A NEW MODEL FOR VOID FRACTION IN SUBCOOLED BOILING

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1. INTRODUCTION

Flow boiling is an important phenomena both to nuclear power plant safety analysts, and to the plant operators. Boiling is usually divided into two stages; i.e. subcooled boiling (also called local boiling) and saturated boiling (also called bulk boiling). Subcooled boiling occurs whenever a sufficiently superheated wall is in contact with a subcooled liquid that has a bulk temperature below the saturation value, while saturated boiling occurs when the temperature is equal to saturation value.

Subcooled boiling heat transfer is one of the steady state heat transfer mechanisms in the CANDU 600 reactor. There is substantial subcooled boiling for most of the channels.

A great deal of work have been done on the subcooled boiling over the last three decades. Among these studies, two distinctly different approaches have been taken to qualify the prediction of void fraction and other interesting parameters. In the first approach, a phenomenological description of the boiling heat transfer process is postulated and, thus, the subcooled flow quality is calculated from a mechanistic model [1,2,3,4]. The other approach is to postulate a convenient mathematical fit for the flow quality or liquid enthalpy profile between the void departure point, x_d, and the point at which thermodynamic equilibrium is achieved, x_{eq}, [5,6,7,8,9]. By using the flow quality thus obtained, void fraction is then calculated from various void-flow quality correlations. Some results from previous research are used in the design and safety analysis of the CANDU type reactors [10,11].

It should be pointed out, however, that in the above mentioned methods the vapour bubble transport process, such as the bubble nucleation, growth, coalescence and collapse, etc. are not fully taken into account. It is these bubbles that play a key role in the fluid voiding. Models not recognizing the bubble dynamics will, to a certain extent, have their applicability severely hindered.

In the present work, the void fraction is obtained from its physical definition. Averaged equations governing the motion of a one-dimensional two-phase flow [12] are used in the analysis. The equal velocity but unequal temperature (EVUT) approximation is applied to solve the momentum and energy equations in steady state to obtain the velocity and temperature distributions, respectively. The bubble nucleation, growth and collapse rate in the bubble number transport equation is then used together with the temperature and velocity distributions to calculate the void fraction at each cross section of the flow channel. The void fraction is finally expressed by an integration as a function of physical properties of the fluid and the system temperature and pressure.

2. GOVERNING EQUATIONS

The 1-D two fluid model is used in the present work. They are written in Cartesian coordinates as:

$$\frac{\partial}{\partial t}(\alpha_k\rho_k) + \frac{\partial}{\partial x}(\alpha_k\rho_k U_k) = m_{ik} \tag{1}$$

$$\frac{\partial}{\partial t}(\alpha_k\rho_k U_k) + \frac{\partial}{\partial x}(\alpha_k\rho_k U_k^2) = -\alpha_k\frac{\partial P_k}{\partial x} + m_{ik}U_k - \tau_{ik} - \tau_{wk} - \alpha_k\rho_k g\frac{\partial Z}{\partial x} \tag{2}$$

$$\frac{\partial}{\partial t}\left(\alpha_k\rho_k\left(h_k+\frac{1}{2}U_k^2\right)\right) + \frac{\partial}{\partial t}\left(\alpha_k\rho_k U_k\left(h_k+\frac{1}{2}U_k^2\right)\right)$$
$$= \alpha_k\frac{\partial P_k}{\partial t} + q_{ik} + q_{wk} + \tau_{ik}U_k + m_{ik}\left(h_k+\frac{1}{2}U_k^2\right) - \alpha_k\rho_k U_k g\frac{DZ}{Dx} \tag{3}$$

where t is the time and x is the flow direction, k (=v or l) denotes the vapour and liquid phase, and α_k, the volume fraction of phase k, ρ_k, the density of phase k, U_k, the average velocity of phase k, m_{ik}, the mass transferred from the interface to phase k, P_k, the pressure of phase k, τ_{ik} the shear stress between the interface and phase k and τ_{wk}, between the wall and phase k, Z, the elevation, h_k, the enthalpy of phase k, q_{ik} the heat transferred from the interface to phase k and q_{wk}, from the wall to phase k.

