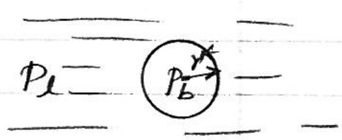
Two-Phase Heat Transfer

Boiling

Nucleation Superheat

$$(P_b - P_l) = \frac{2\sigma}{r^*}$$



$$\frac{dp}{dT} = \frac{h_{fg}}{T_{sat}(v_g - v_f)}$$ – Clausius–Clapeyrons (relation between p and T at sat),

$$\frac{dP_g}{dT} = \frac{h_{fg}}{T_g(v_g)}$$ for bubble $v_g >> v_f$

$P_g v_g = RT_g$ perfect gas law.

$$\frac{dP_g}{P_g} = \frac{h_{fg}}{RT_g^2}\, dT_g$$

Integrate between P_b and P_l

$$\ln\left(\frac{P_b}{P_l}\right) = -\frac{h_{fg}}{R}\left(\frac{1}{T_b} - \frac{1}{T_{sat}}\right)$$

$$(T_b - T_{sat}) = \frac{RT_bT_{sat}}{h_{fg}} \ln\left(\frac{P_b}{P_l}\right) = \frac{RT_bT_{sat}}{h_{fg}} \ln\left(1 + \frac{2\sigma}{P_l r^*}\right)$$

$$\simeq \frac{RT_bT_{sat}\,2\sigma}{h_{fg}\cdot P_b r^*} \simeq \frac{2\sigma T_{sat} v_{fg}}{h_{fg}}\left(\frac{1}{r^*}\right)$$

$(\because RT_b/P_b = v_b \simeq v_{fg})$

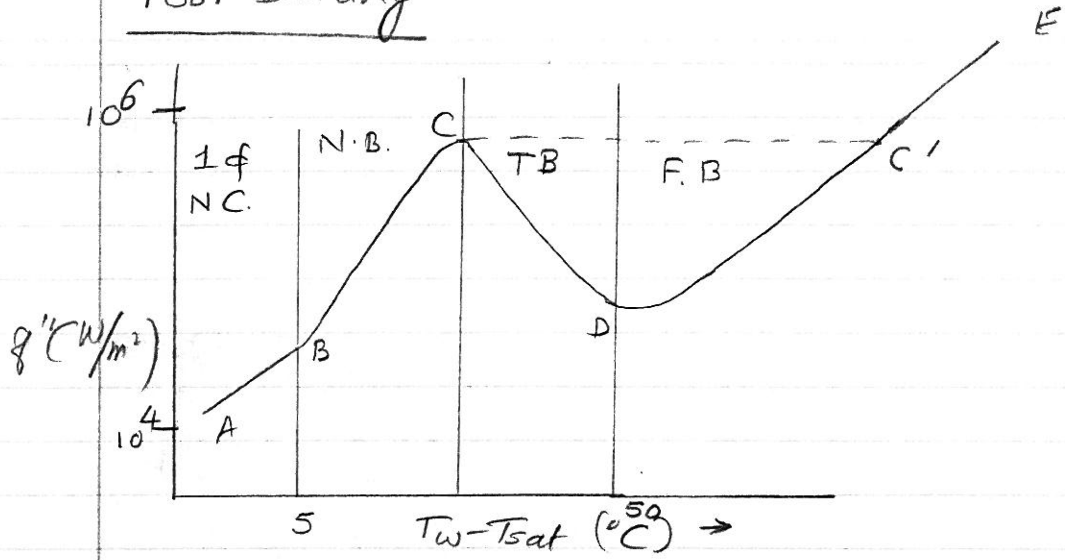
For water at atmospheric pressure

$$T_b - T_{sat} = 220^\circ C$$

for homogeneous nucleation.

– Dissolved gases

Pool Boiling



Critical Heat Flux. : Fig. 12-3.

Film Boiling Table 12-1.

