CONVECTION PROCESSES OF BOILING AND CONDENSATION

- **Dimensionless Parameters**
- **Boiling**

  Pool Boiling

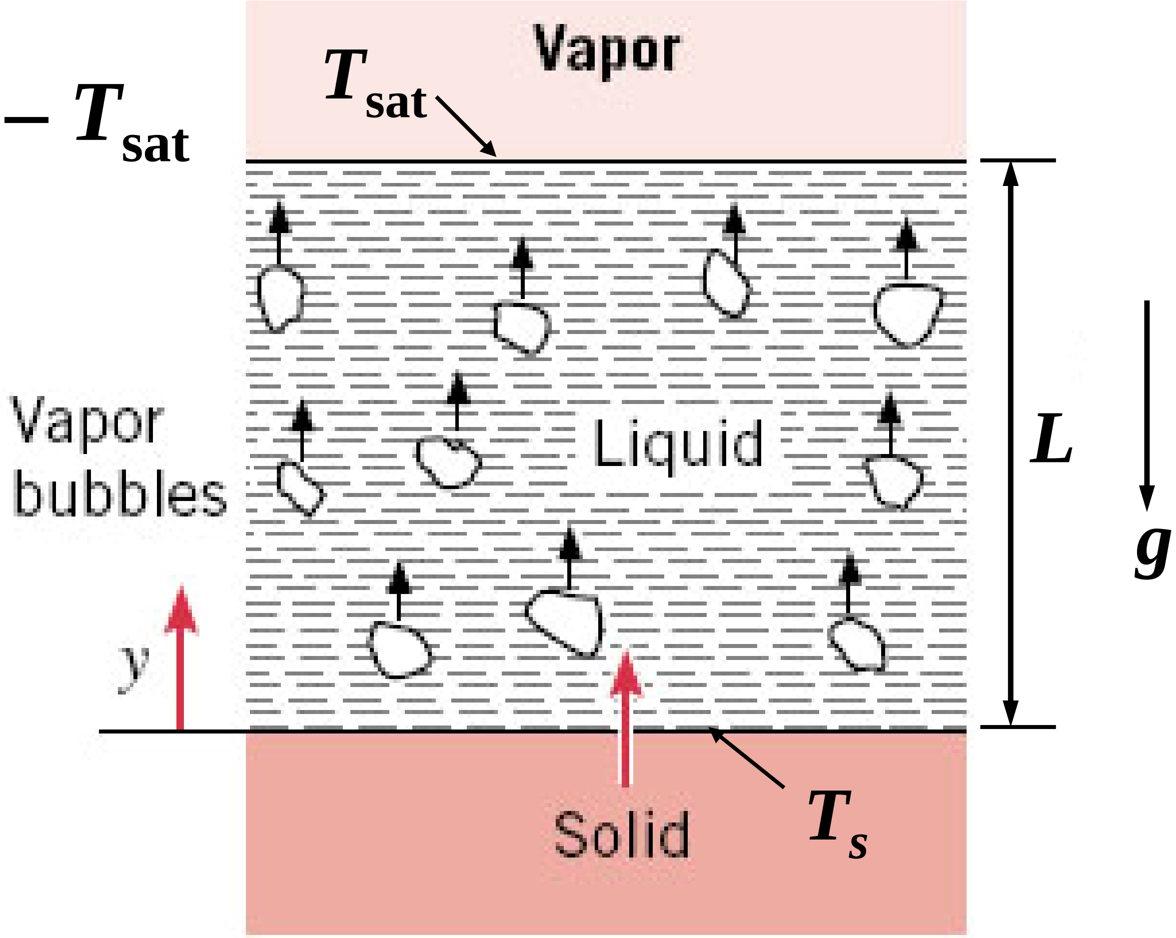
  Forced Convection Boiling
- **Condensation**

  Laminar Film Condensation

  Turbulent Film Condensation

Dimensionless Parameters

$$\Delta T = T_s - T_{sat}$$



$$h = h[\Delta T, g(\rho_l - \rho_v), h_{fg}, \sigma, L, \rho, c_p, k, \mu]$$

Dimensionless Parameters

$$h = h[\Delta T, g(\rho_l - \rho_v), h_{fg}, \sigma, L, \rho, c_p, k, \mu]$$

$$Nu_L = \frac{hL}{k} = f\left(\frac{\rho g(\rho_l - \rho_v)}{\mu^2}, \mathrm{Ja}, \mathrm{Pr}, \mathrm{Bo}\right)$$

$$\frac{\rho g(\rho_l - \rho_v)}{\mu^2} = \frac{\text{buoyancy force}}{\text{viscous force}} \quad \left(\mathrm{Gr} = \frac{g\beta \Delta T L^3}{\nu^2}\right)$$