Eqs. (1) to (3) are constrained by the following conditions:

$$\sum \alpha_k = 1, \quad \sum m_{ik} = 0, \quad \sum \tau_{ik} = 0, \quad \sum q_{ik} = 0$$

The above equations result in:

$$\alpha_v = \alpha, \quad \alpha_l = (1-\alpha), \quad m_{iv} = -m_{il} = m_i, \quad \tau_{iv} = -\tau_{il} = \tau_i,$$

$$q_{iv} = -q_{il} = q_i$$

where α is the so called void fraction.

It is assumed that both phases have the same velocity U, that the flow channel is horizontally placed and that the kinetic energy is negligible compared with the thermal energy. Summing up the Eqs. (1) to (3) with respect to both phases, the governing equations for mixture, under steady state conditions, are obtained as:

$$\frac{d}{dx}(\alpha\rho_v + (1-\alpha)\rho_l)U = 0 \tag{1'}$$

$$\frac{d}{dx}(\alpha\rho_v + (1-\alpha)\rho_l)U^2 = -\frac{dP_l}{dx} - \alpha\frac{d(P_v - P_l)}{dx} - (\tau_{wv}+\tau_{wl}) \tag{2'}$$

$$\frac{d}{dx}(\alpha\rho_v h_v + (1-\alpha)\rho_l h_l)U = m_i(h_v - h_f) + (q_{wv} + q_{wl}) \tag{3'}$$

In the present work, the cross section averaged void fraction is calculated from its physical definition as:

α = bubble volume * bubble number density

To calculate the void fraction, the bubbles' radius and the bubble number density (bubbles/m^3) are needed. The calculation of bubble radius will be left to the next section for consistency. The governing equation for the bubble number density in steady state is written as:

$$\frac{\partial}{\partial x}(N_b U_b) = \Phi_{bn} + \Phi_{wn} + \Phi_{dis} - \Phi_{cond} \tag{4}$$

where N_b is the bubble number density (averaged over a cross-sectional area of the channel), U_b, the velocity of the bubbles, ϕ_{bn}, the bulk liquid bubble nucleation rate, ϕ_{wn}, the heated wall cavity nucleation rate, ϕ_{dis}, the generation rate due to bubble disintegration and ϕ_{cond}, the sink rate due to bubble coalescence and collapse.

It is noted that under the subcooled conditions, bubble nucleation rate in the bulk liquid is zero because the bulk liquid is subcooled. The disintegration of bubbles in subcooled boiling is not as important as the other terms. The terms, ϕ_{bn} and ϕ_{dis}, are therefore neglected in the following analysis.

The expression for $\phi_{wn}-\phi_{cond}$ is given by [13] as:

$$\Phi_{wn}(x)-\Phi_{cond}(x) = \frac{T_l(x)-T_l(0)}{T_{sat}(x)-T_l(0)} \times \frac{F(\rho^*(x))}{R_c^{*4.4}(x)\,D_d^2(x)} \times \frac{f(x)\,\xi_h}{A} \quad (5)$$

where T_l and T_{sat} denote the liquid temperature and the saturation temperature corresponding to the local liquid pressure. ξ_h and A are the heated perimeter and the cross-sectional area of the boiling channel. $F(\rho^*)$, R_c^*, D_d and f are functions given below:

$$F(\rho^*) = 2.157\times10^{-7}\rho^{*-3.2}(1+0.0049\rho^*)^{4.13} \qquad \rho^* = \frac{\rho_l-\rho_v}{\rho_v}$$

$$D_d = 2.64\times10^{-5}\theta\left(\frac{\sigma}{g\rho_v}\right)^{0.5}\rho^{*0.4}$$

$$R_c^* = \frac{2\sigma}{P_l}\left(1+\frac{\rho_v}{\rho_l}\right)/\left(\exp\left(\frac{h_{fg}\Delta T_{sat}}{RT_vT_{sat}}\right)-1\right)/(D_d/2) = R_c/(D_d/2), \quad (5a)$$

$$f = 1.18\left(\frac{\sigma g\rho_v\rho^*}{\rho_l^2}\right)^{1/4}$$

where θ and σ are the contact angle and surface tension of the liquid, respectively, g is the gravity, h_{fg}, the latent heat, ΔT_{sat}, wall superheat $(=T_w-T_{sat})$, R, gas constant and T_v, the vapour temperature.

