Two Phase Flows

(Section 10)

Pool Boiling

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Assignment set 4

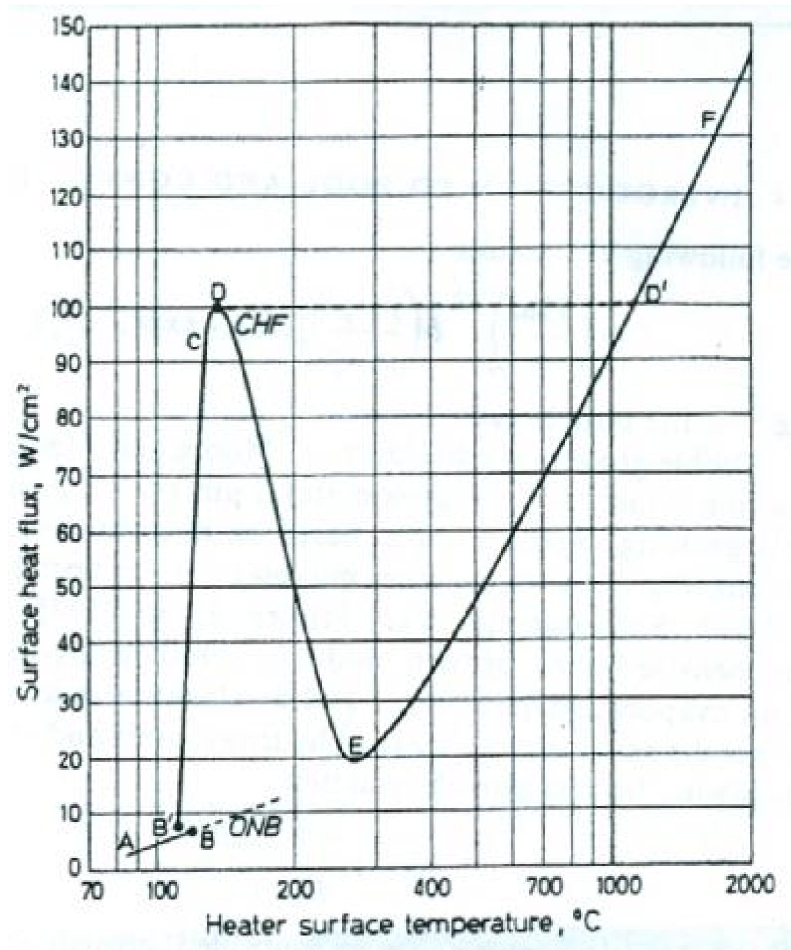
Problems 6-11

Chapter 2

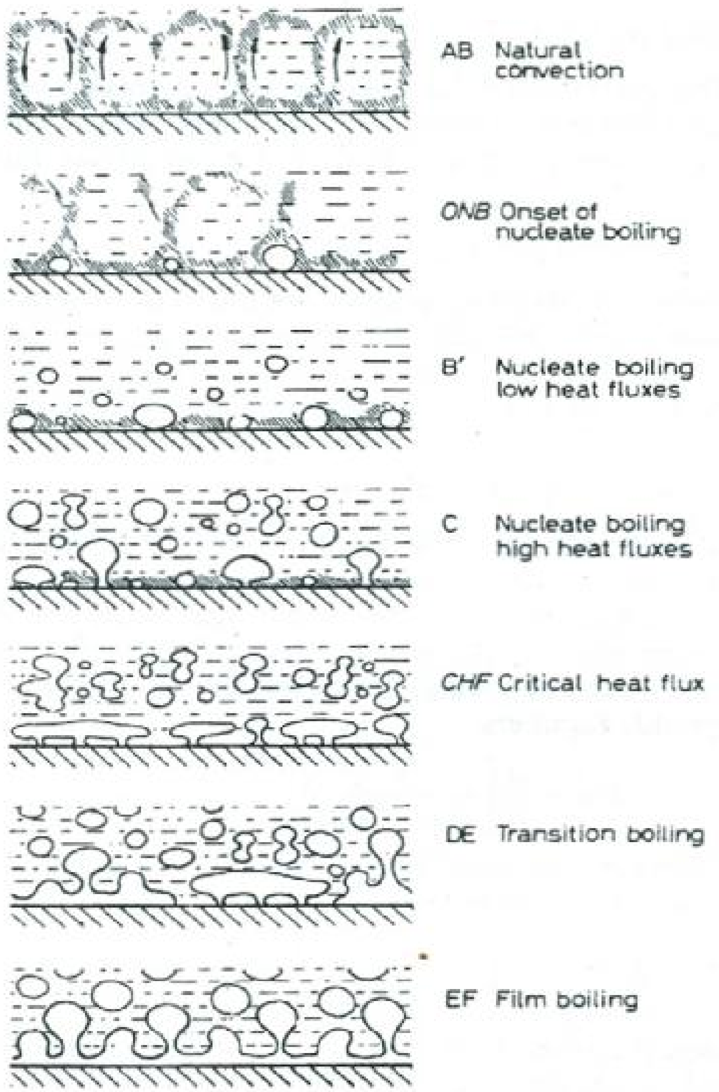
Due to next Tuesday

Boiling curve

AB	Natural convection region
AB-B'C	Onset of Nucleate boiling
B'C	Nucleate boiling region
