arrive at the continuity equation for the vapor phase:

$$\frac{\partial}{\partial t}(cA) + c_1\frac{\partial}{\partial x}(\bar{u}_1 cA) = \int \dot{v}\varphi dv + \int n_c P_c \varphi_c v dv \equiv H_1 + H_2 \equiv H. \tag{10}$$

Here $cA = \int v\varphi dv$, $c_1\bar{u}_1 cA = \int u_1\varphi v dv$, and $u_1 = u + u_S$. According to (10), c_1 can be determined if the form of the profile $u_S(v)$ is known:

$$c_1 = \frac{\int u_1 \varphi v dv}{(\int \varphi v dv)\bar{u}_1};\ \bar{u}_1 = \frac{\int u_1 \varphi dv}{\int \varphi dv}. \tag{11}$$

By averaging Eq. (1), we have lost some information and, therefore, c_1 must be determined either from tests or from the solution to (1) with simplifying assumptions. If u_1 = const, then $c_1 = 1$. The vapor supply generated by the buildup of bubbles during the time of flow is equal to $H_1 = \int \dot{v}\varphi dv$. The quantity H_1 must be proportional to the quantity of vapor in the bubbles which arrive at point (t, x) from the bottom and from the lateral walls from x to $x - u_1 t \leq 0$:

$$H_1(t, x) = \int_0^\infty \int_{x-u_1 t > 0}^{x} n_c P_c \varphi_c(t', x_0, v_0)\, v_x dx_0 dv_0 + \int_0^\infty n_0 A_0 \varphi_0(t'', v_0)\, v_x dv_0 \equiv A_1 + A_2; \tag{12}$$

Here $A_2 = 0$, if $x - u_1 t > 0$, $t' = t - \int_{x_0}^{x} dx/u_1$, $t'' = t - \int_0^x dx/u_1$, and x_0, v_0 are the bubble coordinates at the instant of separation from the wall. In order to determine $v_x(t, t', x, x_0, v_0)$, we modify Zavoiskii's formula (2) [2, 3] with $\Delta T = \Delta T(t, x)$:

$$v_x = \frac{\alpha(t, x)}{u_1}\left[v_0^{1-n} + \frac{1-n}{u_1}\int_{x_0}^{x}\alpha\left(t - \frac{x - x''}{u_1},\ x''\right)dx''\right]^{\frac{n}{1-n}};\quad \frac{d}{dt} = u_1\frac{d}{dx}. \tag{13}$$

With the bubble distribution on the walls given as $\varphi_c = \delta(v - v_0)$ and $\varphi_0 = \delta(v - v_0)$, we obtain for H_1 with $n = 1/2$ [8]

$$H_1(t, x) = \left[\alpha(t, x)\int_{x-u_1 t > 0}^{x} \frac{n_c P_c v_0^{\frac{1}{2}}}{u_1} dx'\right] + \left[\alpha(t, x)\int_{x-u_1 t > 0}^{x} \frac{n_c P_c}{2u_1^2}\int_{x'}^{x}\alpha\left(t - \frac{x - x''}{u_1},\ x''\right)dx'' dx'\right]$$

$$+\left[\alpha(t,\ x)\frac{n_0A_0v_0^{\frac{1}{2}}}{u_1}\right]+\left[\frac{\alpha(t,x)}{2u_1^2}\int_0^x\alpha\left(t-\frac{x-x''}{u_1},\ x''\right)dx''\right]=C_1+C_2+C_3+C_4, \tag{14}$$

where C_1, C_2 characterize boiling at the lateral walls and C_3, C_4 characterize boiling at the container bottom. If $x-u_1t > 0$, then $C_3 = C_4 = 0$. Inserting (14) into (10) yields the (t, x)-distribution of vapor content:

$$cA=(cA)_0+\int_{x-u_1t>0}^{x}\frac{n_cP_cv_0}{u_1}dx'+\int_{x-u_1t\geq 0}^{x}\alpha(t',\ x')\int_{x'-u_1t'\geq 0}^{x'}\frac{n_cP_cv^{\frac{1}{2}}}{u_1^2}dx''dx'$$

