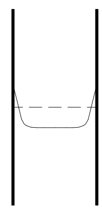
2. Forced Convective Boiling

(1) Single phase forced convection

o laminar flow

o turbulent flow



standard form of heat transfer coefficient ($h_{1\phi}$)

$$Nu = C_1 Re^a Pr^b$$

1) Dittus Boelter equation for the turbulent flow

$$Nu_{bulk} = 0.023 Re_{bulk}^{0.8} Pr_{bulk}^{0.4}$$

$\langle T \rangle = \frac{1}{A} \int\int T dA$: bulk temp.

2) Sieder Tate equation : modified D-B equation for high heat flux

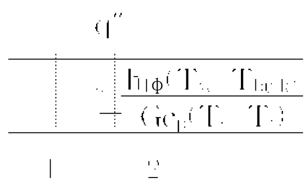
$$Nu = 0.023 Re^{0.8} Pr^{0.4} \left(\frac{\mu_B}{\mu} \right)^{0.14} \quad \text{at } T_{bulk} \text{ and } \mu_w \text{ at } T_{wall}$$

3) Colburn equation

$$St \cdot Pr^{2/3} = 0.023 Re^{-0.2} \quad at \quad T_{film} \left(= \frac{T_{wall} + T_{bulk}}{2} \right)$$

where $St = \frac{Nu}{RePr} = \frac{H_{1\phi}}{Gc_p}$

: the ratio of heat added from wall to the heat transfer by flow



good for 0.5 < Pr < 100

need iteration if $h_{1\phi}$ is function of T_w

★ Guess T_w and calculate $H_{1\phi}$ with Colburn Eq using T_{film}

then $T_w^{new} = T_b + \frac{q''}{H_{1\phi}(T_f)}$ if $T_w^{new} \neq T_w^{old}$, iteration

4) For superheated steam at high pressure

$$Nu = 0.0214 Re^{0.8} Pr^{1/3} \left[1 + \frac{2.3}{L/D_H} \right] \quad \text{at } T_{film}$$

5) For multirod bundle [Weisman]

$$Nu = c Re^{0.8} Pr^{1/3}$$

where c = 0.042 P/D − 0.024 for square pitch lattices

= 0.026 P/D − 0.006 for triangular pitch lattices

(2) Subcoole boiling

1) Onset of subcooled nucleate boiling

The minimum limiting condition for nucleation($T_w > T_{sat}$) is,

$$\Delta T_{sat} < \dot{q}''\left[\frac{1z}{Gc_p D_H} + \frac{1}{h_{1\phi}}\right] \qquad (3.2.1)$$

- By Bergles and Rohsenow based on Hsu's assumption

$$(\dot{q}_{ONB})'' = 15.6p^{1.156}(T_w - T_{sat})^{(2.3/p^{0.0234})} \qquad (3.2.2)$$

, for steam water system in the pressure range of 15 2000 psi

- By Davis and Anderson

$$(\dot{q}_{ONB})'' = \frac{k_l}{4B}(T_w - T_{sat})^2, \qquad B = \frac{2\sigma T_{sat} v_{fg}}{J h_{fg}} \qquad (3.2.3)$$

- Empirical correlation by Jens and Lottes

$$(T_w - T_{sat}) = 1.9e^{-p/900}\dot{q}''^{1/4} \qquad (3.2.4)$$

, for 100<p<2500 psi, $\dot{q}''$>1x10^6 Btu/hr ft^2, G>7.7x10^6 lbm/hr ft^2

2) Partial nucleate boiling (Wall voidage region)

$$\dot{q}'' = (\dot{q}_{1\phi})'' + (\dot{q}_{SCB})''$$

1. Begining of fully developed nucleate boiling is defined as,

$(\dot{q}_{FDB})'' = (\dot{q}_{c})''$ at the point D' McAdams

$= (1.4\,\dot{q}_{c})''$ Forster and Grief

2. Emperical correlations for convective partial nucleate boiling heat transfer

From the saturated nucleate pool boiling heat transfer suggested by Rohsenow, which is given as,

$$\left[\frac{C_{pl}\Delta T_{sat}}{h_{fg}}\right] = C_{sf}\left[\frac{q''}{\mu_l h_{fg}}\left(\frac{\sigma}{g(\rho_l - \rho_g)}\right)^{\frac{1}{2}}\right]^{n}\left[\frac{C_p\mu}{k}\right]^{m+1}_{l}$$