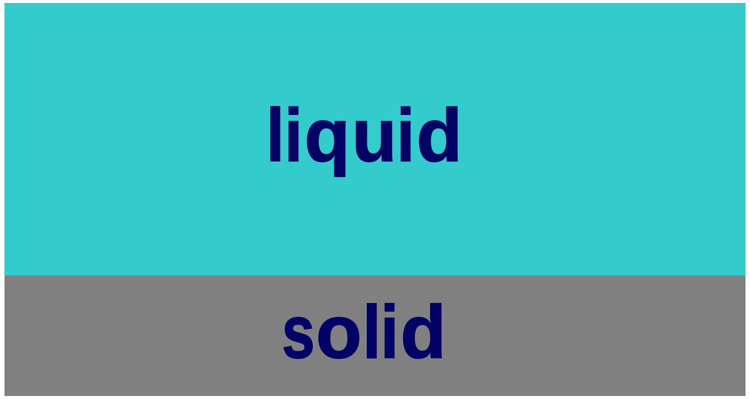
$$\mathrm{Ja} = \frac{c_p \Delta T}{h_{fg}} = \frac{\text{sensible heat}}{\text{latent heat}}$$ **:Jacob No.**

$$\mathrm{Pr} = \frac{\mu c_p}{k} = \frac{\nu}{\alpha} = \frac{\text{viscous diffusion}}{\text{thermal diffusion}}$$

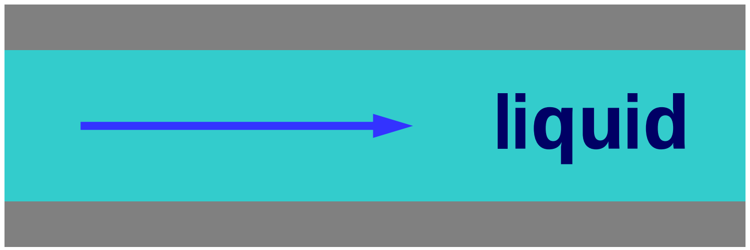
$$\mathrm{Bo} = \frac{g(\rho_l - \rho_v)L^2}{\sigma} = \frac{\text{gravity force}}{\text{surface force}}$$ **:Bond No.**