$$+\int_{x-u_1t\geq 0}^{x}\alpha(t',\ x')\int_{x'-u_1-t'\geq 0}^{x'}\frac{n_cP_c}{2u_1^3}\int_{x'}\alpha(t''',\ x''')\,dx'''dx''dx'+\int_0^x\frac{n_0\left(t'-\frac{x'}{u_1}\right)A_0v_0^{\frac{1}{2}}}{u_1^2}\alpha(t',\ x')\,dx'$$

$$+\int_0^x\frac{n_0\left(t'-\frac{x'}{u_1}\right)A_0}{2u_1^3}\alpha(t',\ x')\int_0^x\alpha(t'',\ x'')\,dx''\,dx'=D_0+D_1+D_2+D_3+D_4+D_5; \tag{15}$$

$$D_0=D_4=D_5=0,\quad \text{if}\quad x-u_1t>0,\ t'=t-\frac{x-x'}{u_1},\ t''=t'-\frac{x'-x''}{u_1},$$

If $x-u_1t > 0$, $t' = t-(x-x')/u_1$, $t'' = t'-(x'-x'')/u_1$, $t''' = t'-(x'-x''')/u_1$, then $D_0 = D_4 = D_5 = 0$. If α = const (ΔT = const), then, according to (15), $c \sim t^3$ when $x-u_1t > 0$ and c(x) is the same as distribution (7) based on (3) when $x-u_1t \leq 0$. If $\alpha(t)-\alpha(t-x/u_1) \ll 1$, then $\alpha(t, x)$ can be taken out of the integral signs and a solution the same as for α = const can be obtained. If the temperature distribution $\Delta T(t, x)$ and thus the $\alpha(t, x)$ distribution are known, therefore, then Eq. (15) defines the vapor content c(t, x) inside a vertical container (pipe). In the general case $\Delta T(t, x)$ must be determined together with c(t, x) from the energy equation. We will write here the one-dimensional continuity equation for the vapor phase and the one-dimensional energy equation for the mixture; the other equations then following analogously:

$$\begin{gathered}(\rho_1cA)_t+(\rho_1u_1cA)_x=\rho_1H;\\ (\rho_1ch_1A+\rho(1-c)hA)_t+(\rho_1u_1ch_1A+\rho(1-c)uhA)_x=q_\Sigma.\end{gathered} \tag{16}$$

According to [12], $T = T_S$ and $h_{10} = c_pT_S + h_{evap}$. If the enthalpy of vapor is $h_1 = h + h_{evap} = c_p\Delta T + h_{10}$, then the relative error $\delta = c_p\Delta T/(c_pT_S + h_{evap}) \ll 1$ for most substances. For instance, $\delta(H_2O) = 10^{-4}$, $\delta(N_2) = 0.006$, $\delta(O_2) = 0.001$, $\delta(Li) = 10^{-5}$. In that case (16) yields, with $\beta = c_p\Delta T/\alpha$ = const (2), the equations

$$\begin{gathered}\beta\left[(A\bar\rho)\,\alpha_t+(GA)\,\alpha_x\right]=q_\Sigma-(\rho_1H)h_{evap}.\\ (\varkappa\bar\rho A)_t+(\chi GA)_x=\rho_1H.\end{gathered} \tag{17}$$

Inserting H(t, x) into (17) yields nonlinear integrodifferential equations (inasmuch as n_c and v_0 are functions of ΔT) for c(t, x) and $\Delta T(t, x)$. For the steady-state case ($\partial/\partial t = 0$ and GA = const) Eqs. (17) and (14) can be written as

$$\beta(GA)\alpha_x=q_\Sigma-\rho_1h_{evap}\Big\{[n_cP_cv_0]+\alpha(x)\left[\int_0^x\frac{n_cP_cv_0^{\frac{1}{2}}}{u_1}dx'+\frac{n_0A_0v_0^{\frac{1}{2}}}{u_1}\right]+\alpha(x)\left[\int_0^x\frac{n_cP_c}{2u_1^2}\int_{x'}^x\alpha(x'')\,dx''\right.$$

