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The Prediction of Void Fraction in the Subcooled Boiling Region

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서브쿨드 비등 영역에서의 기포계수 계산에 관한 연구

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Abstract

A state-of-the-art mechanistic model has been developed to accurately predict the void fraction in the subcooled boiling region having axial nonuniform heat flux. In this study, the void-dependent drift-flux parameters of the Lahey/Ohkawa model were introduced and the mass flux-depent condensation coefficient were determined by fitting with the experimental data. This model was tested against several experimental data sets to verify its accuracy. Finally the comparision between the predicted void fraction profiles with this model and the profile-fit model for the hot assembly of Kori-Unit 1, Cycle 1 has been performed. It is conclusive that the results show the good agreement between the measured and predicted void fractions, and the profile-fit model has been found to underestimate the void fraction in the subcooled boiling region.

요약

축방향 비균일 열유량을 가지는 서브쿨드 비등영역에서 첨단적인 mechanistic 모델을 사용하여 기포계수를 정확히 계산하고저 한다. 이 모델에서는 Lahey/Ohama model에서 구한 기포계수에 의존하는 drift-flux계수를 사용하였고 또한 실제 실험치와 비교하여 질량유량에 의존하는 응축계수의 상관식을 구하여 사용하였다. 이 모델은 그 정확도를 증명하기 위해 잘 알려진 실험치들과 비교 되었고 최종적으로 고리 1호기 1주기의 고온 연료집합체 기포계수를 계산하므로서 profilefit 모델과 비교되었다. 이러한 계산결과는 실험치와 잘 일치하고 있으며 profile-fit model은 서브쿨드 비등영역에서 기포계수를 낮게 계산하고 있음이 밝혀졌다.

Nomenclature

A_{x-s} ; flow area (ft^2)

$C_0=\langle j\alpha\rangle/(\langle\alpha\rangle\langle j\rangle)$; void concentration parameter

$C_k=C_0\langle j\rangle+V_{gj}$; kinematic wave velocity (ft/sec)

D_H ; hydraulic diameter (ft)

C_p ; specific heat (Btu/1bm-°F)

G_o ; mass flux (1bm/hr-ft^2)

h ; enthalpy (Btu/1bm)

j ; superficial velocity (ft/sec)

k ; thermal conductivity (Btu/ft-°F-hr)
p ; pressure (psia)
P_H ; Heated perimeter (ft)
q'' ; heat flux (Btu/hr-ft^2)
T ; temperature (°F)
u_g ; vapor-phase velocity (ft/sec)
V_{gj} ; $\langle (u_g-j)\alpha\rangle/\langle\alpha\rangle$; drift velocity (ft/sec)
v ; specific volume (ft^3/1bm)
x ; quality
α ; void fraction
ρ ; density (1bm/ft^3)
$\Delta\rho=\rho_f-\rho_g$
$\langle\ \rangle$; cross-sectional averaging notation

Subscript

d ; void departure point
e ; thermal equilibrium
f ; saturated liquid
g ; saturated vapor
fg ; the difference between saturated vapor and liquid properties
l ; liquid
io ; steady-state inlet value

I. Introduction

The accurate prediction of void fraction in the subcooled region is of interest in the analysis of reactors, since a considerable portion of the nuclear heated channel of BWR is in that region and the NRC has also required the precise analysis for that region as a TMI action plan even though for PWR.

So far most predictions of void fraction in the subcooled boiling region have been performed with the profile-fit model to obtain the flow quality profile in that region and the void-quality correlation which has the constant drift-flux parameter. However the profile-fit model is based on a fit to uniform axial heat flux data and, thus, is unconfirmed for the prediction of subcooled void fraction in case of nonuniform axial heat flux and the transient case. Moreover the constant drift-flux parameter assumption is known to be so rough in the subcooled boiling region since the concentration parameter is less than 1 and varies rapidly in that region.

In this paper, the analytical mechanistic model has been introduced to obtain the mean liquid enthalpy and the characteristic frequency of phase change. The void fraction can be calculated from the Zuber's vord propagation equation including the void fraction dependent drift-flux parameters of Ohkawa/Lahey model. In this calculation, since all parameters of the characteristic frequency, void fraction, drift-flux parameters and mean liquid enthalpy were coupled, the numerical iteration was implemented by nodalizing to take account of the nonuniform axial heat flux profile and assuming the node-averaged value of the characteristic frequency.