Attention should be paid to the velocity of the bubbles, U_b, in Eq. (4) . It is well known that the subcooled boiling process can be further subdivided into two regions, namely wall voidage and detached voidage. In wall voidage region, the bubbles travel in a narrow bubble layer close to the wall [14], while in the detached voidage region, the bubbles ejected from the bubble layer travel along with the bulk liquid. U_b for these two regions is therefore different. In the present study, for the wall voidage region, U_b is equal to the average velocity of the thermal boundary layer, and for the detached region, it equals the average velocity of the bulk liquid.

3. SOLUTION FOR THE VOID FRACTION

Eqs. (1') to (3') constitute a boundary value problem which can be solved under specified boundary conditions.

Integrating Eq. (1') yields:

$$\alpha = \frac{G - \rho_l U}{\rho_v - \rho_l}\frac{1}{U} \tag{6}$$

where G denotes the mass flow rate, which is a constant in steady state.

Integrating Eq. (2'), results in:

$$U(x) = U(0) - \frac{1}{G}(P_l(x) - P_l(0)) - \frac{1}{G}\int_0^x \alpha(x)\frac{d(P_v - P_l)}{dx}dx$$
$$- \frac{1}{G}\int_0^x (\tau_{wv}(x) + \tau_{wl}(x))\,dx \tag{7}$$

In Eq. (7), the term $d(P_v - P_l)/dx$ is small when compared with the other terms and is thus neglected. The frictional pressure drop term,

$$\int_0^x (\tau_{wv}(x) + \tau_{wl}(x))\,dx$$

is evaluated by using the pressure drop multiplier, ϕ_{lo}^2, as:

$$\int_0^x (\tau_{wv}(x) + \tau_{wl}(x))\,dx = \int_0^x \frac{\Phi_{lo}^2(x)\,f_{lo}GG}{2D_e\rho_l} = \frac{f_{lo}GG}{2D_e}\int_0^x \frac{\Phi_{lo}^2}{\rho_l}dx$$
$$= [\Phi_{lo}^2]\,\frac{f_{lo}GG}{2D_e}$$

where f_{lo} is the friction factor for liquid single phase flow at the same mass flux G, D_e is the hydraulic diameter of the channel, $[\phi_{lo}^2]$ is obtained by:

$$[\Phi_{lo}^2] = \int_0^x \frac{\Phi_{lo}^2}{\rho_l}dx = \int_0^x \frac{\left(1 + \frac{\alpha(\rho_l - \rho_v)}{\alpha\rho_v + (1-\alpha)\rho_l}\right)}{\rho_l}dx \tag{8}$$

The average velocity is then obtained as:

$$U(x) = U(0) - \frac{1}{G}(P_l(x) - P_l(0)) - [\Phi_{lo}^2]\,\frac{f_{lo}G}{2D_e} \tag{7'}$$

In the energy equation, Eq. (3'), the terms in the right hand side represent the heat transferred to the coolant through different mechanisms. In steady state they equal the total heat generated by the fuel, which only varies along flow direction. Denoting this heat by q_{tot} and integrating Eq. (3'), it results

$$\begin{aligned}&(\alpha(x)\rho_v(x)h_v(x) + (1-\alpha(x))\rho_l(x)h_l(x))U(x)\\ &= \rho_l(0)h_l(0)U(0) + \int_0^x q_{tot}(x)\,dx = H(0) + \int_0^x q_{tot}(x)\,dx\end{aligned} \tag{9}$$

where $H(0)=\rho_l(0)h_l(0)U(0)=Gh_l(0)$.