- Flow Boiling : Fig. 12-4
- Subcooled boiling. Fig. 12-8
- Saturated boiling : $h_{2\phi} = h_{NB} + h_c$ (Chen correlation)

$$h_c = 0.023 \cdot \left(\frac{G(1-x)D_e}{\mu_f}\right)^{0.8} (P_{rf})^{0.4} \frac{k}{D_e} F$$

$F = 1$ for $X_{tt} < 0.1$

$F = 2.35\left(0.213 + \frac{1}{X_{tt}}\right)$ for $X_{tt} > 0.1$

$$X_{tt} = \left(\frac{x}{1-x}\right)^{0.9} \left(\frac{\rho_f}{\rho_g}\right) \left(\frac{\mu_g}{\mu_f}\right)^{0.1}$$

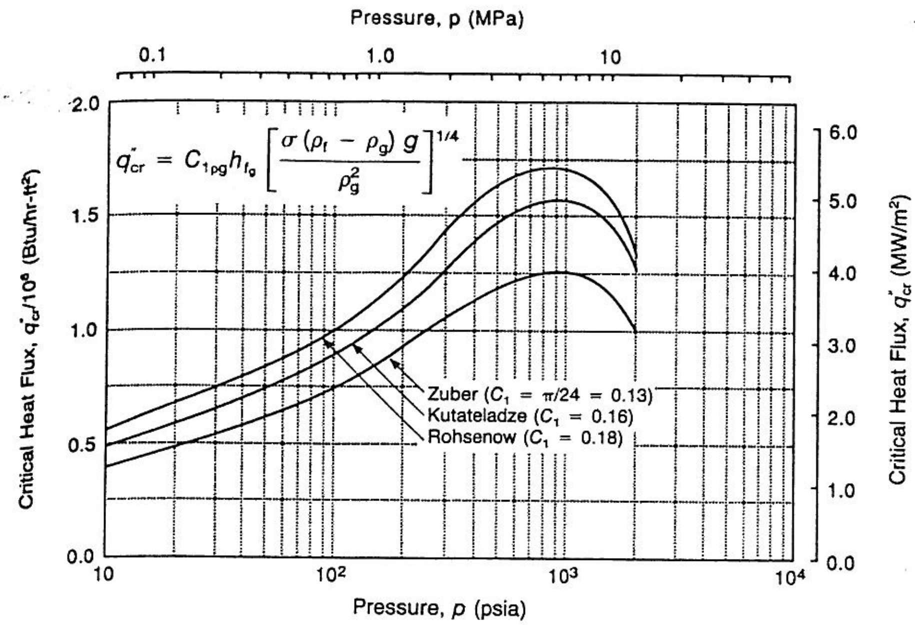


Figure 12-3 Effect of pressure on pool boiling CHF.

Table 12-1 Summary of correlations for prediction of minimum wall temperature to sustain film boiling (T^M)*

Author	Correlation
Berenson [6]	$T_B^M - T_{sat} = 0.127 \frac{\rho_{vf} h_{fg}}{k_{vf}} \left[\frac{g(\rho_f - \rho_g)}{\rho_f + \rho_g}\right]^{2/3} \left[\frac{g_c \sigma}{g(\rho_f - \rho_g)}\right]^{1/2} \left[\frac{\mu_{vf}}{g_c(\rho_\ell - \rho_v)}\right]^{1/3}$
Spiegler et al. [57]	$T_S^M = 0.84\, T_c$
Kalinin et al. [40]	$\frac{T_K^M - T_{sat}}{T_c - T_\ell} = 0.165 + 2.48 \left[\frac{(\rho k c)_\ell}{(\rho k c)_w}\right]^{0.25}$
Henry [33]	$\frac{T_H^M - T_B^M}{T_B^M - T_\ell} = 0.42 \left[\sqrt{\frac{(\rho k c)_\ell}{(\rho k c)_w}} \frac{h_{fg}}{c_w(T_B^M - T_{sat})}\right]^{0.6}$

*(1) The subscripts given to T^M in the correlations refer to the originator(s) of the correlation. (2) The British system of units is to be used in Berenson's correlation. Absolute temperatures are to be used in the correlation of Spiegler et al. The other correlations include only dimensionless parameters. (3) Properties with the subscript vf are to be evaluated at the average temperature in the vapor film.