One more problem is how to determine the condensation coefficient in the characteristic frequency, which was assumed to be constant in most previous works. However it is actually a function of pressure, heat flux and mass flux. Since the mass flux is the dominant parameter, in this study the coefficient has been expressed in terms of mass flux and two empirical coefficients which were determined by comparing with several experimental data.

The computer implementation of this model was used to verify the accuracy of this model by testing against several experimental data sets and predict the void fraction in the hot assembly of the Ko-ri Unit 1, BOL. The results show the good agreement between the measured and predicted void fractions.

II. Mechanistic Model

In order to predict the void fraction in the subcooled boiling region, two models are generally introduced; the profile-fit model and the mechanistic model. The profile-fit model is simple and common to be used in the computer implementation(1),(2). In this model, a profile of the mean liquid enthalpy, $h_l(z)$, in the subcooled boiling region is assumed as a function of the bulk enthalpy, such that

$$\frac{(h_f-h_l)}{[h_f-(h_l)_d]}=F\left[\frac{h-(h_l)_d}{h_f-(h_l)_d}\right] \qquad (1)$$

where $(h_l)_d$ is the liquid enthalpy at the void departure point, z_d, shown in figure 1.

The function, F, has limits that it goes to unity and zero when the mean liquid enthalpy will be $(h_l)_d$ and the bulk enthalpy will be much greater than the saturated liquid enthalpy, respectively. Thus it can be fitted to the exponential function or the hyperbolic tangential function as,

$$F=\exp\left[-\frac{h-(h_l)_d}{h_f-(h_l)_d}\right] \qquad (2)$$

Now Levy(3) has developed the relation between the flow quality and the thermal equilibrium quality by substituting Eq. (1) to the flow quality-enthalpy relation which was obtained from a simple steady-state heat balance as,

$$\langle x\rangle=\langle x_e\rangle-\langle x_e\rangle_d\left(\exp\frac{\langle x_e\rangle}{\langle x_e\rangle_d}-1\right) \qquad (3)$$

This relation can yield the void fraction in the subcooled boiling region by combining the void-quality correlation which has been used in the well-known computer codes(1) (2) with various optional forms under homogeneous flow assumption, the constant drift-flux parameter or the modified Armond model, etc. However this model is based on a fit to uniform axial heat flux data and, thus, is uncomfirmed for the prediction of subcooled void fraction in case of nonuniform axial heat flux and the transient case. Moreover the constant drift-flux parameter assumption is known to be so rough in the subcooled boiling region since the concentration parameter is less than 1 and increases rapidly along the axial heated length in that region.

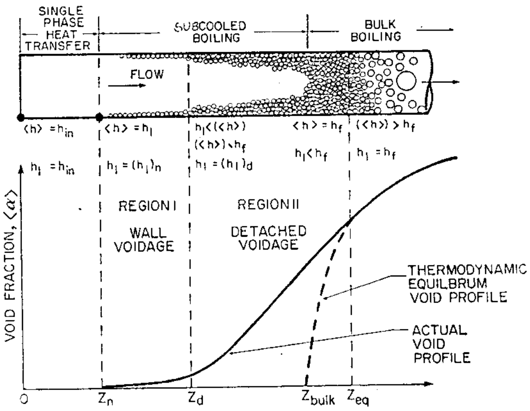

Fig. 1. Void Fraction During Forced Convection Subcooled Boiling

In this paper, the analytical mechasistic model, which was previously attempted by Bowring(4) and Rouhani,(5) has been introduced to obtain the mean liquid enthalpy and the characteristic frequency of phase change. Figure 1 is a schematic of the typical subcooled void-fraction profile in a heated channel. Region 1 is commonly reerred to as the region of wall voidage, wfhich will be neglected in our calculation, since the void fraction in that region is quite small. Thus the begining point of the subcooled boiling region will be the void departure point, z_d, which can be determined by the well-known Saha and Zuber's empirical relation,

$$h_f-(h_1)_d \begin{cases} =0.0022\dfrac{q''D_hC_{p1}}{k_1}, & \text{for } P_e<70,000 \\ =154\ q''/G, & \text{for } P_e>70,000 \end{cases}$$