C_{sf} is experimentally adjusted for the forced(and natural) convective subcooled boiling

Author	Geometry	ID(mm)	C_{sf}	Fluid sufface
Rohsenow & Clark	수직 튜브	1.56	0.006	water/Ni
Krieth & Summerfield	수평 튜브	1[illegible].9	0.15	Water/SS
Piret & Isbin	수직 튜브	27.1	0.013	Water/Cu
Berges & Rohsenow	수평 튜브	2.39	0.02	Water/SS

Kutateladze estimate the curve in the region of partial nucleate boiling as,

$$\frac{\dot{q}''}{(\dot{q}_{l\phi})''} = \left[1+\left\{\frac{(\dot{q}_{FDB})''/(T_w - T_{sat})}{(\dot{q}_{l\phi})''/(T_w - T_l)}\right\}^2\right]^{1/4},$$

where $(\dot{q}_{FDB})''$ is taken from saturated pool boiling data

Bergles and Rohsenow observed from experiments that the curve for a flow boiling must be based on actual flow boiling data, not data for saturated pool boiling. Thus,

$$\frac{\dot{q}''}{(\dot{q}_{l\phi})''} = \left[1+\left\{\frac{(\dot{q}_{B})''}{(\dot{q}_{l\phi})''}\left(1-\frac{(\dot{q}_{Bi})''}{(\dot{q}_{l\phi})''}\right)\right\}^2\right]^{1/2}$$

where $(\dot{q}_{B})''$: fully developed nucleate boiling

$(\dot{q}_{Bi})''$: fully developed nucleate boiling at the onset of subcooled boiling

The wall and coolant temperature difference is given by Weatherhead as,

$$T_w - T_{sat} = 0.015x10^6\sigma(\dot{q}''/10)^{1/4}$$

3) Fully developed subcooled boiling

1. Mechanism of subcooled nucleate boiling

a) sequential rate process model by Bankoff

- heat from the wall surface to adjacent two phase boundary layer
- heat flows through the two phase boundary layer
- pass into main single phase core

b) thermocapillarity model by Brown

- flow jet in the wake of the bubble

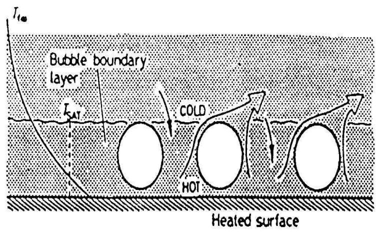


Fig. 5.20. Thermocapillarity mechanism of subcooled boiling (Brown 1967).

2. Heat transfer in fully developed subcooled boiling

$$(T_w)_{sat} = T_{sat} + \psi(\dot{q}'')^n$$

McAtams : n=0.259

ψ=22.62 ~ 28.92 (← physical properties of fluid and liquid surface combination)

Krieth and Summerfield,

$$\Delta T_{sat} \propto p^{-0.55}$$

Jens and Lottes

$$\Delta T_{sat}(^{\circ}C) = 25\,\dot{q}''^{0.25}(MW/m^2)e^{-p/62}$$

Thom

$$\Delta T_{sat} = 22.65\,\dot{q}''^{0.5}e^{-p/87}$$

3. Effect of dissolved gas

- increases the heat transfer since the gas bubble agitates the liquid
- affects on the position where the first evolution of bubbles occurs
- dies out at higher heat flux near CHF

4. Effect of system subcooling

- D, lifetime and population of bubble decrease as Δh_{sub} increases
- also decrease as the flow velocity increases at constant heat flux

5. 기타

For constant velocity and Δh_{sub} as the heat flux increases,

- diameter and lifetime of bubble moderately increase.
- bubble population increases sharply.

