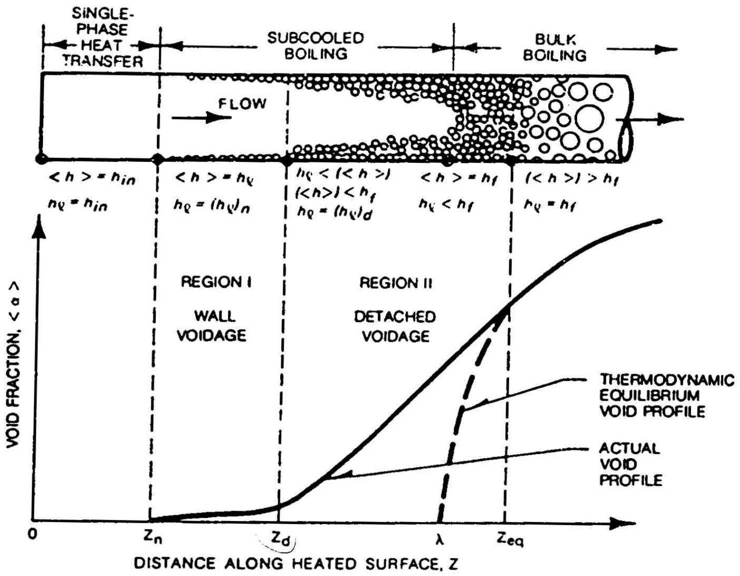
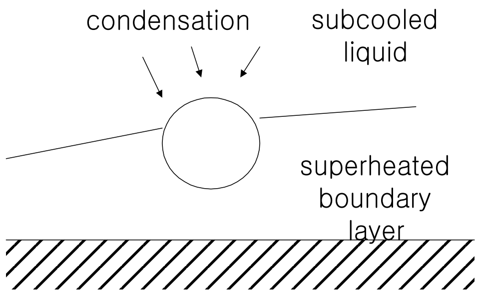
IV. Subcooled Boiling Model



√ bubble formation

√ bubble condensation

➡ complicate phenomena



For calculating the void fraction in subcooled boiling, we have to know

1. Z_n , $(h_l)_{Z_n}$

2. Z_d , $(h_l)_{Z_d}$

3. $h_l(z)$ or $\delta w'$

∵ thermodynamic nonequilibrium ($h_l \neq h_f$)

4. recondensation ratio of the detached bubbles

5. slip ratio

(1) Determination of void departure point, Z_d

- wall voidage region
- detached voidage region

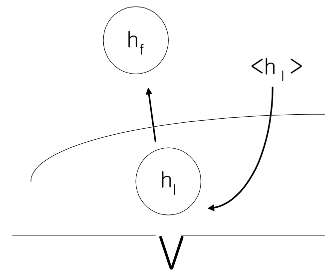
- location of the initial void ejection into the subcooled liquid core
- determined by the void departure criterion of Table 5.1

(2) Heat removal mechanism from the heated surface during subcooled boiling

1) latent heat to form the vapor, q''_{evap}

$$q''_{evap} = V_B \rho_g h_{fg} , \qquad \text{where} \quad V_B = n f B_d \tag{1.1.1}$$

2) by convection caused by bubble agitation or pumping by boundary layer, q''_{pump}



q''_{pump} = energy flux to raise from $\langle h_l \rangle$ to h_f

+ energy flux for saturation

$$= V_B [\rho_l (h_f - \langle h_l \rangle) + \rho_g (h_f - h_l)] \tag{1.1.2}$$

Bowing(1962) defined

$$\varepsilon = \frac{q''_{pump}}{q''_{evap}} = \frac{\rho_l (h_f - \langle h_l \rangle) + \rho_g (h_f - h_l)}{\rho_g h_{fg}}$$

$$\approx \frac{\rho_l (h_f - h_l)}{\rho_g h_{fg}} \tag{1.1.3}$$

3) by condensation at the top of growing bubble while stilled attached to the wall

4) singe phase convection, $q''_{1\phi}$

Neglecting the third mechanism,

$$q'' = q''_{1\phi} + q''_{evap} + q''_{pump} \tag{1.1.4}$$

(3) Models to determine the void fraction profile in subcooled boiling region

- profile fit model
- mechanistic model

1. Profile Fit Model by Levy

Assume $h_l = h_l(\langle h \rangle)$

$$\text{i.e.} \quad \frac{h_f - h_l}{h_f - (h_l)_d} = F\left[\frac{\langle h \rangle - (h_l)_d}{h_f - (h_l)_d}\right] \tag{1.1.5}$$

B. C : F = 1 at $h = (h_l)_d$

F → 0 for $\langle h \rangle \gg h_f$

The function that satisfy these requirements are the form of F = EXP

$$\therefore \frac{h_f - h_l}{h_f - (h_l)_d} = \exp\left[-\frac{\langle h \rangle - \langle h_l \rangle_d}{h_f - (h_l)_d}\right] = F \tag{1.1.6}$$