To obtain the void profile in the subcooled boiling region, we can introduce the void propagation equation for the steady-state as,

$$C_K\frac{\partial\langle\alpha\rangle}{\partial Z}=\left(\frac{\rho_f}{\Delta\rho}-C_0\langle\alpha\rangle\right)\Omega_0 \qquad (4)$$

where the characteristic frequency, Ω_0, is defined(7) as,

$$\Omega(z)=\frac{v_{fg}P_Hq_b(z)}{A_{xs}h_{fg}[1+\epsilon(z)]}-\frac{v_{fg}P_Hq''_{\text{cond}}(z)}{A_{x-s}h_{fg}} \qquad (5)$$

The second term of Eq. (5) represents the condensation heat transfer process in the region away from the heated wall. For this term we will use the empirical correlation derived previously by Lahey,(8)

$$P_H q''_{\mathrm{cond}} = \frac{H_0 h_{fg} A_{x-s}}{v_{fg}} \langle \alpha \rangle \Delta T_{\mathrm{sub}} \tag{6}$$

In the above equation, the condensation coefficient, H_0, was taken as a constant value. However it is actually a function of the pressure, heat flux and mass flux. Since the mass flux is the dominant parameter, in this study the cofficient has been expressed in terms of the mass flux as,

$$H_0 = \frac{1}{1 + a\left(\frac{\langle j \rangle}{j_{i0}}\right)^b} \tag{7}$$

where a and b are the empirical parameters, which correspond to Lahey's original model(7) ($H_0 = 0.0417$/sec$-$°F) with $a = 23.0$ and $b = 0$.

In order to optimize a and b, we compared Eq. (7) against the steady-state void fraction profile measurement of several experiments. Figures 2 and 3 indicate that, when the Ohkawa/Lahey model is used for the steadystate drift-flux parameters, the recommended values are $a = 4.0$ and $b = 2.0$. Next, the ratio of the heat flux due to microconvection(i.ee; pumping) to that causing vapor formation is given by Rouhani(5) as,

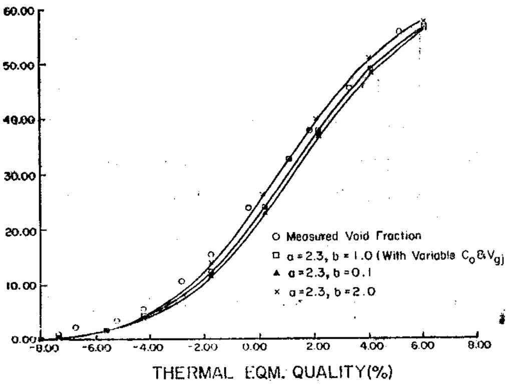

Fig. 2. Measured and Predicted Void Fraction Profile of Rouhani's Experiment with Fixed a(=2.333) and Varying b

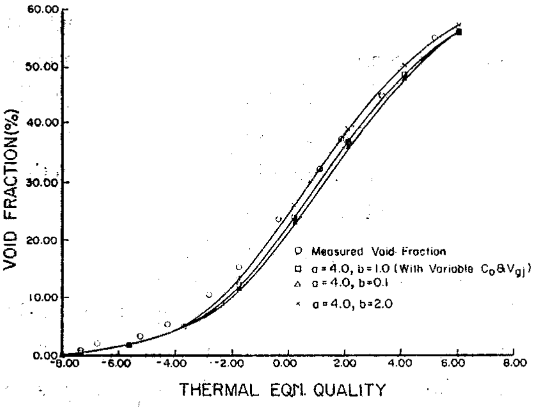

Fig. 3. Measured and Predicted Void Fraction Profile of Rouhani's Experiment with Fixed a(=4.0) and Varying b

$$\epsilon(z) = \frac{\rho_1 (h_f - h_1)}{\rho_g h_{fg}} \tag{8}$$

and the boiling heat flux was approximated by(8)

$$q''_b(z) = q''(z) \left\{ 1 - \frac{h_f - h_1(z)}{h_f - (h_1)_d} \right\} \tag{9}$$

