11.4 Hydrodynamic theory of Boiling and CHF

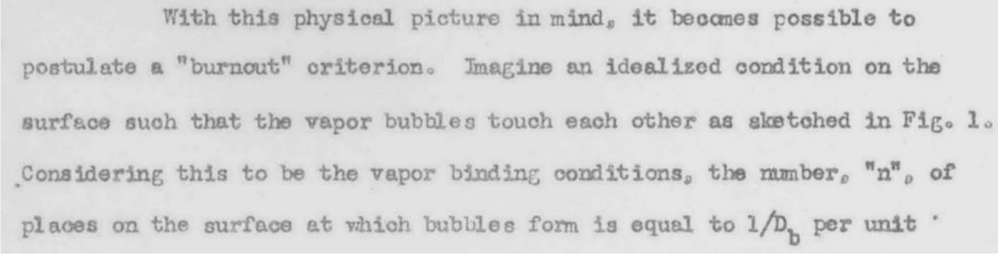
- Hydrodynamic instability model
  - ✓ Formation of droplet from vapor column and inhibition its falling back to the surface due to high vapor velocity (Kutateladze, 1948)
  - ✓ Insufficient liquid due to the rate of vapor leaving the surface (Zuber, 1959)

- Bubble interaction or bubble packing model
  - ✓ Increase of nucleation site density
  - ✓ Formation of critical bubble packing which inhibits liquid flow to the surface (Rohsenow & Griffith, 1956)

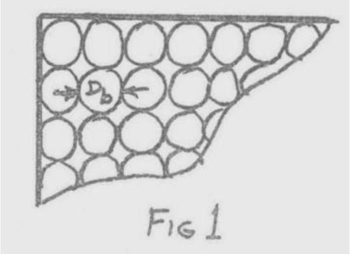
- Micro-layer dryout model
  - ✓ Depletion of liquid layer under the large bubbles (Haramura and Katto, 1983)

11.4 Hydrodynamic theory of Boiling and CHF

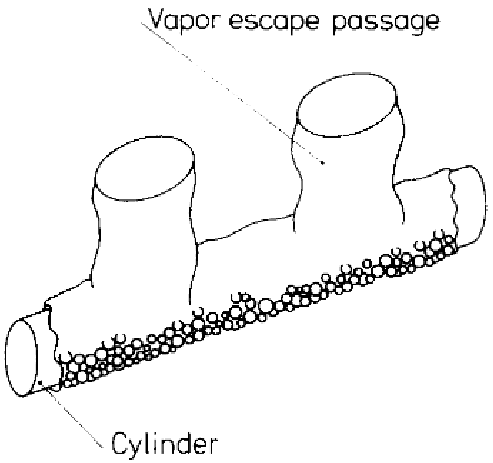
- Bubble interaction theory (Rohsenow & Griffith, 1956)



With this physical picture in mind, it becomes possible to postulate a "burnout" criterion. Imagine an idealized condition on the surface such that the vapor bubbles touch each other as sketched in Fig. 1. Considering this to be the vapor binding conditions, the number, "n", of places on the surface at which bubbles form is equal to $1/D_b$ per unit



- Micro-layer dryout model (Haramura and Katto, 1983)



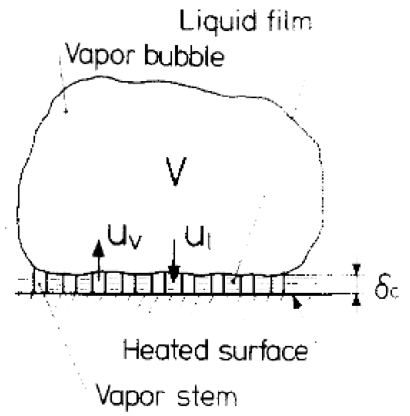
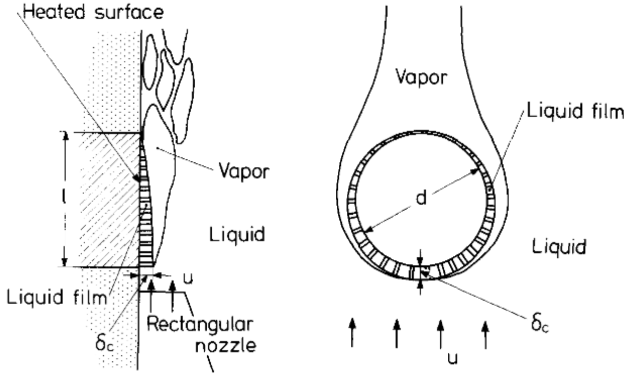


FIG. 2. Vapor structure near heated surface at high heat fluxes.