The liquid temperature distribution is then obtained by

$$\begin{aligned}T_l(x) &= \frac{H(0) + \int_0^x q_{tot}(x)\,dx - \alpha(x)\rho_v(x)h_v(x)U(x)}{C_{p,l}U(x)(1-\alpha(x))\rho_l(x)}\\ &= \frac{H(0) + \int_0^x q_{tot}(x)\,dx - \dfrac{G-\rho_l(x)U(x)}{\rho_v(x)-\rho_l(x)}\rho_v(x)h_v(x)}{C_{p,l}\rho_l(x)\dfrac{U(x)\rho_v(x)-G}{\rho_v(x)-\rho_l(x)}}\end{aligned} \tag{9'}$$

where $C_{p,l}$ is the liquid specific heat at constant pressure. In deriving Eq. (9'), Eq. (6) has been used.

It is realized that the vapour phase enthalpy appears in the solution of the liquid temperature distribution. To find out the enthalpy, the temperature of the vapour phase is needed. For convective boiling, the effective liquid superheat to which the bubbles nucleate and grow at the wall are exposed to a fluctuation between (T_w-T_{sat}) and 0. To have a steady vapour temperature which reflects the fluctuation, Chen's correlation [8] is used:

$$\begin{aligned}T_v-T_{sat} &= S^{\frac{1}{0.99}}(T_w-T_{sat})\\ S &= \frac{1}{(1+1.5\times10^{-5}Re_{TP})}\\ Re_{TP} &= G\left(1-\frac{\alpha\rho_v}{\alpha\rho_v+(1-\alpha)\rho_l}\right)D_e/\mu_l\end{aligned} \tag{10}$$

where μ_l is the dynamic viscosity of the liquid.

The vapour enthalpy is then calculated by:

$$h_v(x) = C_{p,v}(T_{sat} + S^{\frac{1}{0.99}}(T_w - T_{sat})) \tag{11}$$

where $C_{p,v}$ is the vapour specific heat at constant pressure.

Integrating the bubble number density equation, Eq. (4), results in:

$$\begin{aligned} N_b(x)\,U_b(x) &= N_b(0)\,U_b(0) + \int_0^x (\phi_{wn}(x) - \phi_{cond}(x))\,dx \\ &= \int_0^x (\phi_{wn}(x) - \phi_{cond}(x))\,dx \end{aligned} \tag{4'}$$

The void fraction can be given by:

$$\alpha(t) = \frac{3}{4}\pi R_b^3(t)\,N_b(x) \tag{12}$$

if the bubbles have a uniform size $R_b(t)$. However, in reality, bubbles in a cross section of the channel have different sizes due to different growth duration. To consider the non-uniformity of the bubble sizes, a Lagrangian approach is adopted. Eq. (4') is rewritten as:

$$\begin{aligned} N_b(x) &= \frac{\int_0^x (\phi_{wn}(\xi) - \phi_{cond}(\xi))\,d(\xi)}{U_b(x)} \\ &= \sum_{\xi_i=0} \frac{(\phi_{wn}(\xi_i) - \phi_{cond}(\xi_i))}{U_b(x)}\Delta\xi_i = \sum_{\xi_i=0} N_b(\xi_i) \end{aligned}$$

where

$$N_b(\xi_i) = \frac{(\phi_{wn}(\xi_i) - \phi_{cond}(\xi_i))}{U_b(x)}\Delta\xi_i$$

stands for the contribution to the bubble number density at point x from the nucleation sites at location ξ_i. The void fraction contributed by the bubbles at location ξ_i to point x is then obtained as:

$$\alpha(\xi_i) = \frac{3}{4}\pi R_b^3(t(\xi_i))\,N_b(\xi_i)$$

where $t(\xi_i)$ is the time required for a bubble to flow from location ξ_i to x. It is given by:

$$t(\xi) = \int_{\xi}^{x} \frac{dx}{U_b(x)} \tag{13}$$

The void fraction at location x is then obtained by summing up the contributions from all upstream locations, namely:

$$\begin{aligned}\alpha(x) &= \sum_{\xi_i=0} \alpha(\xi_i) \\ &= \frac{1}{U_b(x)} \int_0^x \frac{3}{4}\pi R_b^3(t(\xi))(\phi_{wn}(\xi)-\phi_{cond}(\xi))\,d\xi\end{aligned} \tag{12'}$$