Thus inserting Equations (6), (8) and (9) into Equation (5), we obtain,

$$\Omega(z) = \frac{\Delta\rho P_H q''}{A_{x-s}\rho_f [h_f - (h_1)_d]} \frac{h_l - (h_1)_d}{\{\rho_g h_{fg} + \rho_f (h_f - h_l\}} - \frac{H_0 \langle \alpha \rangle}{C_{pf}} (h_f - h_1) \tag{10}$$

The other equation governing the subcooled boiling is the liquid-phase energy equation based on the assumptions of the constant system pressure and negligible internal heat generation, potential and kinetic energy in the fluid, which is given as,

$$v_{fg} G (1 - \langle x \rangle) \frac{dh}{dz} = \frac{q'' P_H v_{fg}}{A_{x-s}} - \Omega_0 (h_g - h_1) \tag{11}$$

In order to integrate these Bernoulli-type first order differential equations, Eqs. (4) and (11), with taking account of the nonuniform heat flux profile, we will nodalize the axial heat flux along the channel and assume the constant node averaged characteristic frequency of phase change, $\bar{\Omega}_k$, in the k-th node. This simplification does not introduce appreciable errors, because for steady-state $\Omega(z)$ is strongly dependent on the heat flux and the liquid enthalpy, which is uniform and nearly linear in the node, respectivey.

Thus, by using the node-averaged flow quality, $\langle\bar{x}\rangle_k$, and a coordinate transformation from z_k to ξ_k, defined by,

$$\xi(z_k)=\frac{\{C_K(z)\}_k}{(C_K)_k{}^{in}} \tag{12}$$

the coordinate-transformed nodal liquid enthalpy equation can be expressed as,

$$\frac{d(h_1)_k}{d\xi_k}-b_{2,k}(h_1)_k=b_{3,k} \tag{13}$$

where,

$$b_{2,k}=\frac{(C_K)_k{}^{in}}{G_0v_{fg}C_0(1-\langle\bar{x}\rangle_k)}$$

$$b_{3,k}=\frac{b_{2,k}}{\bar{\Omega}_k}\left(\frac{q_k{}''P_Hv_{fg}}{A}-\bar{\Omega}_kh_g\right)$$

By solving Eq. (13), the result for the k-th node is,

$$(h_1)_k=b_{5,k}e^{b_{2,k}}+b_{4,k} \tag{14}$$

where,

$$b_{4,k}=-\frac{b_{3,k}}{b_{23k}}$$

$$b_{5,k}=(h_1)_k^{in}-b_{3,k}e^{-b_{2,k}}$$

For constant system pressure, the continuity equation for a two-phase mixture in the k-th node is given as,

$$\frac{\partial\langle j\rangle_k}{\partial z}=\bar{\Omega}_k \tag{15}$$

Therefore the kinematic wave velocity in the k-th node can be obtained by inserting the superficial velocity profile, which will be calculated from Eq. (15), into its definition as,

$$C_K(z_k)=(C_K)_k^{in}+C_0\bar{\Omega}_k(z-z_{k-1}) \tag{16}$$

By combining equation (4) and (16), the coordinatetransformed void propagation is given as,

$$\xi_k\frac{d\langle\alpha\rangle_k}{d\xi_k}+\langle\alpha\rangle_k=\frac{\rho_f}{C_0\Delta\rho} \tag{17}$$

Using the node inlet boundary condition, $\langle\alpha\rangle_k^{in}$, Eq. (17) will be integrated to yield,

$$\langle\alpha\rangle_k=\frac{\rho_f}{C_0\Delta\rho}(1-\xi_k^{-1})+\langle\alpha\rangle_k^{in}\xi_k^{-1} \tag{18}$$

For the drift-flux parameters, C_0 and V_{gj}, in the above equations, the Lahey/Ohkawa model[8] is used in this study instead of the constant drift-flux parameters, Since C_0 and V_{gj} are strongly dependant on the void fraction in the subcooled void region and the high quality region, respectively.

As mentioned previously, Equation (15) was derived based on a constant $\bar{\Omega}_k$ which is a function of $(h_1)_k$ and $\langle\alpha\rangle_k$. Thus in order to find $\bar{\Omega}_k$, we insert $(\bar{h}_1)_k$ and $\langle\bar{\alpha}\rangle_k$ into Eq. (10), which are obtained by averaging Eqs. (14) and (18), respectively. The resultant equation will be iterated using an initial guess for $\bar{\Omega}_k$, until the convergence will be achieved.