(a) Flat plate (b) Cylinder

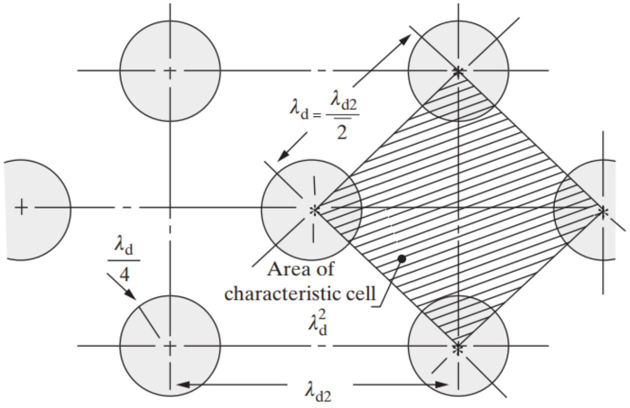
11.4 Hydrodynamic theory of Boiling and CHF

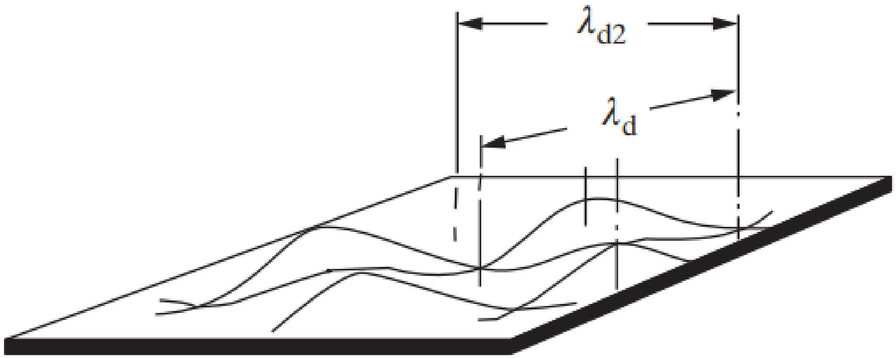
- Hydrodynamic theory of boiling
  - ✓ The vapor–liquid interfacial stability phenomena play a crucial role in processes such as the critical heat flux (CHF) and film boiling (Lienhard and Witte, 1985)
  - ✓ CHF and film boiling is determined by
    - The hydrodynamic limitations associated with the vapor–liquid interfacial stability
    - The transport of vapor near the heated surface
  - ✓ Hydrodynamic theory model have been relatively successful and extensively used
- According to hydrodynamic theory (Zuber, 1959; Zuber et al., 1963)
  - ✓ CHF and minimum film boiling are Taylor instability-driven processes
  - ✓ CHF: vapor jets rise
    - The highest rise velocity – Helmholtz instability
  - ✓ Minimum film boiling: the surface is blanketed by vapor
    - Vapor bubbles are periodically released from the nodes of Taylor waves at the liquid-vapor interface
  - ✓ In transition boiling: partially rising jets and partially vapor bubbles

11.4 Hydrodynamic theory of Boiling and CHF

- Zuber et al.'s CHF model
  - ✓ The CHF in pool boiling is a process controlled by hydrodynamic stability.
  - ✓ Controlling factor
    - Preventing the development of large dry patches on the heated surface
    - Transferring vapor from the vicinity of the surface
  - ✓ Assumption
    - Rising vapor jets with radius R_j on a square grid with pitch equal to the fastest growing wavelength according to Taylor instability $\lambda_{\mathrm{d}} = 2\pi\sqrt{3}\sqrt{\sigma/g\Delta\rho}$
    - The rising jets are assumed to have the critical velocity dictated by the Helmholtz instability $U_{\mathrm{g}} = \sqrt{2\pi\sigma/(\rho_{\mathrm{g}}\lambda_{\mathrm{H}})}$ $\lambda_{\mathrm{H}} = 2\pi R_{\mathrm{j}}$

neutral wavelength for the rising jets





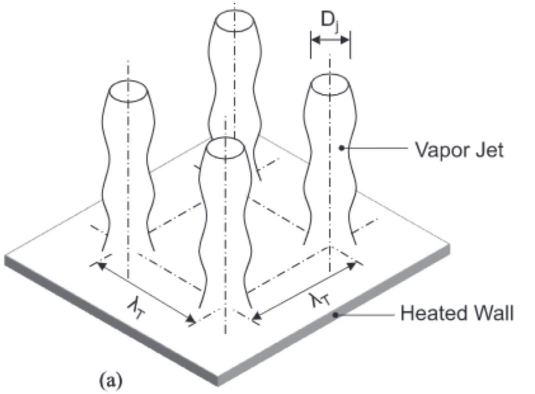
11.4 Hydrodynamic theory of Boiling and CHF

