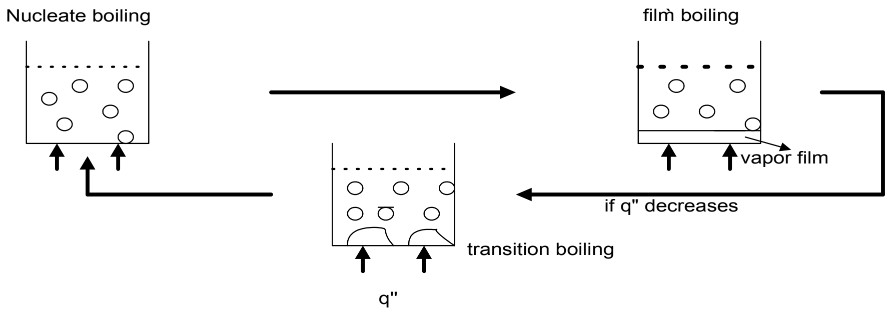
Chapter 3 Boiling Heat Transfer

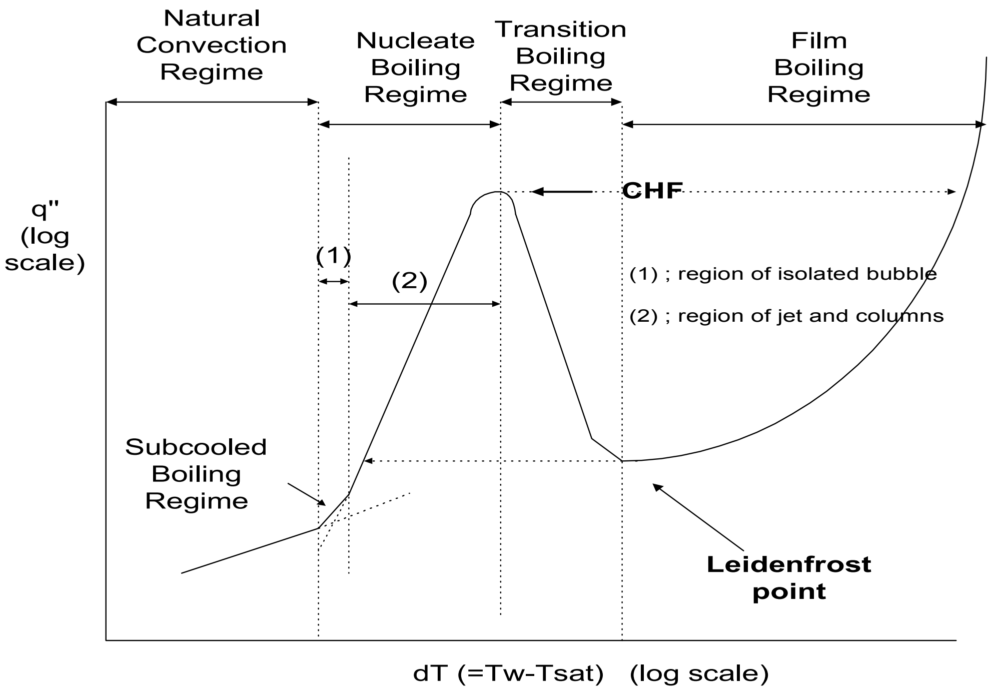
1. Pool Boiling

: Boiling inside the stagnant liquid through the heated surface



(1) *Characteristic Boiling Curve*

I- Temperature controlled experiment



In partially nucleate boiling region, a small number of nucleation center come into play and only a few bubble exits(ONB)

These bubble rise quickly and are collapsed. Thus the slight agitation causes q'' to increase more rapidly with $(T_w - T_{sat})$