Boiling

- **Pool boiling**



- **Forced convection boiling**



- **Subcooled boiling**

  Temperature of the liquid:
  below the saturation temperature

  Bubbles formed at the solid surface:
  condense in the liquid

- **Saturated boiling**

$$T_{sat} = T_{sat}(p)$$

Newton's law of cooling

$$q_s'' = h\left(T_s - T_{\text{sat}}\right) = h\Delta T_e$$

ΔT_e: excess temperature

formation of vapor bubble

detach process from the surface

- Vapor bubble growth and dynamics

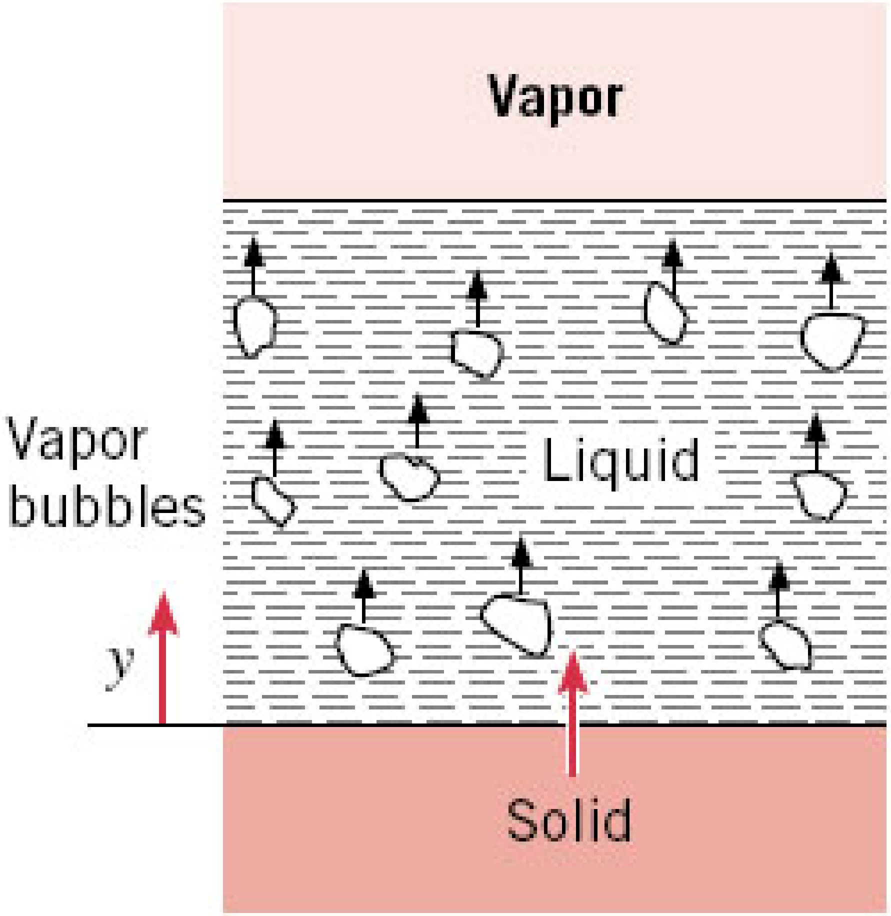
    excess temperature