- Zuber et al.'s CHF model
  - ✓ CHF = the rate of latent heat leaving by way of a single jet, divided by the area of a square grid

$$q''_{\mathrm{CHF}} = \rho_g h_{fg} U_g \frac{\pi R_j^2}{\lambda_d^2} \qquad R_j = \lambda_d/4.$$

Zuber's assumption

$$q''_{\mathrm{CHF,Z}} \approx \frac{\pi}{24} \rho_g^{1/2} h_{fg} (\sigma g \Delta\rho)^{1/4}$$

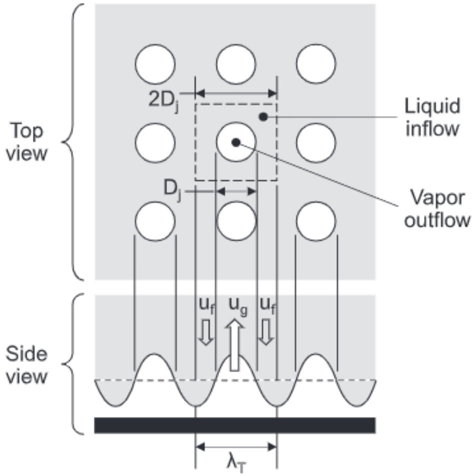


(a)

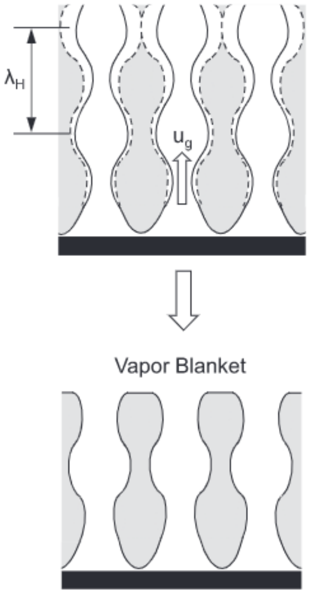
- Sun and Lienhard (1970)
  - ✓ Neutral wavelength of the rising jets

$$\lambda_H = \lambda_{dl}$$

$$q''_{\mathrm{CHF}} = 0.149 \rho_g^{1/2} h_{fg} (\sigma g \Delta\rho)^{1/4}$$



(b)



(c)

11.4 Hydrodynamic theory of Boiling and CHF

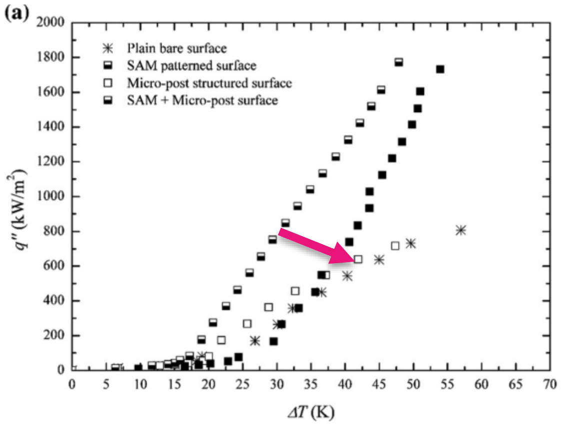
- Effect of heated surface size and geometry (Lienhard, 1970)
  - ✓ Hydrodynamic theory: when the heated surface are much larger than λ_d
    - Acceptable assumption as long as the principal radii of curvature of the surface are much larger than λ_d
    - Valid when the surface is flat and large enough for its end effects to be unimportant
  - ✓ Lienhard and Dhir (1973)

$$\frac{q''_{\mathrm{CHF}}}{q''_{\mathrm{CHF,Z}}} = f(l') \qquad l' = l/\sqrt{\sigma/g\Delta\rho},$$