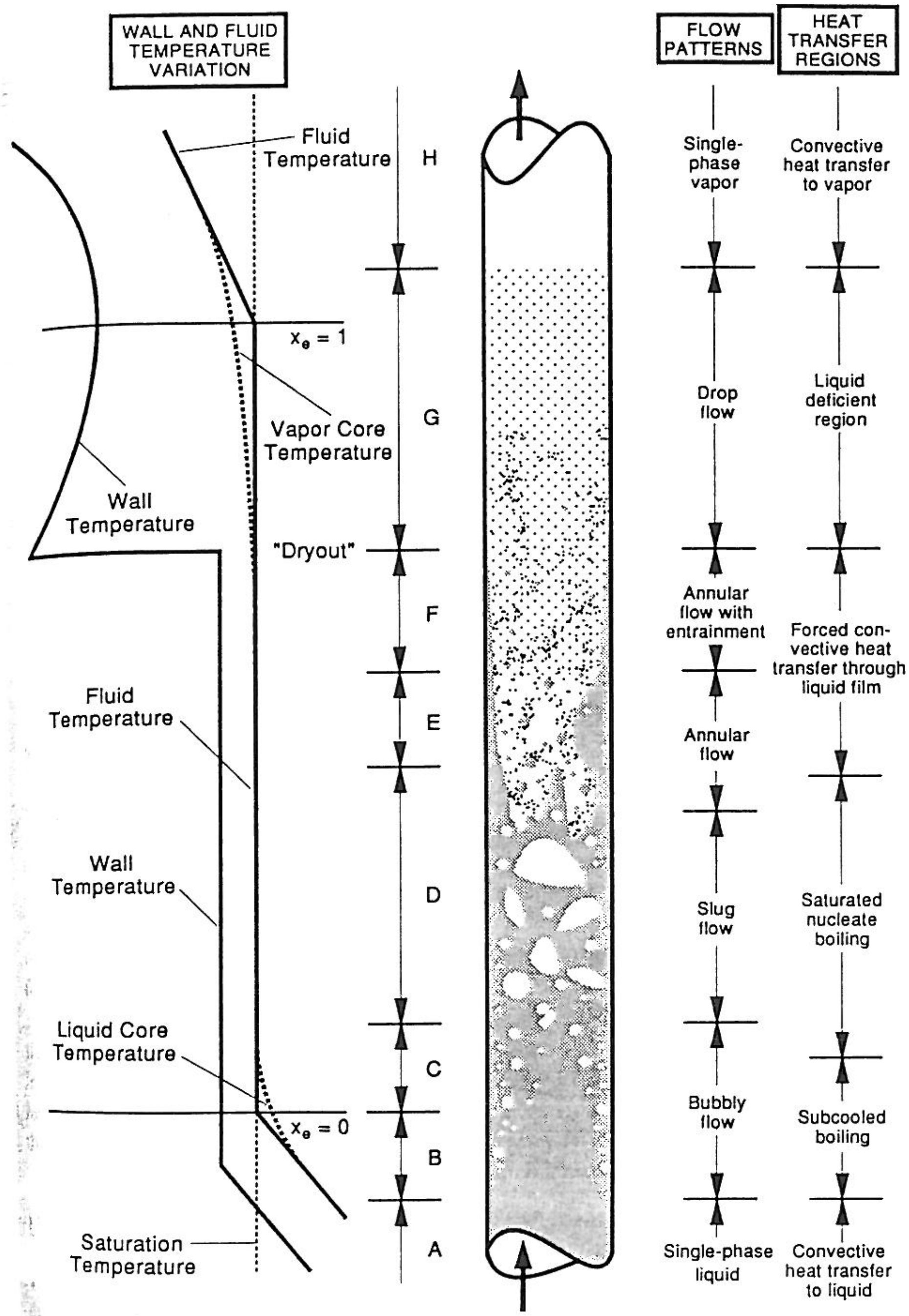


Figure 12-4 Regions of heat transfer in convective boiling. *(From Collier [17].)*