(3) Nucleate boiling

$$\frac{\dot{q}''}{10^6} = \kappa\,(T_w - T_{sat})^m \qquad (3.2.5)$$

Jens Lottes : m=1, $\kappa = \dfrac{\exp(4p/900)}{(60)^1}$

Thom : m=2, $\kappa = \dfrac{\exp(2p/1260)}{(72)^2}$

⇒ insensitive to flow rate and quality

■ Forced Convective vaporization

For high quality annular flow

o nucleation is suppressed

o heat transfer by conduction through thin film

o evaporation at interface

Thus, dramatically improvement of heat transfer

$$\dot{q}'' = \frac{k\,\delta T}{\sigma} \qquad (\dot{q}''_c : 35{,}000\ \text{Btu/hr ft}^2\ \text{for water})$$

$$\frac{H_{2\phi,FC}}{H_{1\phi,lo}} = A\left(\frac{1}{X_{tt}}\right)^{n} \qquad (3.2.6)$$

where A = 3.5, n = 0.5 by Dengler and Addams

A = 2.9, n = 0.66 by Bennett

★ ***Turbulent Martinelli parameter.*** X_{tt}

※ function of quality and pressure

$$= \sqrt{(dp/dz)_l/(dp/dz)_g}$$

$$\frac{1}{X_{tt}} = \left(\frac{\langle x\rangle}{(1-\langle x\rangle)}\right)^{0.9}\left(\frac{\rho_l}{\rho_g}\right)^{0.5}\left(\frac{\mu_g}{\mu_l}\right)^{0.1} \qquad (3.2.7)$$

※ criterion for the suppression of nucleate boiling

$$\delta^{+} = 7$$

The heat transfer within the liquid film

The turbulent heat transfer is

$$q'' = -(k_l + \varepsilon_H c_p \rho_l)\frac{dT}{dy} \qquad (3.2.8)$$

B.C : T = T_w at y=0

T = T_δ at y=δ

Integrating Eq.(3.2.8) from y=δ(T=T_δ ≈ T_{sat}) to y=0,

$$h_{tp} = \frac{c_p \rho_l u^*}{T_\delta^+} \qquad \text{where} \quad T^+ = \frac{c_p \rho_l u^*}{q''}(T_w - T)$$

$$u^* = \sqrt{\tau_w/\rho_l}$$

여기서, T_δ^+ 는 Re 와 Pr 의 함수이다.

■ **Chen correlation** for both the fully developed nucleate boiling and forced convection vaporization region

$$h_{2\phi} = h_{NCB} + h_C \qquad (3.2.9)$$

In this equation, the h_c is given by a modified Dittus Boeter equation as,

$$h_c = 0.023\left[\frac{G(1-\langle x\rangle)D_H}{\mu_l}\right]^{0.8}\left(\frac{c_p\mu_l}{k_l}\right)^{0.4}\left(\frac{k_l}{D_H}\right)F \qquad (3.2.10)$$

where F : ratio of an effective $Re_{2\phi}$ to Re used in $h_{1\phi}$

$$= \left[\frac{Re_{2\phi}}{Re_l}\right]^{0.8} = \left[\frac{Re_{2\phi}}{G(1-\langle x\rangle)D_H/\mu_l}\right]^{0.8} \qquad (3.2.11)$$

$$= f(X_{tt})$$

And h_{NcB} is modified Foster Zuber equation by a nucleation suppression factor as,

$$h_{NcB} = 0.00122\left[\frac{k_l^{0.79}c_{pl}^{0.45}(g_c)^{0.25}}{\sigma^{0.5}\mu_l^{0.29}h_{lg}^{0.24}\rho_g^{0.24}}\right]\left(\frac{h_{lg}}{T_{sat}v_{lg}}\right) \Delta T_l^{0.24}\ \Delta p_l^{0.75} S \qquad (3.2.12)$$

where S : ratio of mean superheat (ΔT_l) in the liquid film to wall superheat (ΔT_{sat})

$$= \left[\frac{\Delta T_l}{\Delta T_{sat}}\right]^{0.99}$$

$$= (\Delta T_l/\Delta T_{sat})^{0.24}(\Delta p_l/\Delta p_{sat})^{0.75} \quad \text{by Clausius Clapeyron}$$

$$\therefore h_{NcB} = 0.00122\left[\frac{k_l^{0.79}c_{pl}^{0.45}(g_c)^{0.25}}{\sigma^{0.5}\mu_l^{0.29}h_{lg}^{0.24}\rho_g^{0.24}}\right]\left(\frac{h_{lg}}{T_{sat}v_{lg}}\right) \Delta T_{sat}^{0.24}\ \Delta p_{sat}^{0.75} S \qquad (3.2.13)$$