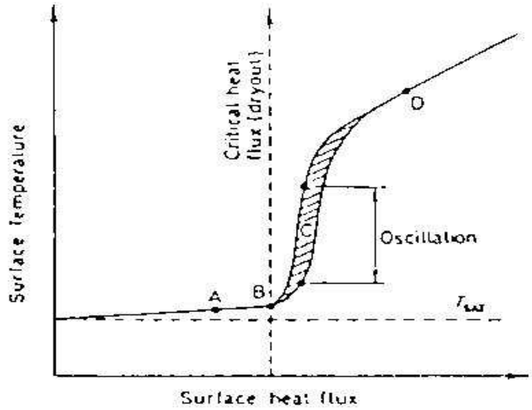
∴ The heat transfer is due to
- natural convection
- bubble agitation

condensing vapor as heat source to prevent the wall failure

2) Heat flux controlled experiment

: nuclear fuel element or electrically heated wire

o In this case, it more difficult to observe TB than the temperature controlled experiment in which the film at the bottom proceeds more slowly.



(2) Natural convection region

$$N_u = 0.55\,[Gr\,Pr]^{\frac{1}{4}} \quad \text{where,}$$

$$\therefore H_{1\phi} \propto (T_w - T_{sat})^{\frac{1}{4}}$$

$$\text{Thus,} \quad q'' \propto (T_w - T_{sat})^{\frac{5}{4}}$$

$$N_u = \frac{hD}{k}, \qquad P_r = \frac{C_p \mu}{k}$$

$$G_r = \frac{\rho_l^2 g \beta\,[T_w - T_{sat}]\,D^3}{\mu_l^2}$$

$$\propto T_w - T_{sat}$$

or for turbulent natural convection from a horizontal flat surface,

$$Nu = 0.14\,[Gr\,Pr]^{\frac{1}{3}} \qquad (3.1.1)$$

(3) Nucleate Boiling

: Heat transfer is enhanced and thus a relatively large change in surface heat flux for very slow increase in the surface temperature.

$$T_w = T_{sat} + C\,(q'')^n, \quad n = 0.25 \sim 0.5$$

And the heat transfer coefficient will be expressed as,

$$Nu = C\,R_e\,P_r \qquad (3.1.2)$$

By Rohsenon at 1952 [Trans. ASME Vol. 74, pp. 967-976]

$$\left[\frac{C_{pl}\,\Delta T_{sat}}{h_{fg}}\right] = C_{sf}\left[\frac{q''}{\mu_l h_{fg}}\left(\frac{\sigma}{g(\rho_l - \rho_v)}\right)^{\frac{1}{2}}\right]^n \left[\frac{C_p \mu}{k}\right]_l^{m+1} \qquad (3.1.3)$$

C_{sf}	fluid – surface
0.014	water – stainless steel (m=1.0)
0.013	water – copper (m=1.0)
0.006	water – nickel (m=1.0)

By Foster and Zuber

: By using their Bubble radius and Bubble growth velocity,

$$\frac{q''}{\rho_g h_{fg}}\left(\frac{\pi}{\alpha_f}\right)^{\frac{1}{2}}\left[\frac{\rho_f r^{*2}}{2\sigma}\right]^{\frac{1}{4}} = 0.0015\left[\frac{\rho_f}{\mu_f}\left(\frac{\Delta T_{sat} k_f}{\rho_g h_{fg}}\right)^{2}\frac{\pi}{\alpha_f}\right] Pr_f^{\frac{1}{3}}$$

for water, $1 < P < 50$ bar

Now since $H_{2\phi} = \dfrac{q''}{(T_w - T_{sat})}$ for water, $m = 0$

$$\frac{C_{pf}^{3}(T_w - T_{sat})^{3}}{h_{fg}^{3}} = C_{sf}^{3}\left[\frac{q''}{\mu_f h_{fg}}\left(\frac{g_c\sigma}{g(\rho_f - \rho_g)}\right)^{\frac{1}{2}}\right] Pr^{3} \qquad (3.1.4)$$

$$\therefore\ q'' \propto (T_w - T_{sat})$$

and

$$H_{2\phi} = \frac{1}{C^{3}}\left\{\frac{(T_w - T_{sat})^{2}k^{3}}{h_{fg}^{2}\mu^{2}}\sqrt{\frac{g(\rho_f - \rho_g)}{g_c\alpha}}\right\} \qquad (3.1.5)$$

☞ Precise physical properties are required.