This model is tested against several experi-

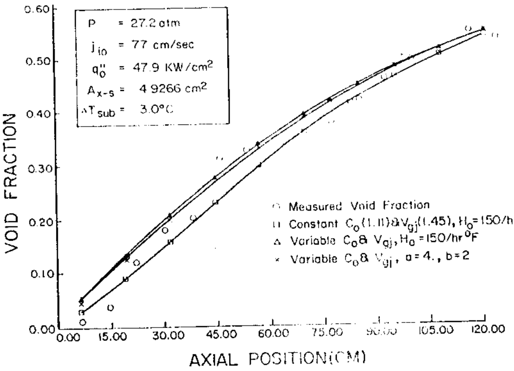

Fig. 4. Measured and Predicted Void Fraction Profile of Christensen's Experiment

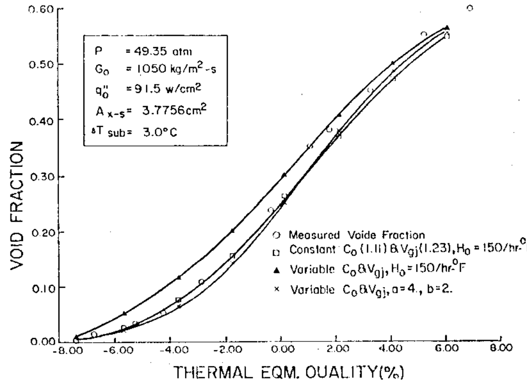

Fig. 5. Measured and Predicted Void Fraction Profile of Rouhani's Experiment

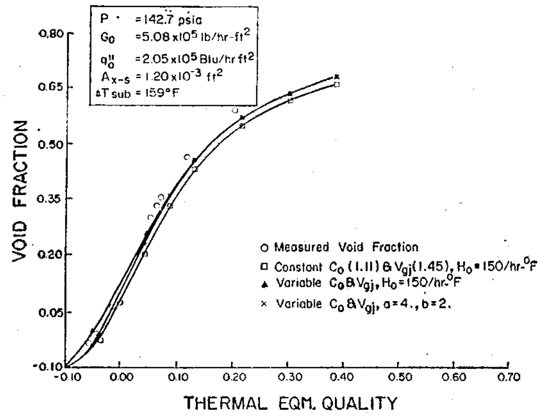

Fig. 6. Measured and Predicted Void Fraction Profile of Lobachev's Experiment

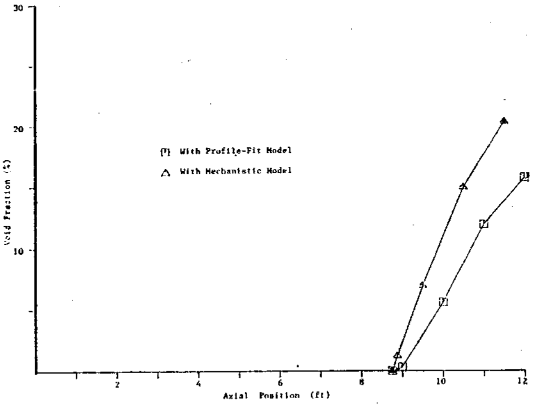

Fig. 7. The Predicted Axial Void Fraction Profile in the Hot Assembly of Kori Unit 1, Cyclel

mental data sets; 1) Christensen's experiment(9), 2) Rouhani's experiment(5) and 3) Lobachev's experiment(10). The results are shown in Figures 4, 5 and 6. Finally the comparision between the predicted void fraction profiles with this model and the profile-fit model for the hot assembly of Kori-Unit 1, BOL is shown in Figure 7.

III. Discussion and Conclusions

In this study, a state-of-the-art mechanistic model has been developed to predict the axial void fraction profile in the subcooled boiling region having nonuniform heat profile. Moreover, in this model, the void-dependent drift-flux parameters were used and the condensation coefficient was fitted as a function of mass flux.

The computer implementation of this model was used to verify the accuracy of this model with testing against several experimental data sets and predict the void fraction in the hot assembly of Kori-Unit 1. The results show the good agreement between the measured and predicted void fractions and the profile-fit model has been found to underestimate the void fraction in the subcooled boiling region.

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