Substituting the expression of $\phi_{wn}-\phi_{cond}$, Eq. (5), into Eq. (12'), the void fraction at location x is finally obtained by:

$$\alpha(x) = \frac{1}{U_b(x)} \int_0^x \frac{3}{4}\pi R_b^3(t(\xi)) \frac{T_l(x)-T_l(0)}{T_{sat}(x)-T_l(0)} \left(\frac{F(\rho^*)}{R_c^{*4.4}D_d^2}\right)\left(\frac{f\xi_h}{A}\right) d\xi \tag{12"}$$

The void fraction is formally obtained by Eq. (12"), however, the bubble radius still remains to be solved. A lot of work has been done to solve for the bubble growth rate, both experimentally and theoretically [15]. It has been discovered that bubbles undergo two growing stages; namely Isothermal and Isobaric growth. In the isothermal stage, the bubble grows due to the excess vapour pressure and the bubble growth rate is proportional to t. This process only takes a few milliseconds. After this, the bubble growth is governed by the rate at which heat can be supplied from the superheated liquid to the bubble interface to facilitate the vapour formation associated with growth. The bubble radius varies as $t^{1/2}$. When bubble radius reaches its departure size, $D_d/2$, it detachs from the heated wall and enters the bulk liquid region, where it will undergo implosion if its surrounding liquid is subcooled. In the present study the first stage of the bubble growth is neglected. It is assumed that the bubble grows under Isobaric condition until its departure size is reached. After the bubble detachs from the heated wall, it undergoes implosion. The bubble radius for the isobaric expansion is then calculated by using the closed form solution of Jones and Zuber [16] when the bubble size is smaller than that of the departure bubble,

$$R_b(t) = \frac{\rho_v(0)}{\rho_v(t)} \left(R_b(0) + \frac{2k_s}{\sqrt{\pi}} Ja_T\sqrt{\alpha_l t} + \frac{2K_s}{\sqrt{\pi}} Ja_p\sqrt{\alpha_l/\Omega}\,(\sqrt{\Omega t}-D(\sqrt{\Omega t})) \right)$$

$$R_b < R_c \tag{14a}$$

where K_s is sphericity correlation factor, α_l, thermal diffusivity of the liquid, Ω and $D(\Omega t)$ represent time constant for vapour pressure variation and the Dawson integration, Ja_T and Ja_p are the Jokob number based on the initial superheat and flashing, which are given by:

$$Ja_T = \frac{\rho_l C_{p,v}[T_l - T_{sat}(P_v(0))]}{\rho_v(0) h_{fg}(0)}$$

$$Ja_p = \frac{\rho_l C_{p,l}[T_{sat}(P_v(0)) - T_{sat}(P_v(t))]}{\rho_v(0) h_{fg}(0)}$$

$P_v(0)$ and $R_b(0)$ in the Jokob number are calculated from:

$$P_v(0) = P_l + \frac{v_{fg} T_{sat}}{h_{fg} \Delta T_{sat}}$$

$$P_v(t) = R \rho_v T_v$$

$$R_b(0) = R_c^* \times \frac{D_d}{2}$$

Analogous to the mode of bubble growth, the bubble radius during the implosion is given by Rayleigh as [15]:

$$R_b(t) = R_{b,\max} \left(\frac{\theta_0^*}{\theta_0}\right)^{\frac{1}{2}} \left(\frac{t_3^* - t}{t_1^*}\right) \exp\left(\frac{t}{t_3^*}\right) \qquad t = [0, t_3^*] \quad (14b)$$

where t_1^* denotes the time for a bubble to grow to its maximum size and t_3^*, for the bubble to collapse. t_1^* and t_3^* are related by $t_3^*/t_1^* = \theta_0/\theta_0^*$, $\theta_0 = \Delta T_{sat}$ and $\theta_0^* = T_{sat} - T_l$. t_1^* can be calculated from:

$$t_1^* = \frac{\theta_0}{\theta_0 + \theta_0^*} \left(\frac{k_l \Delta T_{sat}}{q_{tot}}\right)^2 \frac{1}{\pi \alpha_l}$$