☞ complicated to calculate depending on the surface condition

Thus, simple dimensional correlation is

$$H_{2\phi} = A'(q'')^{0.7}F(P)$$

where $A' = 0.1011\,P_{cr}^{0.69}$,

$$F(P) = 1.8\,Pr^{0.17} + 4\,Pr^{1.2} + 10\,Pr^{10} \qquad \text{by Mostinski}$$

(3) Burnout in Pool Boiling

Burnout occurs when the conditions are no longer such as to allow the vapor generated in nucleate boiling to be removed from the vicinity of the heated surface.

1) Mechanism of pool boiling CHF

1. Hydrodynamic instability model [Zuber, 1958]

Localized flooding

: occurs when v_g is sufficient to prevent an adequate amount of liquid from rearching the heated surface

∵ when the bubble poplulation increases with heat flux, the outgoing bubbles jam the path of the incoming liquid.

- Helmholtz instability : incipience of the boiling crisis
- Taylor instability : incipience of stable film boiling

★ Helmholtz Instability

o When two immiscible fluids flow relative to each other along an interface of separation, there's a maximum relative velocity above which a small disturbance of the interface will amplify and grow and thereby distort the flow.

o the incipience of the boiling crisis

maximum vapor velocity for a stable vapor stream is given as,

$$V_v = \left[\frac{\rho_l \sigma 2\pi g_c}{\rho_v \lambda(\rho_l + \rho_v)}\right] \qquad (3.1.6)$$

where λ : waver length of column

When V_v exceeds the above value, the stable surface can be no longer sustained and a vapor blanket is formed, which prevents bubbles from escaping on the heated surface.

★ Taylor Instability

o criterion for stable film boiling

o The stability of an interface of <u>two fluids of different densities</u> depends on the balance of the surface tension exergy and the sum of the kinetic and potential energy of the wavy interface.

$\therefore$ If σ > K.E & P.E,

→ Stable film boiling cond. for a horizontal surface.

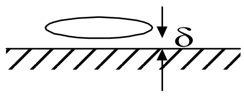
condition of a stable wave for stable film boiling

$$\lambda = 2\pi\sqrt{\frac{g_c \sigma}{g(\rho_l - \rho_v)}} \qquad (3.1.7)$$

2 Microlayer dryout model [Haramura & Katto, 1983]

exist the liquid layer of thickness, δ, between vapor and heated surface

CHF when the layer is evaporated..



3 Bubble interaction model

the critical heat flux is limited by the removal rate of bubbles which carry away the heat in the form of evaporation

$$q''_c = h_{fg}\rho_v \frac{\pi}{6} D_b^3 n f$$

Rohsenow and Griffith adopted a correcting coefficient C_1 to account for conductive and convection composite of heat transfer, and assumed

$$nD_b^2 = C_{sk}$$

Then, $$\frac{q''}{h_{fg}}\rho_g = \frac{\pi}{6} C_d C_{sk}(fD_d)$$

With empirical data,

$$q_c'' = 143 h_{fg}\rho_g[(\rho_f-\rho_g)/\rho_g]^{0.6}[g/gc]^{0.25}$$

2) Critical vapor volumetric flux for pool boiling CHF

From Eq. (3.1.6),

$$(j_g)_{crit} = \left[\frac{\rho_f \sigma 2\pi g_c}{\rho_g^2 \lambda_H (\rho_f + \rho_g)}\right]^{1/2}$$

Assume $\lambda_H = \lambda_{c,ff}$, then

$$(j_g)_c = K\left[\frac{\sigma g g_c(\rho_f - \rho_g)}{\rho_g^2}\right]^{1/4}\left(\frac{\rho_f}{\rho_f + \rho_g}\right)^{1/2}$$

For $\rho_f \gg \rho_g$

$$(j_g)_c = K\left[\frac{\sigma g g_c(\rho_f - \rho_g)}{\rho_g^2}\right]^{1/4} \quad \text{: by Kutateladze}$$