By curve fit

$F = 1$ for $1/X_{tt} \le 0.1$

$= 2.35\,(1/X_{tt}+0.213)^{0.736}$ for $1/X_{tt} > 0.1$ (3.2.14)

$S = 1\,/\,(1+2.53x10^{-6}Re_{2\phi}^{1.17})$ (3.2.15)

- Method to calculate $h_{2\phi}$ at a known q'', G and <x>
  1. calculate $1/X_{tt}$ from Eq.(3.2.7)
  2. evaluate F from Fig. 7.5 (Collier) or Eq.(3.2.14)
  3. calculate h_c from Eq.(3.2.10)
  4. calculate $Re_{2\phi}$ from Re_l and F [See Eq.(3.2.11)]
  5. evaluate S using $Re_{2\phi}$ from Fig. 7.6 (Collier) or Eq.(3.2.15)
  6. calculate h_{NcB} from Eq.(3.2.13)
  7. calculate $h_{2\phi}$ from Eq.(3.2.9)
  8. Plot q''(= $h_{2\phi}\ \Delta T_{sat}$) for a range of ΔT_{sat} and interpolate $h_{2\phi}$ at a given q''

(4) Boiling Transient in Forced Convection

- Boiling crisis : low quality DNB
- CHF : local heat flux
- DNB : high pressure & high flow (PWR)
- Burnout
- Dryout : high quality

1) Mechanism of boiling transient

A) Subcooled and low quality region

1 Dryout under a vapor dot

: A dry patch on heating surface by micro layer evaporation can be rewetted when the bubble departures. However, in the case of high heat flux, a large bubble makes the surface temperature under the dry patch increase abruptly before the bubble departure, which meets the CHF condition.

2 Bubble crowding and vapor blanketing

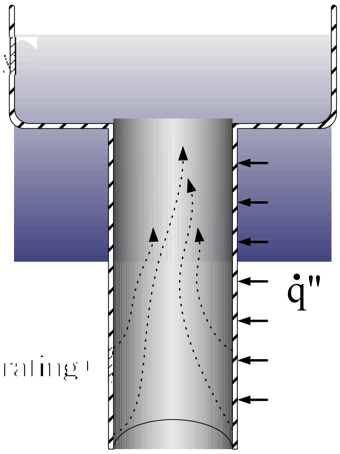
At high heat flux, bubbles are crowded.

∴ bubbly boundary layer is formed and it prevent the liquid from incoming toward the surface ≡ vapor blanket

3 Evaporation of liquid surrounding a slug flow bubble

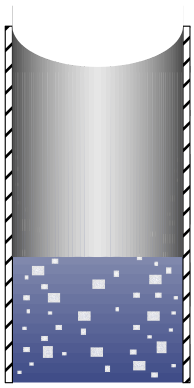
At low flow rate, slug flow exists.

For high flux, the liquid film may be completely evaporated and thus dries out



B) Counterflow CHF

C) Film dryout



- due to

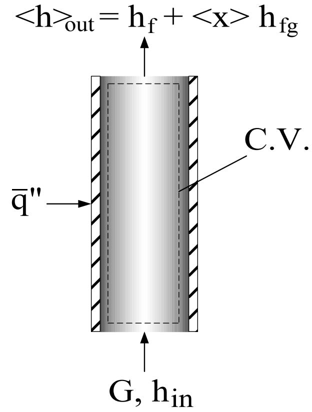
1 x will be 1 by adding continuous heat (evaporating)

2 entrainment

→ Those phenomena depends on

- mass velocity
- subcooling

2) BT Analysis



For bulk boling : "local condition hypothesis"
From the heat balnace

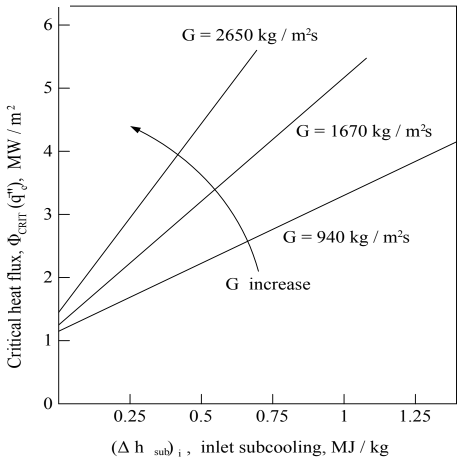
$$\dot{Q} - \dot{T} + \dot{S} = 0 \qquad \text{for S.S}$$

$$GA_{x-s}[h_f + \langle x \rangle h_{fg}] - [GA_{x-s} h_{in} + \bar{q}'' P_H L_H] = 0$$

$$\therefore \bar{q}'' = \left[\frac{GA_{x-s} h_{fg}}{P_H L_H}\right]\langle x_e \rangle + \left[\frac{GA_{x-s}}{P_H L_H}\right]\Delta h_{sub}$$