4. COMPARISONS AND DISCUSSIONS

Eqs. (5), (7'), (12") and (14a-b) constitute the solution for the void fraction distribution along a boiling channel. A computer program was developed to solve these equations. The computation is only carried out for the void fraction in the detached voidage region since the void fraction in the wall voidage region is very small compared with that in the detached voidage region.

A boiling channel is simplified as shown in the Figure 1.

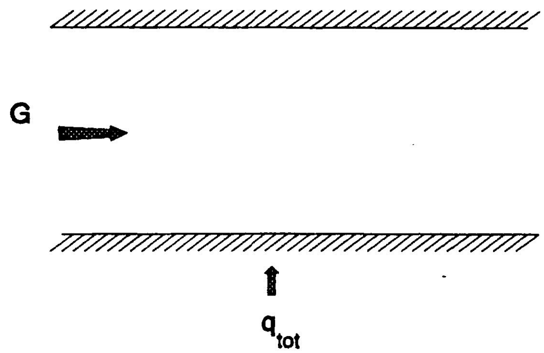

Figure 1. Simplified Boiling Channel

The whole channel is discritized into many cross sections. The liquid and vapour properties are assumed to be constants across each cross section, but vary from one cross section to another. For each cross section, the properties of the liquid and vapour are found from the D_2O table [17]. The mass flux, G, is 7015.5 $kg/(m^2s)$, the value is so chosen to reflect the single channel flow at full power steady state. The pressure gradient is assumed to be a constant along the channel. The total heat flux, q_{tot}, and the wall temperature, T_{wall}, are taken from the NUCIRC simulation data of the Point Lepreau Generating Station [18]. The void fraction is calculated for each cross section as follows:

1) Initialize void fraction distribution,
2) Calculate $[\phi_{lo}^2]$ from Eq. (8),
3) Calculate the average velocity U(x) by Eq. (7'),
4) Calculate the average liquid temperature $T_l(x)$ from Eqs. (10), (11) and (9'),
5) Calculate the net bubble density generation term by Eq. (5),
6) Calculate the bubble radius from Eqs. (13), (14a) or (14b),
7) Calculate the viod fraction $\alpha(x)$ by Eq. (12"),
8) Compare the present void fraction with the previous one, check the stability of the solution, and go to step 2) until the solution becomes stable.

In the boiling studies, there are some correlations derived specifically for the subcooled boiling void fraction. Among them, the subcooled boiling correlation of Kroeger and Zuber together with the correlation of Saha and Zuber, which calculates the point where void becomes significant, is recommended by [10], and an extrapolation of modified Armand correlation is used in the CANDU reactor safety analysis related program [11]. Due to lack of sufficient information, the predictions from the present work will be mainly compared