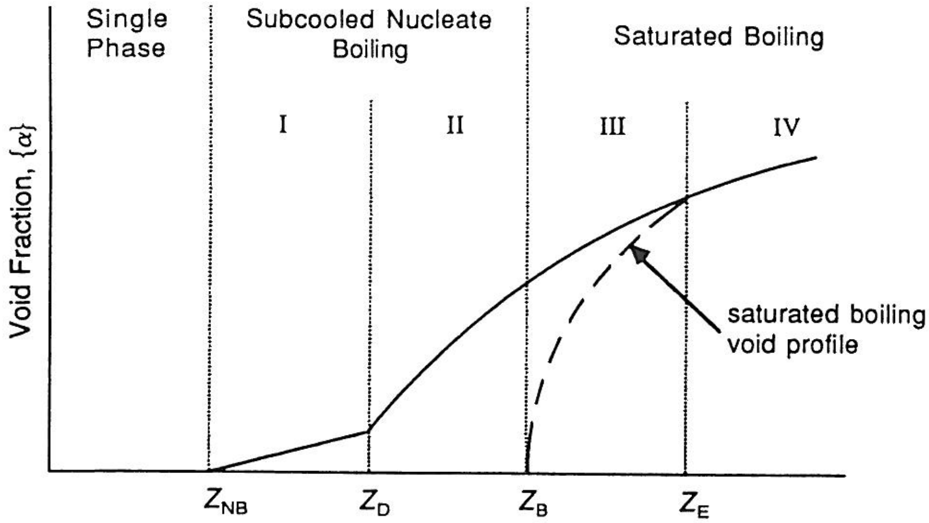


Figure 12-8 Development of area-averaged void fraction in a heated channel. Region I: $\{\alpha\}$ is small and may be neglected. Region II: Bubbles are significant; they are ejected from the wall into the bulk and collapse there. Region III: Bubbles do not collapse, as thermal equilibrium exists in the channel. Region IV: Void fraction loses the subcooling history.

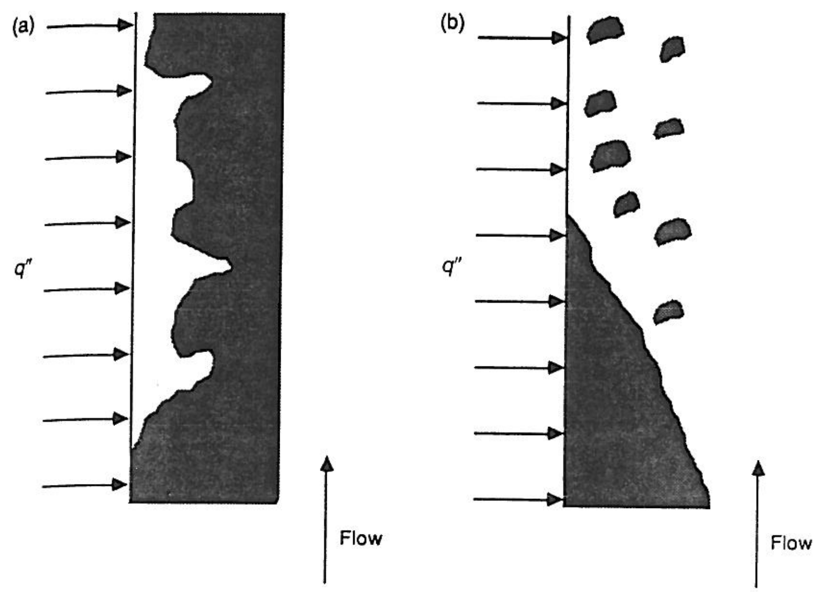


Figure 12-21 CHF mechanisms. (a) DNB. (b) Dryout.