D	Critical heat flux
DE	transition boiling region
EF	film boiling region



Various stages in boiling curve

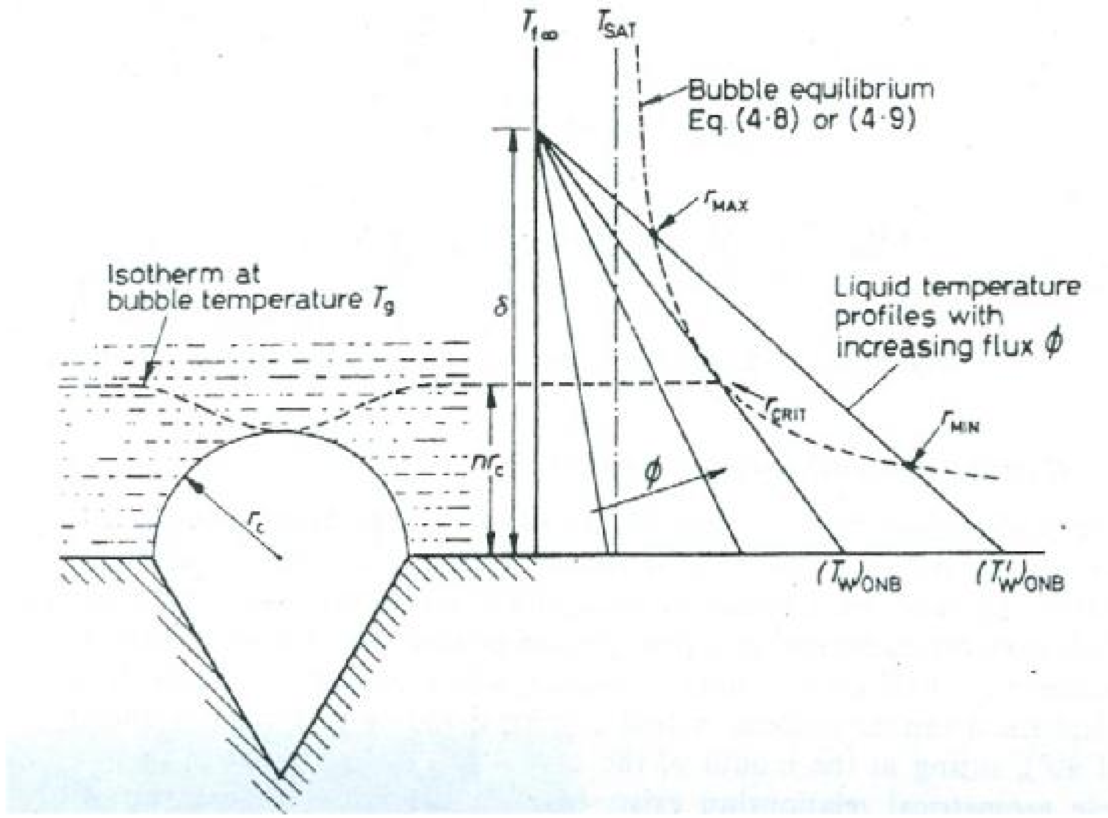


Natural Convection
By: Fishenden and Saunders

$$\left[\frac{hD}{k_f}\right] = 0.14\left[\left(\frac{b\,g\Delta T D^3 r_f^2}{m_f^2}\right)\left(\frac{c_p m}{k}\right)_f\right]^{1/3}$$