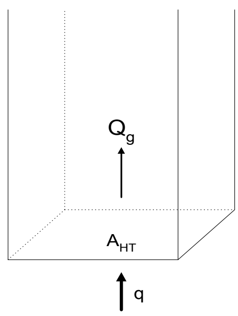
Or, from factional analysis **(Droplet Fluidization)**

$$\frac{\frac{\rho_g}{g_c} j_g^2(\frac{1}{4}\pi D^2)C_D}{\frac{1}{6}\pi D^3(\rho_f - \rho_g)\frac{g}{g_c}} \times \frac{\frac{\rho_g}{g_c} j_g^2(\frac{1}{4}\pi D^2)C_D}{\pi D\sigma} = K_g^4$$

where,
- drag force term : $\frac{\rho_g}{g_c} j_g^2\left[\frac{1}{4}\pi D_d^2\right]C_D$
- buoyancy force term : $\frac{1}{6}\pi D_d^3(\rho_f - \rho_g)\frac{g}{g_c}$
- surface tension term : $\pi D_d \sigma$

Then,

$$K_g = \frac{j_g\rho_g^{1/2}}{[\sigma g g_c(\rho_f - \rho_g)]^{1/4}} \qquad (3.1.8)$$



The volumetric flowrate of vapor formation is

$$Q_g = \frac{q}{h_{fg}\rho_g}[ft^3/hr]$$

$$\therefore\ j_g = \frac{Q_g}{A_{HT}} = \frac{q/A_{HT}}{h_{fg}\rho_g} = \frac{q''}{h_{fg}\rho_g}[ft/\sec]$$

Thus, $\quad q''_c = h_{fg}\rho_g(j_g)_c$

From Eq.(3.1.8),

$$q''_c = K_c h_{fg}\rho_g^{1/2}[\sigma g g_c(\rho_f - \rho_g)]^{1/4} \qquad (3.1.9)$$

where, $\quad K_c$ = 0.16 by Kutateladge

0.13 Zuber

= 0.18 Rohsenow

= 0.2 for droplet fluidization

3) Factors affecting on Pool Boiling

1 Effect of subcooling

- increases CHF than that in the saturated liquid due to vapor condensation and sensible heat on the subcooled liquid

$$q''_{c,sub}/q''_{c,sat} = 1 + B(T_{sat} - T_{bulk}) \qquad (3.1.10)$$

- Zuber's correlation for ΔT_{sub}

$$q''_{c,sub} = q''_{c,sat}\left[1 + \frac{2k(T_{sat} - T_{bulk})}{\sqrt{\pi\alpha\cdot\tau}}\right]$$

where τ : period of growth and departure for bubble

$$\approx \frac{\lambda_{cri}}{v_{crit}} = \left(\frac{3\pi}{2}\right)^{1/2} A\left(\frac{\rho_g^2}{g\sigma\Delta\rho}\right)^{1/4} \quad \text{and} \quad A = \left[\frac{\sigma}{g\Delta\rho}\right]^{1/2}$$

- Ivey and Morris

$$q''_{c,sub} = q''_{c,sat}\left[1 + 0.1\left(\frac{\rho_g}{\rho_f}\right)^{1/4} Ja\right], \quad Ja = \frac{\rho_f c_{pf}\Delta T_{sub}}{\rho_g h_{fg}}$$

- As $q''_{CHF,sat}$ and/or ΔT_{sub} *increases*, $q''_{CHF,sub}$ *increases*.
- generally not well established, but depends on the geometry.

2 Pressure effect

- Lower ΔT requires to activate cavities of a given size as the pressure increases
- CHF increases as the pressure increases until a certain pressure. However, above the pressure CHF decreases as the pressure increases due to the change of liquid properties.