$$\left.+\frac{n_0A_0}{2u_1^2}\int_0^x\alpha(x')\,dx'\right]\Big\}=q_\Sigma-B_1-B_2-B_3; \tag{18}$$

where B_1 denotes the energy consumed on generating bubbles of size v_0 at the height x, B_2 denotes the energy consumed on the bubble buildup because of their initial size v_0, and B_3 denotes the energy consumed on the bubble buildup because of the superheat (considering now that $v_0 \sim 0$). Within certain ranges of ΔT the quantities n_c and n_0v_0 can be represented in terms of power functions in ΔT [1-6, 10, 11] (letting P_c = const and A = const):

$$\begin{gathered}n_c=n_c(\Delta T)=\bar n_c\alpha^s;\quad n_0=\bar n_0\alpha_0^s;\quad v_0=\bar v_0\alpha^k;\\ n_cP_c=a_1\alpha^s;\ n_cP_cv_0=a_2\alpha^r;\ n_cP_cv_0^{\frac{1}{2}}=a_3\alpha^p.\end{gathered} \tag{19}$$

If the bubbles build up only slightly during the flow, i.e., when the liquid is superheated only at the walls, then $B_2 \sim B_3 \sim 0$, $v \sim v_0$,

$$\beta (GA)\, \alpha_x = q_\Sigma - A_2 \alpha^r,\ (GA)\, \chi_x = B_2 \alpha^r,\ A_2 = a_2 \rho_1 h_{evap},\ B_2 = a_2 \rho_1, \tag{20}$$

and the solution for $q_\Sigma = \text{const}$, $\text{Ja} \gg 1$, $r = 2$ [4] is

$$\alpha(x) = \frac{\alpha_0 \sqrt{\bar{A}_2 \bar{q}_\Sigma} + \bar{q}_\Sigma \operatorname{th}\left(\sqrt{\bar{A}_2 \bar{q}_\Sigma}\, x\right)}{\sqrt{\bar{A}_2 \bar{q}_\Sigma} + \bar{A}_2 \alpha_0 \operatorname{th}\left(\sqrt{\bar{A}_2 \bar{q}_\Sigma}\, x\right)};$$

$$\chi = \bar{B}_2 \int_0^x \alpha^2 (x')\, dx'; \tag{21}$$

$$\bar{q}_\Sigma = q_\Sigma / GA\beta;\ \bar{A}_2 = A_2 / GA\beta;\ \bar{B}_2 = B_2 / GA\beta.$$

For $q_\Sigma = 0$ and any value of r

$$\alpha(x) = [\alpha_0^{1-r} + (1-r)\bar{A}_2 (x - x_0)]^{\frac{1}{1-r}}. \tag{22}$$

If the liquid is sufficiently superheated over the entire volume, then $B_2 \gg B_1$, $B_3 \gg B_1$, and for $B_2 \gg B_3$ (i.e., when the bubble buildup is determined mainly by size v_0 at separation) Eq. (18) yields

$$\beta (GA)\, \alpha_x = q_\Sigma - A_2 \alpha(x) \alpha^p - A_3 \alpha(x) \int_0^x \alpha^p (\xi)\, d\xi. \tag{23}$$

For $\text{Ja} \gg 1$, according to [10], $p = 0$ and the solution to (23) is

$$\alpha(x) = \exp\left(-\left(\bar{A}_2 x + \frac{\bar{A}_3}{2} x^2\right)\right)\left[\int_0^x \bar{q}_\Sigma \exp\left(\bar{A}_2 x + \frac{\bar{A}_3}{2} x^2\right) dx + \alpha_0\right]. \tag{24}$$

When $v_0 \sim 0$, i.e., when $B_3 \gg B_2$, Eq. (18) yields

$$\ddot{Z} = \bar{q}_\Sigma - \dot{Z}\left[Z\left(a\dot{Z}^s + b\int_0^x \dot{Z}^s d\xi\right) - b\int_0^x Z\dot{Z}^s d\xi\right];$$

$$Z(0) = 0;\ \dot{Z}(0) = \alpha_0. \tag{25}$$

For $s = 0$ Eq. (25) reduces to

$$\dddot{Y} = \bar{q}_\Sigma - \dot{Y}[\ddot{Y}(a + bx) - bY];\ Y(0) = 0;\ \dot{Y}(0) = 0;\ \ddot{Y}(0) = \alpha_0. \tag{26}$$