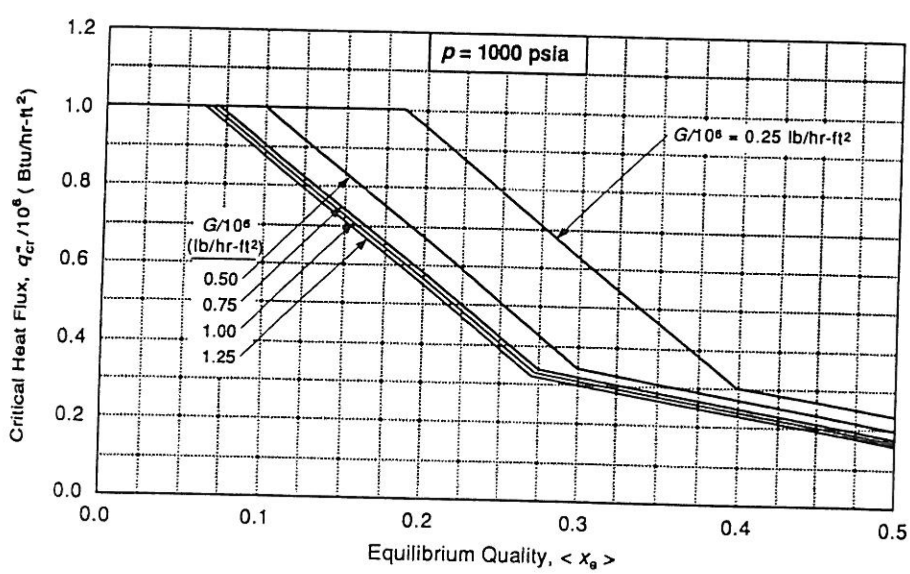


Figure 12-25 Hench–Levy limit lines.

$$h_{NB} = S(0.00122)\left[\frac{\left(k^{0.79}\cdot c_p^{0.45}\,\rho^{0.49}\right)_f}{\sigma^{0.5}\,\mu_f^{0.29}\,h_{fg}^{0.24}\,\rho_g^{0.24}}\right]\Delta T_{sat}^{0.24}\,\Delta p^{0.75}.$$

$$S = \frac{1}{1+2.53\times 10^{-6}\,Re^{1.17}}, \quad \underline{Re = Re_l\,F^{1.25}}$$

- <u>Critical Heat Flux (at low quality)</u> (DNB)

1. Pool. Boiling ' Fig 12-3.
2. Flow boiling.

ii. CHF (at high quality) (Dryout)

PWR - DNB. (Tong) W-3.

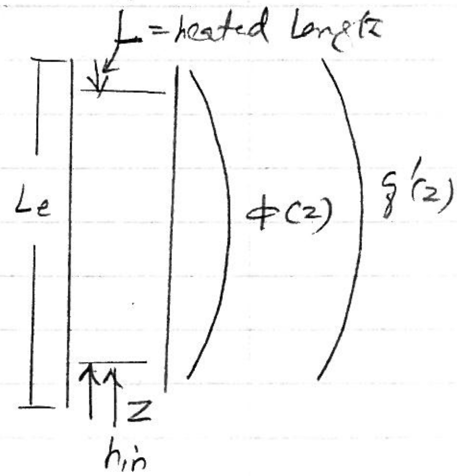
BWR - Dryout GE. Hench-Levy Limit Lines Fig. 12-25

Thermal-hydraulics:
<u>Steady State Analysis</u>

Single-phase: Coolant and Fuel Rod.

$$\dot m \frac{d}{dz} h_m = q'(z)$$

$$q'(z) = q_0' \cos\frac{\pi z}{L_e}$$



Coolant Temperature:

$$\dot m \int_{h_{in}}^{h_m(z)} dh_m = q_0' \int_{-L/2}^{L/2} \cos\left(\frac{\pi z}{L_e}\right) dz$$

$$\dot{m} c_p \int_{T_{in}}^{T_m(z)} dT = q_0' \int_{-L/2}^{z} \cos\left(\frac{\pi z}{L_e}\right) dz$$

Single-phase
$dh = \dot{m} c_p dT$

$$T_m(z) = T_{in} + \frac{q_0'}{\dot{m} c_p} \frac{L_e}{\pi} \left(\sin\frac{\pi z}{L_e} + \sin\frac{\pi L}{2L_e} \right)$$

$$T_{out} = T_{in} + \frac{2 q_0' L}{\pi \dot{m} c_p} \qquad (L_e \simeq L)$$

Cladding Temperature

$$h\left(T_{co}(z) - T_{in}(z)\right) = q''(z) = \frac{q'(z)}{P_h}$$

$P_h = 2\pi R_{co}$, h = heat transfer coeff.

$$T_{co}(z) = T_m(z) + \frac{q_0'}{2\pi R_{co} h} \cos\left(\frac{\pi z}{L_e}\right)$$

maximum cladding surface temperature

$$\frac{dT_{co}}{dz} = 0.$$

$$\longrightarrow \quad z_e = \frac{L_e}{\pi} \tan^{-1}\left[\frac{2\pi R_{co} L_e h}{\pi \dot{m} c_p}\right]$$