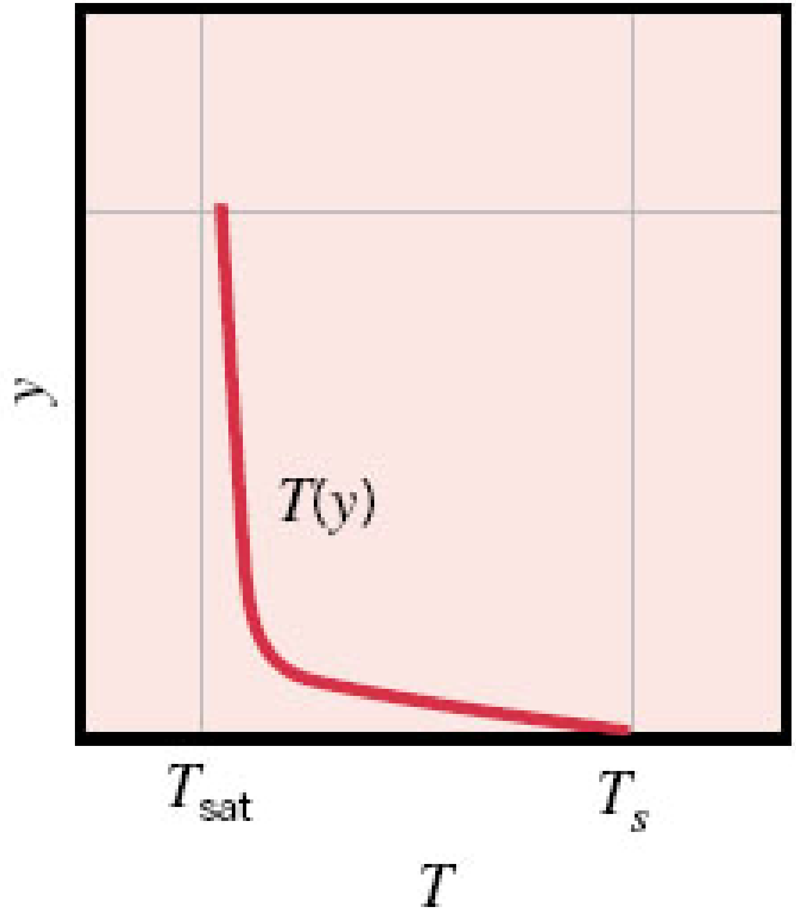
    nature of surface

    thermopysical properties

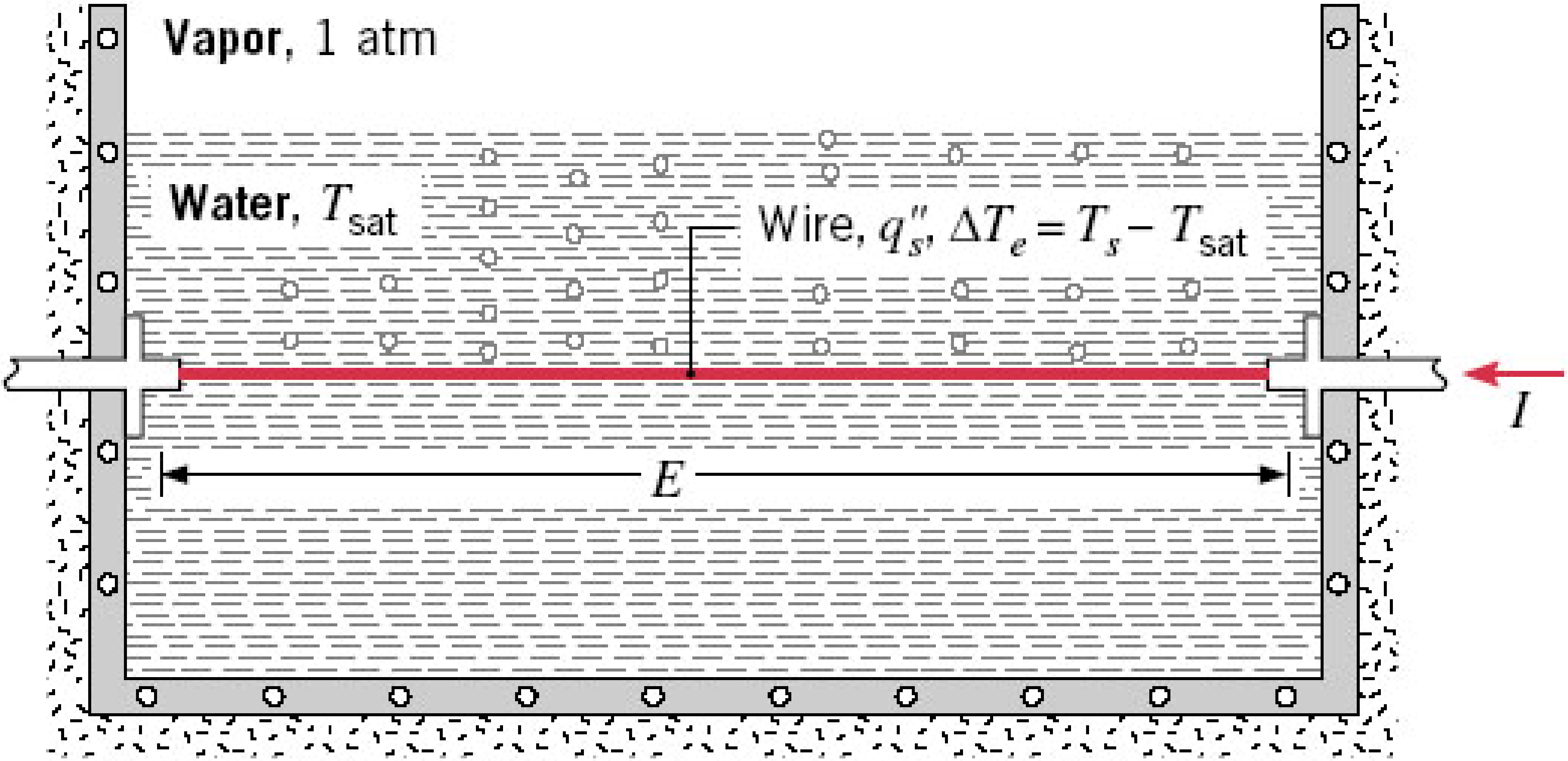
Pool Boiling

- **Saturated pool boiling**





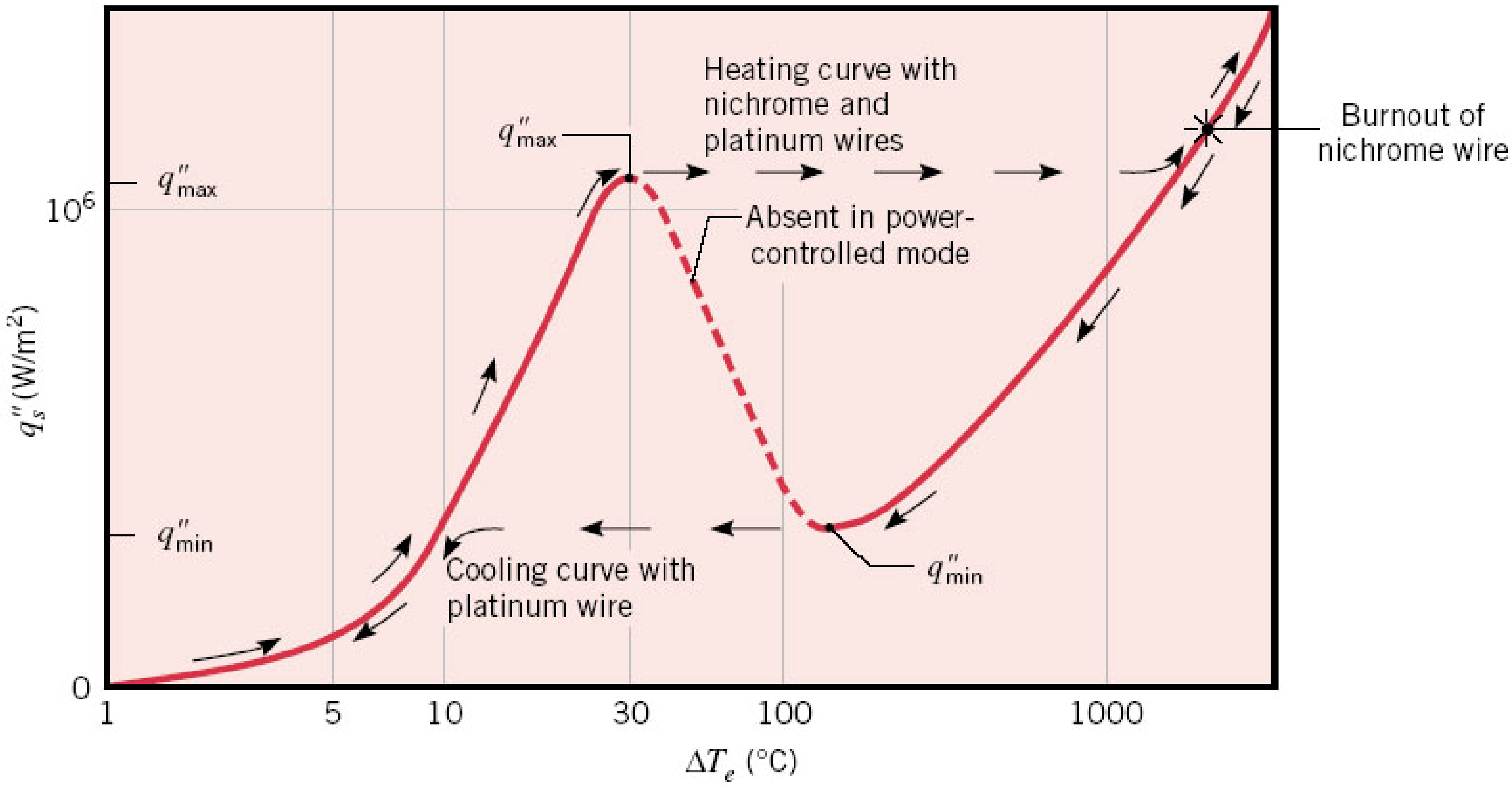
Nukiyama's power-controlled heating apparatus: boiling curve