3 Effect of Surface Finish or Roughness

- o The boiling data including ONB for the rough surfaces lie to the left, at lower wall superheat.
- o At low heat fluxes, the direction of surface finish orientation affects on boiling.
- o Horizontal scratches require lower superheat to produce the same heat flux.
- o The influence of surface roughness on CHF is negligible.

4 Existance of Dissolved Gas

- o The dissolved gases from the hot surface tend to move the q-ΔT curve to the left and reduce the magnitude of CHF.
- o generates unstable boiling and bumping with changing back and forth between nucleate boiling and natural convection.
- o The effect of noncondensible gases on CHF is most significant at high subcooling.

5 Effect of Acceleration

: cause the fluctuations of void, and the variance of gravity in Eq.(3.1.9) as,

$$q''_{crit} \sim (a/g)^{0.25}$$

By Adams(1962) with distilled water and graphite heaters,

$$q''_{crit} \sim (a/g)^{0.15} \quad \text{for } 0 < a/g < 10$$

$$q''_{crit} \sim (a/g)^{0.25} \quad \text{for } 10 < a/g < 100$$

Note that the exponent may vary with surface characteristics as well as hydrodynamic condition such as pressure.

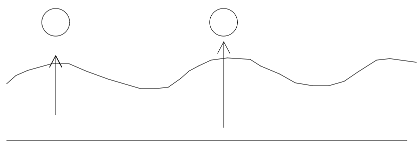
(4) *Leidenforst point (MFB)*

★ *dancing of a liquid drop*

: lower limit of stable film boiling corresponding to the breakdown of the continuous insulating film and the onset of liquid solid contact.

$$\frac{q''_{CHF}}{\rho_g h_{fg}} = \alpha_g v_g$$

What is $v_{\min}$ for the Taylor instability(i.e terminal velocity) ?



In the hydrodynamic stability theory, the force balance gives

$$\frac{C_D \rho_v v^2}{2}\frac{\pi D_b^2}{4} = (\rho_l - \rho_v) g \frac{\pi}{6} D_b^3$$

$$\therefore \; v_{\min} = \left(\frac{1}{3} \frac{g D_b \Delta\rho}{C_D \rho_v} \right)^{1/2}$$

Let, $D_b \sim \dfrac{\lambda_{\mathrm{cr}}}{2}$, where the most dagerous wavelenth : $\lambda_{\mathrm{cr}} = 2\pi\sqrt{3}A$

and $A = \dfrac{\sigma}{\sqrt{g(\rho_l - \rho_v)}}$,

then, $q''_{\min} = C\rho_v h_{fg} A^{1/2} \left(\dfrac{g \Delta\rho}{\rho_g + \rho_l} \right)^{1/2}$

$$= C\rho_v h_{fg} \left[\frac{\sigma g(\rho_l - \rho_v)}{(\rho_l + \rho_v)^2} \right]^{1/4}$$

where, $c = 0.13$ *by Zuber* (1958)

$= 0.177$ *by Zuber* (1959)
$= 0.09$ *by Berneuson* (1961)

(5) Film Boiling

: the boiling mode in which a continuous blanket of vapor is generated and maintained to isolate the liquid from the heating surface

1) vertical surface

o Analytical treatment of film boiling on vertica surface [Bromley, 1950]
The vapor rise by a gravitational buoyancy is retarded by fluid shear stresses.

$$g(\rho_l - \rho_v) = \mu \frac{d^2 T}{dy^2}$$

B.C : At $y = 0$, $u = 0$

At $y = \delta$, $u = 0$ (for stagnant interface)

$\dfrac{du}{dy} = 0$ (for moving up surface with vapor)

Then,

$$u = \frac{g \Delta\rho}{\mu_v} \left(C\frac{\delta y}{2} - \frac{y^2}{2} \right)$$

where C=2 for the dynamic interface and C=1 for the stagnant interface
If the heat transport is assumed to be by molecular conduction only, the heat balance is

$$h_{fg}\frac{dw}{dx} = \frac{h_{fg}\rho_v g\Delta\rho}{2\mu_v}\left(\frac{C}{2}-\frac{1}{3}\right)3\delta^2\frac{d\delta}{dx} = \frac{k_v\Delta T}{\delta} \qquad (3.1.11)$$