Since

$$\langle x(z)\rangle = \frac{\langle h(z)\rangle - h_{l}(z)}{h_{fg} - h_{l}(z)}$$

$$\therefore \quad \langle x\rangle = \frac{\langle h\rangle - h_{ls} + [h_{ls} - (h_{l})_{d}]F}{h_{fg} + [h_{ls} - (h_{l})_{d}]F} \qquad (1.1.7)$$

Then,

$$\langle x\rangle = \frac{\langle h\rangle - h_{ls}}{h_{fg}} + \frac{h_{ls} - (h_{l})_{d}}{h_{fg}} F$$

$$\therefore \quad \langle x\rangle = \langle x_{e}\rangle - \langle x_{e}\rangle_{d} F$$

Finally,

$$\langle x\rangle = \langle x_{e}\rangle - \langle x_{e}\rangle_{d} \exp\left(\frac{\langle x_{e}\rangle}{\langle x_{e}\rangle_{d}} - 1\right) \qquad (1.1.8)$$

Now from the flow quality, we can obtain the void fraction from void quality correlation.

(例) Zuber Findley Void Quality Correlation

$$\langle \alpha\rangle = \frac{\langle x\rangle}{C_{o}\left[\langle x\rangle + \frac{\rho_{g}}{\rho_{f}}(1-\langle x\rangle)\right] + \frac{\rho_{g} V_{gj}}{G}}$$

Modified Armond model

$$\langle \alpha\rangle = \frac{(0.833 + 0.167\langle x\rangle)\langle x\rangle v_{g}}{(1-\langle x\rangle)v_{f} + \langle x\rangle v_{g}}$$

2 Mechnistic Model

1) Determination of the void departure point

neglect the wall voidage region

solve the energy balance equation to calculate $\langle h_{l}(z)\rangle$

find the position which satisfy Zuber Saha correlation,

$$h_{ls} - (h_{l})_{d} = \begin{cases} 0.0022\dfrac{q'' D_{H} c_{pl}}{k_{l}}, & \text{for } Pe = \dfrac{G D_{H} c_{pl}}{k_{l}} < 70{,}000 \\ 151\, q''/G, & \text{for } Pe > 70{,}000 \end{cases} \qquad (1.1.9)$$

2) Void propagation equation

$$\frac{\partial\langle \alpha\rangle}{\partial t} + C_{K}\frac{\partial\langle \alpha\rangle}{\partial z} = \left(\frac{\rho_{l}}{\Delta\rho} - C_{o}\langle \alpha\rangle\right)\Omega \qquad (1.1.10)$$

where $C_{K} = C_{o}\langle j\rangle + V_{gj}$

and the characteristic frequency of the phase change is defined as,

$$\Omega = v_{fg}\Gamma$$

The net amount of vapor formed per unit volume for constant pressure is,

$$\Gamma = \frac{p_H q''_B(Z,t)}{A_{x-s} h_{fg}[1+\varepsilon(Z,t)]} - \frac{p_H q''_{cond}(Z,t)}{A_{x-s} h_{fg}} \tag{1.1.11}$$

3) Condensation heat transfer

$$p_H q''_{cond} = \frac{H_c h_{fg} A_{x-s}\langle\alpha\rangle}{v_{fg}} - T_{sat} \tag{1.1.12}$$

where H_c is a condensation coefficient.

4) Ratio of the heat flux due to microconvection to that causing vapor formation is given by Rouhani as,

$$\varepsilon(Z,t) = \frac{\rho_l (h_f - h_l)}{\rho_g h_{fg}} \tag{1.1.13}$$

And the boiling heat flux is approximated as,

$$q''_B(Z,t) = q''(Z,t)\left[1 - \frac{h_f - h_l(Z,t)}{h_f - h_{ld}(t)}\right] \tag{1.1.14}$$

Inserting Eqs. (1.1.12), (1.1.13) and (1.1.14) into Eq. (1.1.11),

$$\Omega(Z,t) = \frac{\rho\, p_H q''}{A_{x-s}\rho_f (h_f - h_{ld})} \cdot \frac{h_f - h_l}{\rho_g h_{fg} + \rho_l (h_f - h_l)} - \frac{H_c\langle\alpha\rangle}{c_p}(h_f - h_l) \tag{1.1.15}$$

5) The energy equation of the two mixture is given as,

$$\frac{\rho}{\rho_f}(1 - \langle\alpha\rangle)\frac{\partial h_l}{\partial t} + v_f G(1 - \langle x\rangle)\frac{\partial h_l}{\partial z} = \frac{q'' p_H v_f}{A_{x-s}} - \Omega(h_g - h_l) \tag{1.1.16}$$

where the assumptions used are :

i) The internal heat generation, q''', is neglected.

ii) The kinetic and potential energy term are neglected.