power setting (or q''_s): independent variable

wire temperature (or ΔT_e): dependent variable

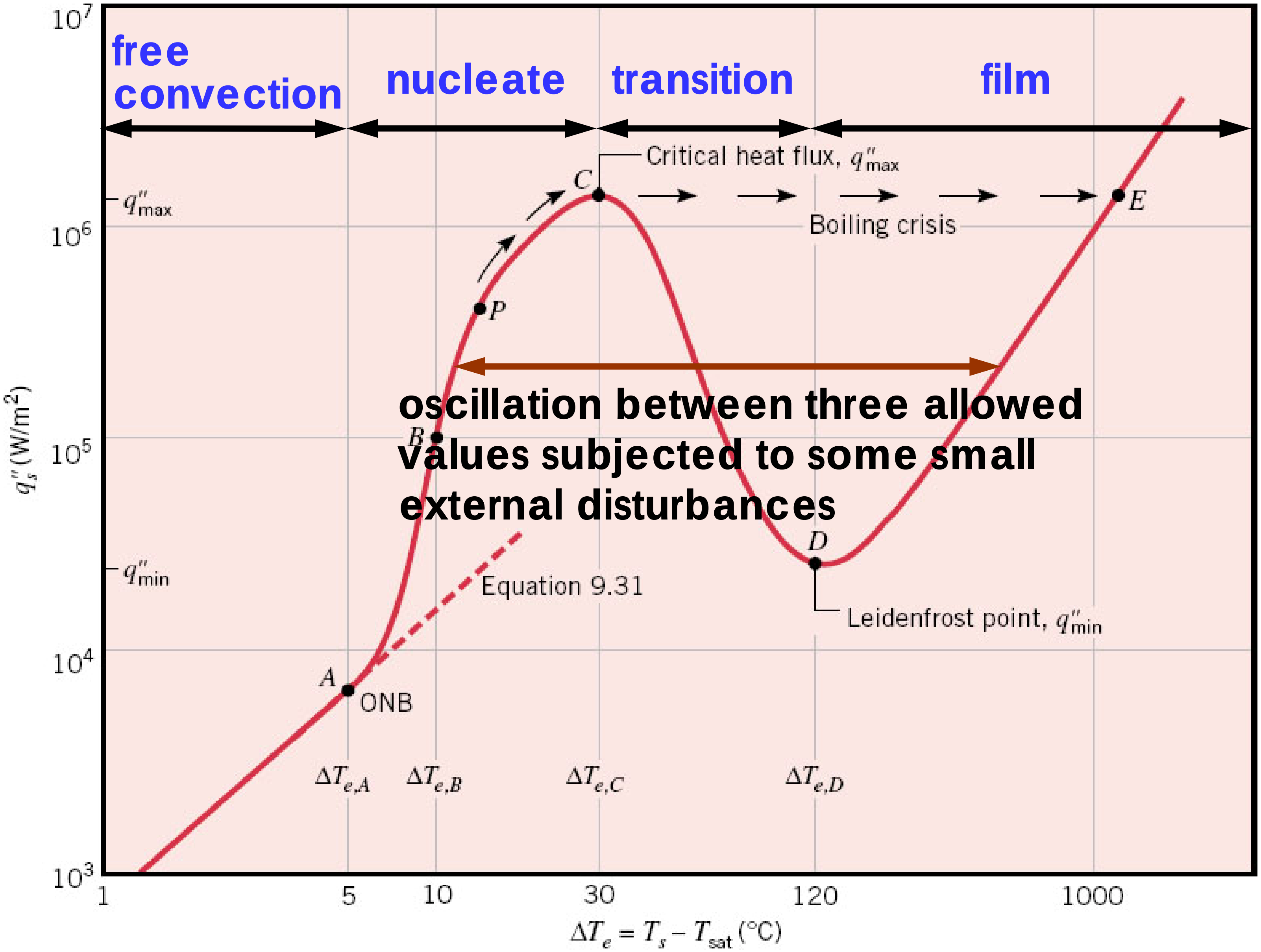
Nukiyama's boiling curve



Nichrome: $T_m = 1500$ K

Platinum: $T_m = 2045$ K

Modes of pool boiling



- **Free convection boiling**

laminar: $h \sim \left(\Delta T_e\right)^{1/4}, \quad q_s'' \sim \left(\Delta T_e\right)^{5/4}$

turbulent: $h \sim \left(\Delta T_e\right)^{1/3}, \quad q_s'' \sim \left(\Delta T_e\right)^{4/3}$

- **Nucleate boiling**

isolated bubbles: heat transfer dominant by fluid mixing near surface

jets or columns: small values of the excess temperature change cause high rates of heat transfer

$$h \sim 10^4 \, \mathrm{W/m^2 \cdot K}$$

- **Transition boiling**

(unstable film boiling, partial film boiling)

blanket begins to form on the surface

oscillation between film and nucleate boiling

$$\frac{\text{film surface}}{\text{total surface}} \propto \text{increase in } \Delta T_e$$

- **Film boiling**

Leidenfrost point: completely covered by a vapor blanket

Heat transfer by conduction only through the vapor film, radiation becomes dominant.

Pool Boiling Correlations

- **Nucleate pool boiling**

number of surface nucleate sites

the rate at which bubble originate from each site

$$\overline{\mathbf{Nu}}_L = C_{fc}\,\mathbf{Re}_L^{m_{fc}}\,\mathbf{Pr}^{n_{fc}}$$

From force balance between buoyancy and surface tension

characteristic length scale: $D_b \propto \sqrt{\dfrac{\sigma}{g\left(\rho_l - \rho_v\right)}}$

characteristic velocity scale:

$$V \propto \frac{D_b}{t_b} \propto \frac{D_b}{\left(\rho_l h_{fg} D_b^3 / q_s'' D_b^2\right)} \propto \frac{q_s''}{\rho_l h_{fg}}$$

t_b**: the time between bubble departures**

correlation for nucleate boiling

Rohsennow (1952)

$$q_s'' = \mu_l h_{fg}\left[\frac{g\left(\rho_l - \rho_v\right)}{\sigma}\right]^{1/2}\left(\frac{c_{p,l}\Delta T_e}{C_{s,f}\, h_{fg}\,\mathrm{Pr}_l^n}\right)^3$$

for $C_{s,f}$ **and** n**: see Table 10.1**

- **Critical heat flux for nucleate boiling**

Operation of a boiling process:

close to the critical point

danger of dissipating heat in excess

Zuber (1958)