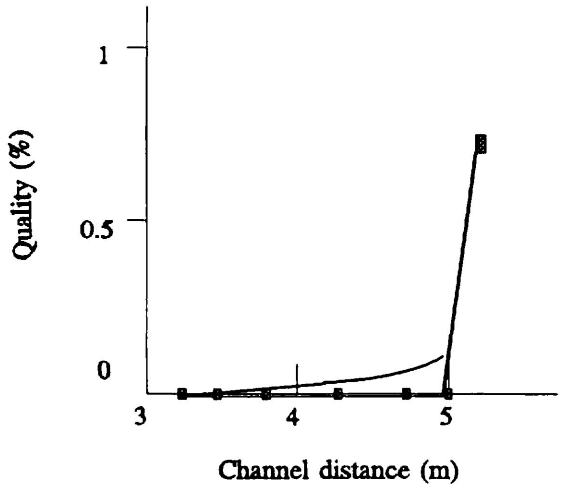

Figure 2. Quality Profile
—■— NUCIRC simulation
—— Present work

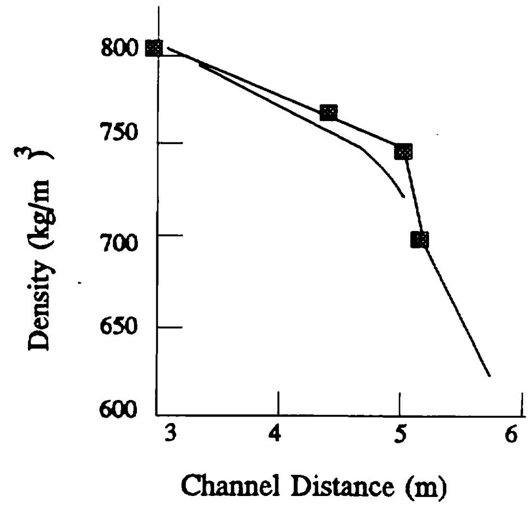

Figure 3. Density Profile
—■— NUCIRI simulation
—— Present work

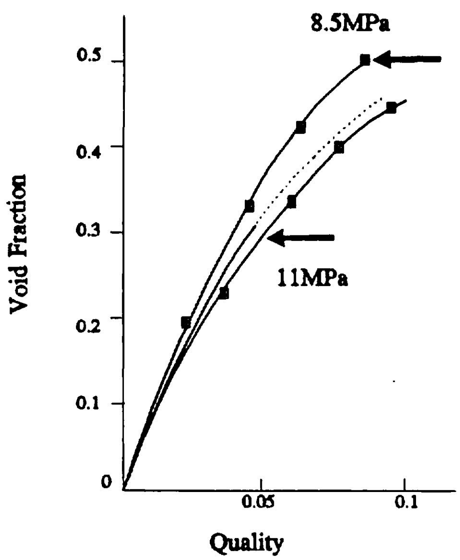

Figure 4. Void versus Quality

—■— Modified Armand Correlation
—— Present work

with the results from the modified Armand correlation [11] and the NUCIRC simulation.

The flow quality from the present work and NUCIRC simulation is compared in the Figure 2. Based on the data of wall and coolant temperature from NUCIRC simulation [18], the subcooled boiling begins about 3.3m from the channel inlet and ends about the 5.2m point (the total channel length is 6m). The present work predicts a small amount of quality in this region.

Figure 3 shows a comparison of computed averag mixture density between the present work and NUCIRC simulation. It can be seen, the density from the present work is less than that of NUCIRC simulation due to the fluid voidage in the subcooled boiling region.

Figure 4 compares the predictions of void versus flow quality from the present work and modified Armand correlation [11]. For the present prediction, the void fraction is calculated from the set of equations mentioned in the previous section while the flow quality is calculated by using the equation suggested by Levy [19] as:

$$\chi(x) = \chi_e(x) - \chi_e(x_d)\exp\left[\frac{\chi_e(x)}{\chi_e(x_d)} - 1\right]$$

where χ and χ_e are the flow and thermaldynamic equilibrium quality with $\chi(x_d)=0$, x_d is the point where the detached voidage region begins. The present prediction is in a good agreement with that of modified Armand correlation.

5. CONCLUSIONS

A new model for subcooled boiling based on bubble dynamics is proposed. The void fraction is finally obtained from its physical definition. This is considered to be more realistic. The model equations are solved in steady state and the predictions are compared with some plant simulation data and existing correlations. To justify the model, however, more detailed testing is needed.

In principle, the model can be applied to the steady state saturation boiling quite readily if the bulk nucleation is considered. It can also be used to predict the flashing flow caused by rapidly depressurizing an initially subcooled liquid when the governing equations are considered to be non-steady.

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