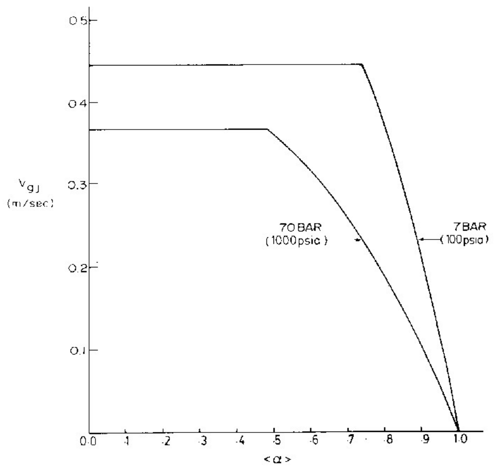
iii) The state is steady.

iv) The vapor is saturated.

6) The drift flux parameters

[A] system constant parameters : Dix model, constant values 등

[B] void dependent model : Okawa Lahey model



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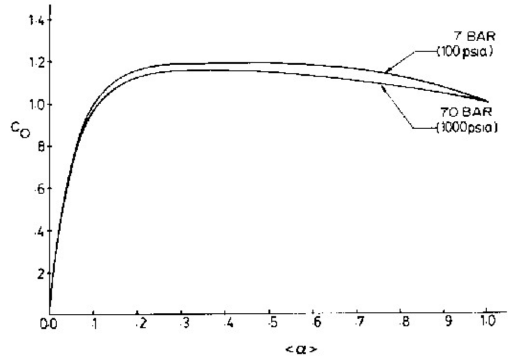

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▶ Finally, we have to solve the each coupled equations, (1.1.10), (1.1.15) and (1.1.16) with void dependent drift flux parameters.

[Example]

A 12ft long and rectangular fuel channel has uniform axial heat flux, $\dot{q}_o''$ (= 55.56 Btu/ft^2 sec), under constant pressure, 1000 psia. the inlet coolant velocity is 12ft/sec. Size and radius of channel and fuel are 0.65 and 0.225 in, repectively.

(a) Determine the void departure point with inlet liquid enthalpy of 511.9 Btu/lbm.

(b) Calculate the exit thermal equilibrium quality.

(c) Extend your calculation to determination of exit flow quality.

(d) Finally, what is the exit void fraction ?

[Answer]

(a) Void departure point, Z_D

$$Pe = \frac{GD_H c_{pl}}{k_l}$$

c_{pl}, k_l for 500°F water = 1.176 Btu/lb°F , 9.76×10^{-5} Btu/ft °F sec

D_H = 4A/P = 0.335 ft   G = 47.85x12 = 574.2 lbm/ft^2 sec

∴ Pe = 2.32×10^5 > 70,000

From Saha and Zuber's Eq.,

$$h_{\ell} \quad (h_f)_d = 154\ q''/G \quad , \qquad \text{for } Pe > 70{,}000$$

$$154 \times 55.56 \ /\ 5712 \quad 14.9 \text{ Btu/lbm}$$

$$\therefore \ (h_f)_d \quad h_f \quad 14.9 \quad 527.5 \text{ Btu/lbm}$$

From energy equation : ROC of energy,

$$w(h_f)_d \quad \dot{q}_o''P\ Z_d \quad wh_{in} = 0$$

$$\therefore \quad \mathbf{Z_d} \quad \mathbf{2.5\ ft}$$

(b) thermal equilibrium quality profile

ROC of energy

$$w\ h(z) \quad \dot{q}_o''P_H L \quad wh_{in} = 0$$

$$h(z) = (1 - x_e)hf + x_e\ h_g$$

$$\therefore \quad x_e = \frac{(\dot{q}_o''P_H\ L)/w + h_{in} \quad h_f}{h_{fg}}$$

$$= (74.7\ 511.9\ 542.4)\ /\ 649.1 \quad = \quad \mathbf{6.8\ \%}$$

(c) exit flow quality

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

$\langle x_e \rangle_d$,

$$\langle x_e \rangle_d = \frac{(\dot{q}_o''P_H\ Z_d)/w + h_{in} \quad h_f}{h_{fg}}$$

$$= (15.6 + 511.9 \quad 542.4)\ /\ 649.1 \quad = \quad \underline{2.3\ \%}$$

$$\therefore \ \langle x \rangle = 0.068 \quad (\ 0.023)\ \exp\ (\ 0.068/(\ 0.023) \quad 1\ )$$

$$0.068 + 1.38 \times 10^{-1} \quad = \quad \mathbf{0.68}$$

(d) exit void fraction

Apply Zuber Findley correlation. Or from Modified Armond model,

$$\langle \alpha \rangle = \frac{(0.833 + 0.167\langle x \rangle)\langle x \rangle\, v_g}{(1. - \langle x \rangle)v_f + \langle x \rangle\, v_g}$$

$$= \{\ (0.833 \quad 0.167 \times 0.68) \times 0.68 \times 0.1456\ \}\ /\ 0.31$$

$$= \mathbf{92.5\%}$$