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

properties at saturation temperature

large horizontal cylinder, sphere, large finite surfaces: $C = 24/\pi \approx 0.131$ **within 16% deviation**

large horizontal plates: $C = 0.149$

- **Minimum heat flux**

for large horizontal plates

Zuber (1958)

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

properties at saturation temperature

$C = 0.09$ **accurate to about 50%**

- **Film pool boiling**

vapor film blanket: no contact between the liquid phase and the surface

for film boiling on a cylinder or sphere of diameter D

$$\overline{\mathrm{Nu}}_D = \frac{\bar{h}_{\mathrm{conv}} D}{k_v} = C\left[\frac{g(\rho_l - \rho_v) h'_{fg} D^3}{\nu_v k_v (T_s - T_{\mathrm{sat}})}\right]^{1/4}$$

$$h'_{fg} = h_{fg} + 0.80 c_{p,v} (T_s - T_{\mathrm{sat}})$$

properties at film temperature: $T_f = (T_s + T_{\mathrm{sat}})/2$

$C = 0.62$ **for horizontal cylinders**

$C = 0.67$ **for spheres**

at elevated surface temperatures: $T_s \geq 300^{\mathrm{o}}\mathrm{C}$

significant radiation across the vapor film

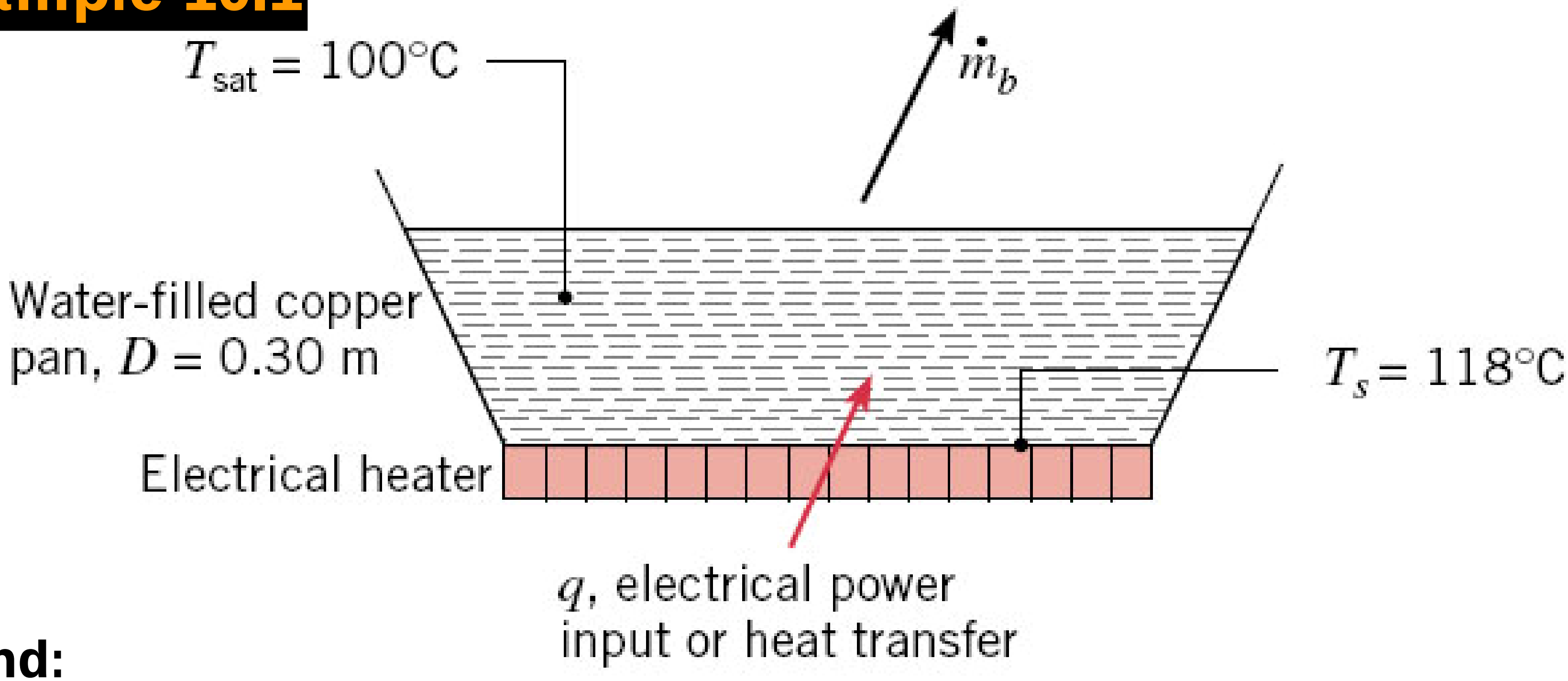
Bromley (1950)