For a round tube at low mass flux ($G/10^6 < 0.5$).
McBeth correlation (world's data within ±5.5%)
will be

$$\frac{\bar{q}_c''}{10^6} = \frac{h_{fg}}{135}\sqrt{G/10^6}\,(1 - \langle x_e \rangle_c) \quad (3.2.16)$$



By Long Sun Tong, from the heat balance.

$$\langle x_e \rangle_c = \frac{(\bar{q}_c''/10^6) P_H L_H}{(G/10^6) A_{x-s} h_{fg}} - \frac{\Delta h_{sub}}{h_{fg}}$$

(3.2.17)

Thus Eqs. (3.2.16) (3.2.17),

$$\therefore \bar{q}_c''/10^6 = \frac{(G/10^6) A_{x-s}[h_{fg} + \Delta h_{sub}]}{135\sqrt{G/10^6}\,A_{x-s} + P_H L_H}$$

A. Flooding and Flow Reversal

- Rewetting from the top or countercurrent flow limiting condition
- Motion of molten cladding material
- Downcomer flow pattern during ECC

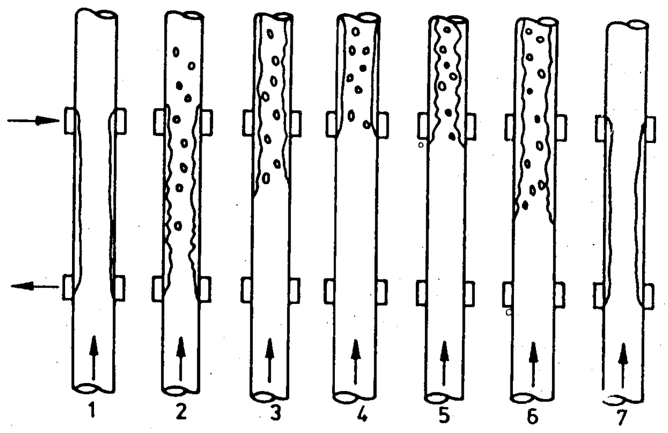


Fig. 3.10 Flooding and flow reversial experiment

For 2 · Liquid become unstable and forms waves of large amplitude

· Entrainment

→ Flooding

For 4 · Liquid injection dries out and no net liquid downflow

· Churn or annular flow in the upper tube

For 5 · When the gas flow rate decrease, liquid film becomes unstable and forms waves of large amplitude

· ΔP increase and the liquid film tends to fall down

· Flow reversal

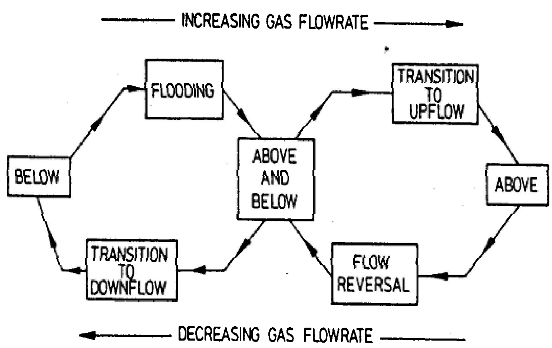


Fig. 3.11 Flooding and flow reversial : Location of the liquid phase above and/or below the liquid injection zone

For 1 in Fig. 3.10. Nussell thickness (const. film thickness based on laminar flow) is

$$e = \left[\frac{3\nu_l \Theta_l}{\pi D g} \right]^{1/3}$$

ν_l : liquid kinematic viscosity

Θ_l : liquid volumetric flow rate

D : pipe diameter

which is valid for $Re_l \left(= \frac{4Q_L}{\pi D \nu_l}\right) < 1{,}000$

Generally, W_g is independent on W_l for the case of flow reversal while decreases as W_l increases during flooding.