$q''_{CHF,Z}$: CHF predicted by Zuber model

Situation	Characteristic length, l	Range	Correction factor, $f(l')$
Infinite flat heater	Heater width or diameter	$l' \geq 27$	1.14
Small flat heater	Heater width or diameter	$9 < l' < 20$	$1.14\lambda_{\mathrm{d}}^2/A_{\mathrm{heat}}$
Horizontal cylinder	Cylinder radius	$l' \geq 0.15$	$0.89 + 2.27\exp(-3.44\sqrt{l'})$
Large horizontal cylinder	Cylinder radius	$l' \geq 1.2$	0.90
Small horizontal cylinder	Cylinder radius	$0.15 \leq l' \leq 1.2$	$0.94 l'^{-0.25}$
Large sphere	Sphere radius	$l' \geq 4.26$	0.84
Small sphere	Sphere radius	$0.15 \leq l' \leq 4.26$	$1.734/\sqrt{l'}$
Any large finite body	Characteristic length	Cannot specify generally; $l' \geq 4$	~0.90
Small horizontal ribbon oriented vertically			
Plain, both sides heated	Height of side	$0.15 \leq l' \leq 2.96$	$1.18/l'^{0.25}$
One-side insulated	Height of side	$0.15 \leq l' \leq 5.86$	$1.4/l'^{0.25}$
Small slender cylinder of any cross section	Transverse perimeter	$0.15 \leq l' \leq 5.86$	$1.4/l'^{0.25}$
Small bluff body	Characteristic length	Cannot specify generally; $l' \leq 4$	$\mathrm{const.}/\sqrt{l'}$

11.4 Hydrodynamic theory of Boiling and CHF

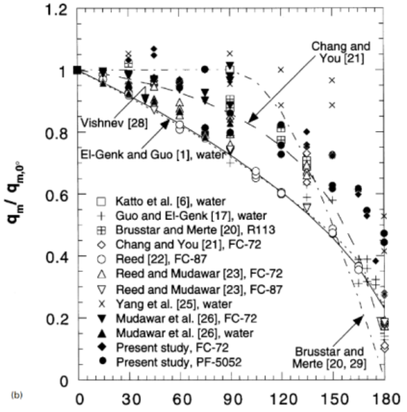


- Other parametric effects
  - ✓ Surface wettability
    - Improve (increase) the CHF

$$\frac{q''_{\mathrm{CHF}}}{\rho_{\mathrm{g}}^{1/2} h_{\mathrm{fg}} (\sigma g \Delta \rho)^{1/4}} = 0.1 \exp(-\theta_{\mathrm{r}}/45^{\circ}) + 0.055$$

  - ✓ Gravitational acceleration
    - The effect is smaller than the predicted $g^{1/4}$
      - Experiment: $10^{-5}g$, a reduction of only 60% in q''_{CHF}, model: 94% reduction
    - Some experiments showed an opposite trend.
    - No consideration on the surface condition effects
    - Shortcomings of hydrodynamics model
  - ✓ Surface orientation
    - CHF is lower on inclined surfaces
    - Correlation by Chang and You (1996)

$$\frac{q''_{\mathrm{CHF}}}{q''_{\mathrm{CHF,Horizontal}}} = 1 - 0.00120\theta \tan(0.414\theta) - 0.122 \sin(0.318\theta)$$

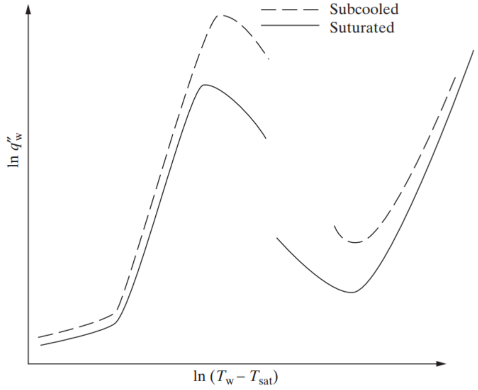


11.4 Hydrodynamic theory of Boiling and CHF

- Other parametric effects
  - ✓ Liquid subcooling: increases the CHF
    - Ivey and Morris (1962)

$$\frac{q''_{\mathrm{CHF}}}{q''_{\mathrm{CHF,sat}}} = 1 + 0.1(\rho_{\mathrm{f}}/\rho_{\mathrm{g}})^{0.75}\frac{C_{\mathrm{PL}}(T_{\mathrm{sat}} - T_{\mathrm{L}})}{h_{\mathrm{fg}}}$$

$$Ja = \frac{c_{p,f}(T_w - T_{sat})}{h_{fg}}$$



- Elkassabgi and Lienhard (1988)
  - For low subcooling conditions ($T_{sat} - T_L < 15^{\circ}C$)

$$\frac{q''_{\mathrm{CHF}}}{q''_{\mathrm{CHF,sat}}} = 1 + 4.28\frac{\rho_{\mathrm{L}}C_{\mathrm{PL}}(T_{\mathrm{sat}} - T_{\mathrm{L}})}{\rho_{\mathrm{g}}h_{\mathrm{fg}}}\left[\alpha_{\mathrm{f}}\frac{[g\Delta\rho]^{1/4}\rho_{\mathrm{g}}^{1/2}}{\sigma^{3/4}}\right]^{1/4}$$

- ✓ Surface roughness
  - Increases the CHF, typically by 25%–35%