B.C : δ=0 at x=0

From obtaining δ by integrating Eq.(3.1.11), the local heat transfer coefficient is,

$$h = \frac{k}{\delta} = \left[\frac{8}{3(C/2-1/3)}\right]^{1/4}\left(\frac{h_{fg}\rho_v g\Delta\rho k^3}{\Delta T x\mu_v}\right)^{1/4}$$

The mean heat transfer coefficient is,

$$\bar{h} = \frac{5}{4}\left[\frac{3(C/2-1/3)}{8}\frac{h_{fg}\rho_v g\Delta\rho k^3}{\Delta T L\mu_v}\right]^{1/4}$$

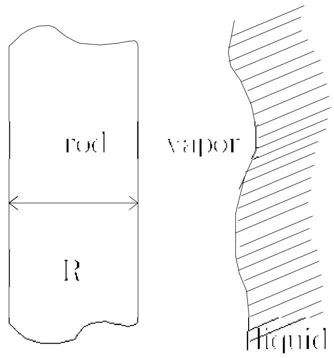
$$= C_1\left(\frac{h_{fg}\rho_v g\Delta\rho k^3}{\Delta T L\mu_v}\right)^{1/4}$$

where C_1 = 0.883 for the dynamic interface,
C_1 = 0.625 for the stagnant interface

o By Nygel Bailey

$$H_{film} = \frac{q''}{(T_w - T_{sat})}$$

$$= 0.1\left[\frac{k_v^3 g\rho_v(\rho_l-\rho_v)h_{fg}'}{\mu_v R(T_w-T_{sat})}\right]^{1/4}$$



where, $h_{fg}' = h_{fg}\left[1+0.68\frac{C_{pv}(T_w-T_{sat})}{h_{fg}}\right]$

2) horizontal plate (or rod) (Berenson) [RELAP]

apply Taylor instability

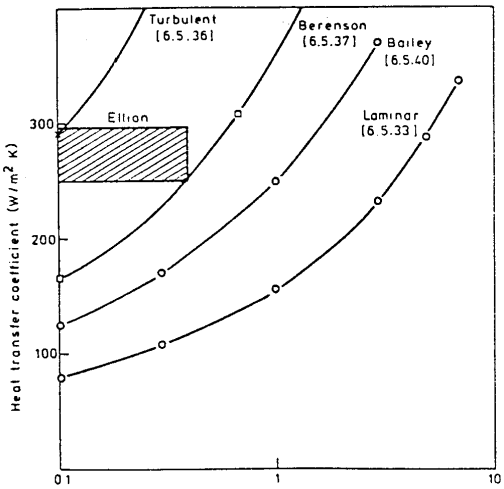
$$H_{film} = \frac{q''}{(T_w - T_{sat})} = 0.425\left[\frac{k_v^3 g\rho_v(\rho_l-\rho_v)h_{fg}'}{\mu_v\left(\frac{\lambda_c}{2\pi}\right)(T_w - T_{sat})}\right]^{1/4}$$

where Tayler wavelength is $\frac{\lambda_c}{2\pi} = \left[\frac{g_c\sigma}{g(\rho_l-\rho_v)}\right]^{\frac{1}{2}}$

■ to take account on the radiation

$$h = h_c + 0.75 h_r$$

where $h_r = \sigma\varepsilon \dfrac{T_w^4 - T_{sat}^4}{T_w - T_{sat}}$



★ Effect of Parameters Affecting Film Boiling

1) Effect of acceleartion

$\propto$ 1/4 power

reduced for a small cylinder

where σ is more important

2) velocity and subcooling effect

suppression of film boiling when the relative motion of a heat surface to the Leidenfrost drop

the film boiling cannot sustain when the subcooling is very high, such that

$$\frac{T_s - T_b}{T_w - T_s} > \frac{h_{radiation} + 1.27 h_{sat,FB}}{h_{subcooling}}$$