ONB

Onset of Nucleation Boiling



Nucleate Boiling Correlations

Power law relationship

$$T_W - T_{SAT} = y\, f^{\,n}$$

$$Nu = C_1 \mathrm{Re}^x \mathrm{Pr}^y$$

Using bubble dia. at departure as characteristic length

$$Nu = \frac{h}{k_f}\left[\frac{s}{g\left(r_f - r_g\right)}\right]^{1/2}$$

Roshenow (1952)

$$\mathrm{Re} = \frac{f}{i_{fg}\, r_f}\left[\frac{s}{g\left(r_f - r_g\right)}\right]^{1/2}\frac{r_f}{m_f}$$

$$Nu = \frac{1}{C_{sf}}\mathrm{Re}^{1-n}\,\mathrm{Pr}_f^{-m}$$

$$\frac{c_{pf}\Delta T_{SAT}}{i_{fg}} = C_{sf}\left[\frac{f}{i_{fg}\, r_f}\left(\left[\frac{s}{g\left(r_f - r_g\right)}\right]^{1/2}\right)\right]^n\left[\left(\frac{c_p m}{k}\right)_f\right]^{m+1}$$

Nucleate Boiling Correlations

Forster and Zuber (1955)

$$\frac{f}{i_{fg}\, r_f}\left(\frac{p}{a_f}\right)^{1/2}\left[\frac{r_f\, r^{*3}}{2s}\right]^{1/4} = 0.0015\left[\frac{r_f}{m_f}\left(\frac{\Delta T_{SAT} k_f}{i_{fg}\, r_f}\right)^2 \frac{p}{a_f}\right]^{5/8}\left[\left(\frac{c_p m}{k}\right)_f\right]^{1/3}$$

Borishanski (1969)

$$h = A^* f^{0.7} F(p)$$

$$A^* = 0.1011 p_{cr}^{0.69}$$

$$F(p) = 1.8 p_r^{3.17} + 4 p_r^{1.2} + 10 p_r^{10}$$

Cooper (1984)

$$h = 55 p_r^{0.12-0.4343 \ln R_p}\left(-0.4343 \ln P_r\right)^{-0.55} M^{-0.5} f^{0.67}$$

Nucleate Boiling Correlations

Gorenflo (1990, 1993)

$$h = h_0 F_{PF} \left[f / f_0 \right]^{nf} \left[R_p / R_{p0} \right]^{0.133}$$

Water:

$$F_{PF} = 1.73 P_r^{0.27} + \left(6.1 + \frac{0.68}{1 - P_r} \right) P_r^2$$

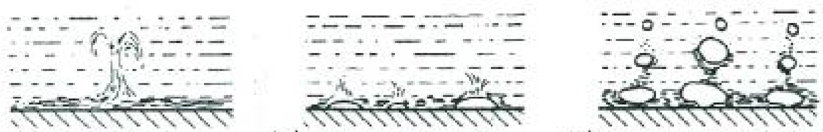
$$nf = 0.9 - 0.3 P_r^{0.15}$$

All fluids except water

$$F_{PF} = 1.2 P_r^{0.27} + 2.5 P_r + \frac{P_r}{1 - P_r}$$

$$nf = 0.9 - 0.3 P_r^{0.3}$$

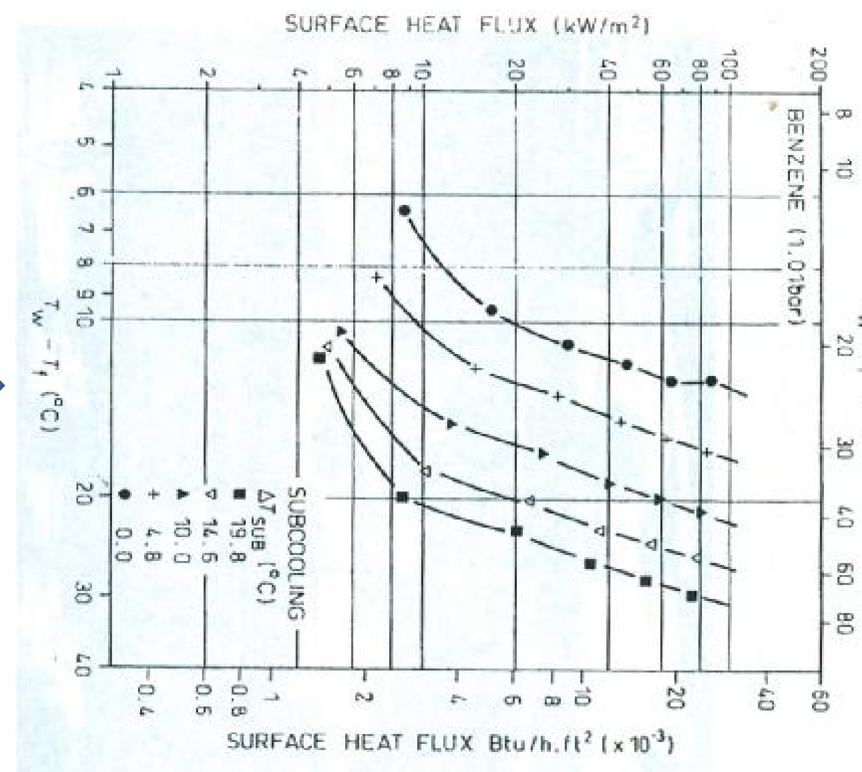
Heat transfer Mechanism



(a) At the onset of subcooled nucleate boiling
(b) At moderate heat fluxes and subcoolings
(c) At low subcoolings

Sub cooled nucleate boiling

Sub cooled boiling of benzene



Heat transfer Mechanism

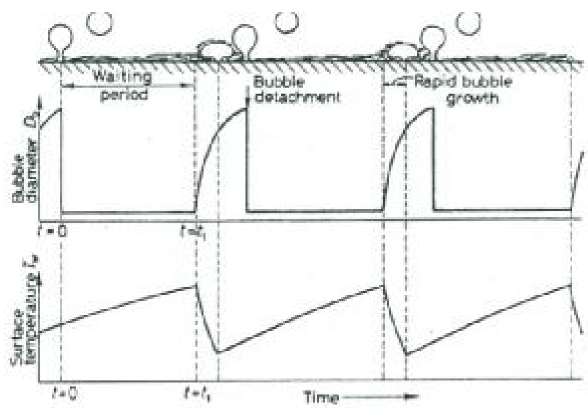
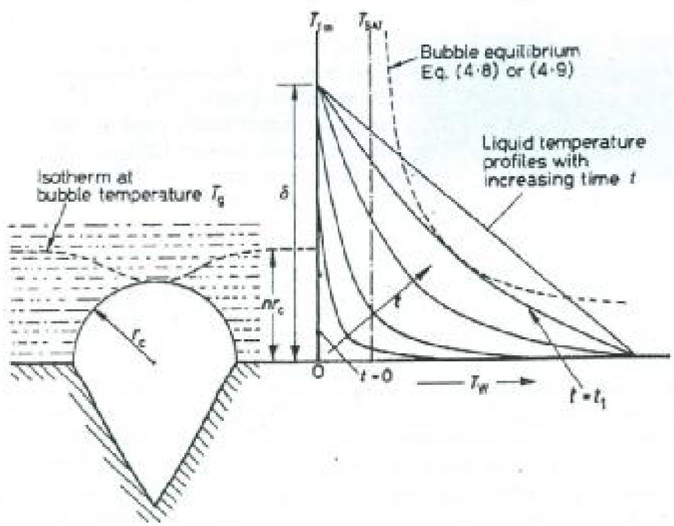