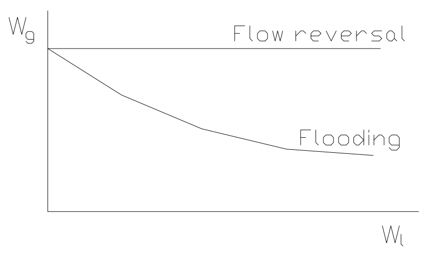


Fig. 3.12 w_g vs w_l for flooding

■ Countercurrent Flow Limit (CCFL)

: Global flooding phenomena in BWR bundles

During the plant transients, when the inlet mass flow decreases, the water in the upper plenum falls down to cover the loss of flow.

But, if the j_g of exit vapor is sufficiently large, CCFL occurs in the upper area restriction, which prevents the water in upper plenum from falling down, and thus make fuel rods dry out.

∴ no steady flow solution is possible

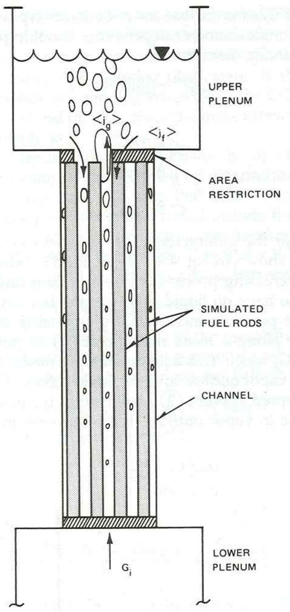


그림 3.13 CCFL in BWR fuel bundle[Lahey, 1993]

1) Empirical CCFL Correlations

- Kutateladge CCFL Correlation

$$K_g^{1/2} + |K_f|^{1/2} = (3.2)^{1/4} \qquad (3.2.18)$$

where, $K_i = \dfrac{(j_i)\sqrt{\rho_i}}{[\sigma g(\rho_f - \rho_g)]^{1/4}}$, i = g or f

- Wallis Correlation

$$(j_g^*)^{1/2} + (j_f^*)^{1/2} = C \qquad (3.2.19)$$

where C is empirical constant which depend on the entrance conditions and ranges usually 0.7 ~ 1.0 (~0.6 by Shiralkar)

j_g^* (Francle 수) = $\dfrac{G_g}{[gD_H\rho_g(\rho_f - \rho_g)]^{1/2}}$: dimensionless flux of gas

$$j_f^* = \frac{G_f}{[gD_H\rho_f(\rho_f - \rho_g)]^{1/2}}$$

2) CCFL Curve

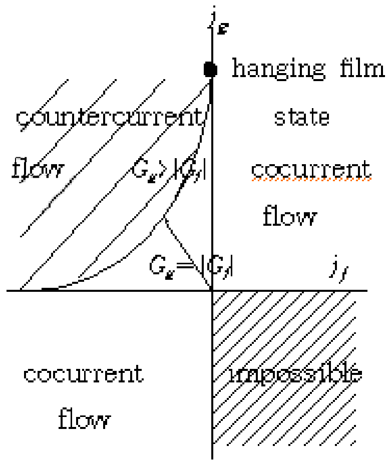
For steady state, a mass balance in Fig 3.13 is

$$G_g A_a = |G_f| A_a + G_i A_{x-s} \qquad (3.2.20)$$

where A_a is a restrict area.

And the energy balance (assuming saturated fluid in the upper plenum) is given as,

$$G_i A_{x-s} h_i + |G_f| A_a h_f + q = G_g A_a h_g \qquad (3.2.21)$$



From Eqs. (3.2.20) and (3.2.21)

$$G_g = \frac{(q - G_f A_{x} \; h_{sub})}{A_g h_{fg}} \qquad (3.2.22)$$

Now Eqs. (3.2.20) and (3.2.22) will give,

$$|G_l| = \frac{(q - G_f A_{x-s} - h_{sub})}{A_g h_{fg}} - G_f\left(\frac{A_{x-s}}{A_g}\right) \qquad (3.2.23)$$

Then, inserting Eqs. (3.2.22) and (3.2.23) into Eq. (3.2.19)

$\Rightarrow q_c$ (critical bundle power)

Now if $q''(z,t) > q''_c(z,t)$, dryout and overheating occurs