Equations (25) and (26) as well as the general equation (18) can be solved only numerically. Let us consider the case where no boiling occurs at the lateral walls and bubbles appear only on the bottom of the container (in a pipe they are brought into a given segment together with the liquid from below). From Eq. (18) we extract the terms which characterize boiling on the bottom:

$$\alpha_x = \bar{q}_\Sigma - \alpha(x)\left[a + b\int_0^x \alpha(\xi)\, d\xi\right];$$

$$a = \frac{n_0 A_0 v^{\frac{1}{2}} \rho h_{evap}}{u_1 GA\beta};\ b = \frac{n_0 A_0 \rho h_{evap}}{2u_1^2 GA\beta}. \tag{27}$$

The nonlinear equation (27) will be now solved for the simplest forms of heat sources $\bar{q}_\Sigma$:

$$\bar{q}_\Sigma = 0;\ \alpha(x) = \frac{C\alpha_0}{\sqrt{C} \operatorname{ch}(\sqrt{C}x) + \frac{a}{2} \operatorname{sh}(\sqrt{C}x)};\ C = \frac{a^2 + b\alpha_0}{2}; \tag{28}$$

$$\bar{q}_\Sigma = \text{const};\ \alpha(x) = \frac{1}{b} \cdot \frac{du}{dx};\ u(x) = \frac{\xi_x \xi^{-1} Z(t) + 2\xi^{\frac{1}{2}} Z_t(t)}{Z(t)}; \tag{29}$$

$$Z = C_1 I_\nu (t) + C_2 I_{-\nu}(t);\ \nu = \frac{1}{3};\ t = \frac{4}{3b\bar{q}_\Sigma} \xi^{3/2};$$

$$t = \frac{b\bar{q}_\Sigma}{2} x + C;\ C = b\alpha_0 + \frac{a}{2};$$

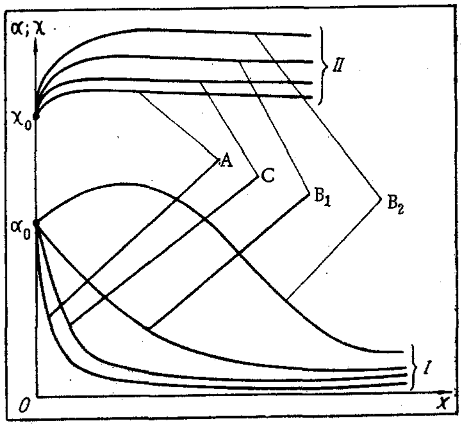

Fig. 1. Distribution of superheat $\alpha(x)$ (I) and of vapor content $\chi(x)$ (II) along a pipe: $q_\Sigma = 0$ (A), q_Σ = const, $q_\Sigma \le \rho_1 H h_{evap}$ (B1), $q_\Sigma = \text{const} \ge \rho_1 H h_{evap}$ (B2), $q_\Sigma = q_0 e^{-mx}$ (C).

$$\bar{q}_\Sigma = q_0 \exp(-\gamma x); \quad \alpha(x) = -\frac{1}{b} \cdot \frac{du}{dx}; \quad u(x) = \frac{Z_t(t)}{Z(t)}\left(-\gamma \sqrt{\frac{q_0}{2}} \exp\left(\frac{-\gamma x}{2}\right)\right); \tag{30}$$

$$Z(t) = C_1 J_\nu(t) + C_2 J_{-\nu}(t); \; t = \sqrt{2q_0} \exp\left(-\frac{\gamma x}{2}\right);$$

$$\nu = \sqrt{2C}; \; C = b\alpha_0 + \frac{a^2 + q_0}{2}; \; u(0) = a; \; u_x(0) = b\alpha_0.$$

Constants C_1 and C_2 are determined from the initial conditions $u(0)$ and $u_x(0)$. Solutions (28)-(30) are shown diagramatically in Fig. 1. Depending on the relation between q_Σ and α_0, the superheat of the liquid along a pipe first rises as long as the heat consumed on bubble buildup does not compensate for the presence of heat sources in the volume, and then drops to zero while the vapor content increases to a constant level or till the flow mode changes. Bubbles coming from the lateral walls (solutions (21), (22), (24), and Eq. (18)) have an analogous effect, but Eq. (18) can be solved only numerically.