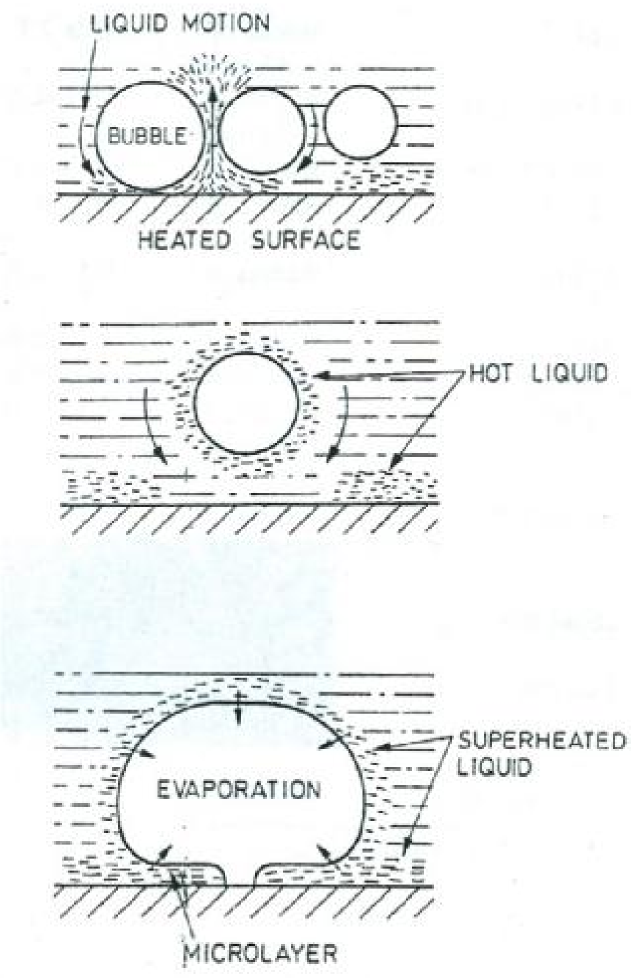
Fig. 4.16. Behaviour at a single nucleation site.

Behavior at a single nucleation site



Waiting period

Heat transfer Mechanism



Plain Surface nucleate boiling

1. Bubble agitation
2. Thermal boundary layer stripping
3. Evaporation

Critical Heat Flux

Helmholtz instability limits

$$\left(j_g\right)_{\max} = \frac{p}{24}\left[\frac{s\, g\left(r_f - r_g\right)}{r_g^2}\right]^{1/4}$$