This method is applicable also to other modes of two-phase fluid flow. We then express the mass source in one phase as [13]

$$M(t, x) = \int_0^\infty \int_{x-u_1 t}^{x} \varphi_c\left(t - \frac{x-x'}{u_1}, x', m_c'\right) \frac{dm_c'(t, x, t', x', m_c')}{dx} dx' dm_c'. \tag{31}$$

In a droplet-annular flow mode φ_c denotes the number of droplets forming at instant $t-(x-x')/u_1$ across section $A(x')$, dm_c/dx denotes the rate of change of droplet mass during the flow, t', x', and m_c' are the time, the location, and the mass of a droplet nucleus. In a projectile mode φ_c denotes the average number of vapor locks and m_c denotes the mass of a vapor lock. The rate of change of mass dm_c/dx is a function of the superheat ΔT and of the slip velocity, it depends on the shape and the area of droplet, bubble, and lock surfaces. Sometimes this relation is a power law [7-9]:

$$\frac{dm_c}{dx} = A \Delta T^n S_e^m \quad \text{or} \quad \frac{dm_c}{dx} = B \Delta T m_c^k. \tag{32}$$

Exponents m and k depend on the flow mode and conditions. For a laminar flow of bubbles, Eqs. (32) and (2) concur. For a turbulent flow of bubbles, the formula

$$\frac{dm}{dt} = A \Delta T m, \; m = m_0 \exp\left(\frac{t}{t_1}\right); \; t_1 = \frac{1}{A \Delta T} \tag{33}$$

has been derived in [9]. By inserting (32) and (33) kind of expressions into (31), one can find both the temperature and the phase content in a system by the method outlined here. When gas bubbles are passed through holes in walls, then v_0, n_c, and n_0 are independent of the superheat ΔT, but the bubble buildup during the flow is a function of ΔT: $v = v(\Delta T)$. When $p_V \gg p_G$ (p_V and p_G denote the respective partial pressures of vapor and gas in bubbles), then the rate of bubble buildup can be determined according to (2). Obviously, $p_V \gg p_G$ at $t \gg 1$ or $x \gg 1$ or $\Delta T \gg 1$. Under such conditions, the general equations (12)-(30) describe the bubbling process in a liquid.

NOTATION

A	is the cross-sectional area;
P_c	is the circumference;
h_{evap}	is the heat of evaporation;
$\bar{\rho} = \rho_1 c + \rho(1-c)$	is the mean density of mixture;
$G = \rho_1 u_1 c + \rho u(1-c)$	is the mean mass rate of mixture flow;
$\varkappa = \rho_1 c/\bar{\rho}$	is the relative vapor content;
$\chi = \rho_1 u_1 c/G$	is the discharge vapor content;
$\alpha(t, x)$	is the relative superheat according to (2);
$c(t, x)$	is the relative vapor content;
Ja	is the Jacob number;
q_Σ	is the volume heat sources;
S_e	is the surface of interphase boundary;
h_1, h_{10}	is the enthalpy of vapor;
T_s	is the saturation temperature;
n_c, n_0	are the total particle currents (per unit time) from unit area of lateral walls and of container bottom respectively;
$\varphi_c(t, x, v)$; $\varphi_0(t, x, v)$	are the probability of bubbles of size v separating from wall and from bottom respectively;
v	is the bubble size;
u	is the velocity of liquid phase;
u_s	is the slip velocity;
u_1	is the velocity of bubbles;
$\bar{u}_1$	is the mean velocity of vapour phase.

Subscripts

1 denotes vapour phase.

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