plates

$$j_g = \frac{f}{i_{fg}\, r_f}$$

$$f_{CRIT} = Ki_{fg}\, r_g^{0.5}\left[s\, g\left(r_f - r_g\right)\right]^{1/4}$$

$$\frac{f_{CRIT}}{\left(f_{CRIT}\right)_{Zuber}} = fn\left(L^{'}\right)$$

Cylinders and spheres

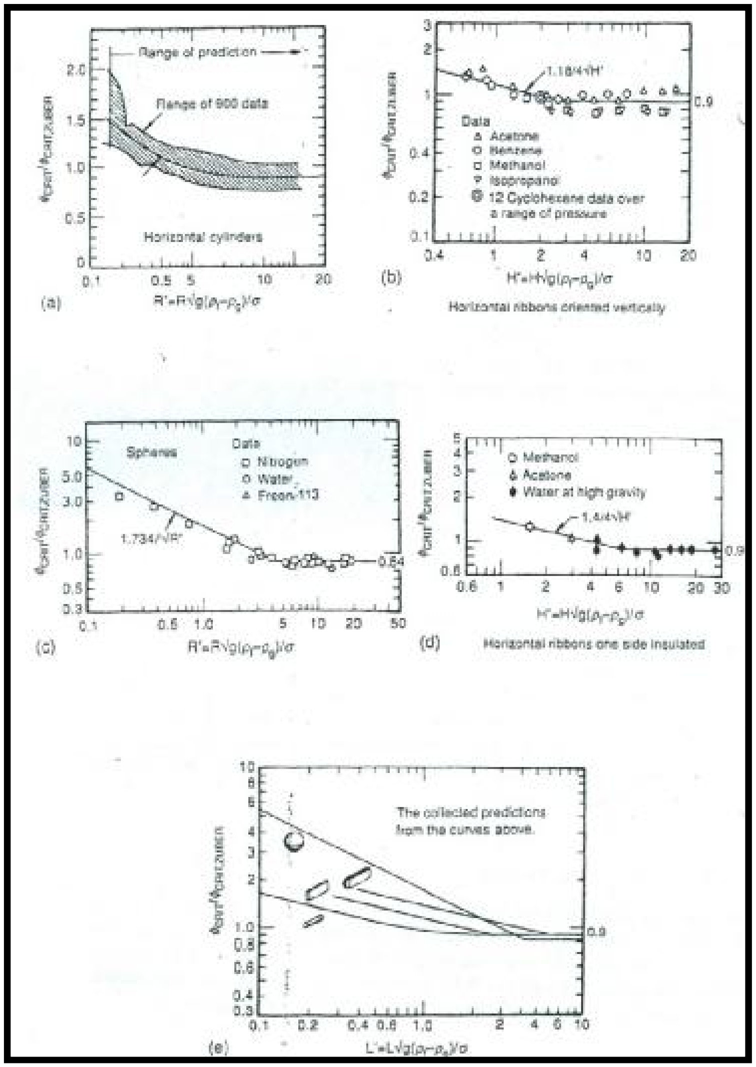
$$L^{'} = 2p\sqrt{3}\,\frac{L}{l_d}$$

$$l_d = 2p\sqrt{3}\left[\frac{s}{g\left(r_f - r_g\right)}\right]^{1/2}$$

Ivey and Morris (1986)

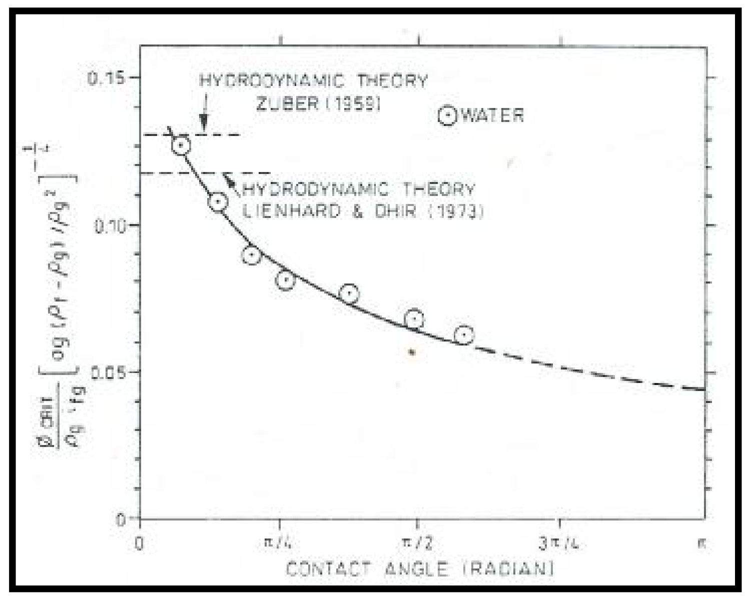
$$f_{CRIT} = Ki_{fg}\, r_g^{0.5}\left[s\, g\left(r_f - r_g\right)\right]^{1/4}\left[1 + B\Delta T_{SUB}\right]$$

CHF



Critical pool boiling heat flux on several heaters

Dependence of CHF on contact angle



Film boiling

Bromely (1950)

$$h = 0.62\left[\frac{g\left(r_f - r_g\right) r_g k_g^3 i'_{fg}}{D m_g \Delta T}\right]$$

where

$$i'_{fg} = i_{fg}\left[1 + 0.68\left(\frac{c_{pg}\Delta T}{i_{fg}}\right)\right]$$

Berenson (1961)

$$h = 0.425\left[\frac{g\left(r_f - r_g\right) r_g k_g^3 i'_{fg}}{m_g \Delta T_{SAT}\left[\frac{s}{g\left(r_f - r_g\right)}\right]^{1/2}}\right]^{1/4}$$

Considering radiation in high temperatures

$$h = h_c + 0.75 h_r$$

$$h_r = s e\left[\frac{T_W^4 - T_f^4}{T_W - T_f}\right]$$