$$\bar{h}^{4/3} = \bar{h}_{\mathrm{conv}}^{4/3} + \bar{h}_{\mathrm{rad}}^{1/3}$$

When $\bar{h}_{\mathrm{rad}} < \bar{h}_{\mathrm{conv}}$, $\bar{h} = \bar{h}_{\mathrm{conv}} + \dfrac{3}{4}\bar{h}_{\mathrm{rad}}$

$$\bar{h}_{\mathrm{rad}} = \frac{\varepsilon\sigma\left(T_s^4 - T_{\mathrm{sat}}^4\right)}{T_s - T_{\mathrm{sat}}}$$

Example 10.1



Find:

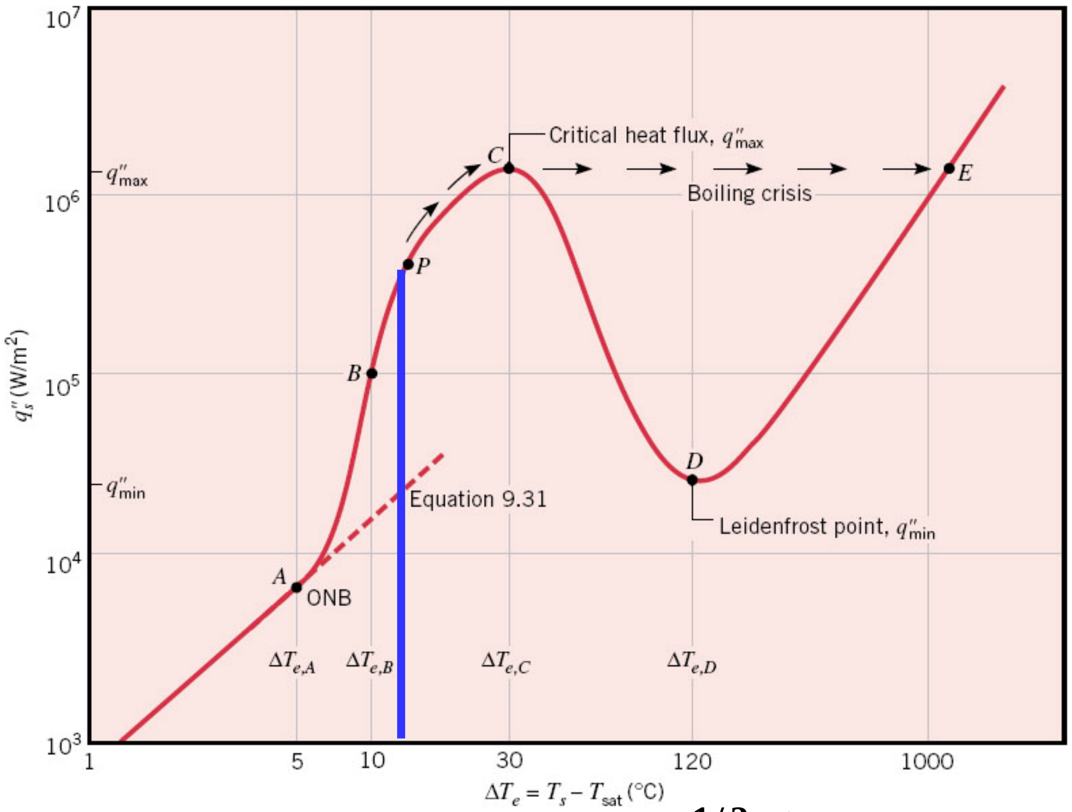
1) **The power required to boil water in the pan,** q_s
2) **Evaporation rate due to boiling,** $\dot{m}_b$
3) **Estimation of critical heat flux,** q''_{max}

Assumption:

Steady-state, atmospheric pressure, water at uniform temperature T_{sat} = 100°C, **large pan bottom: polished copper, negligible heat loss from heater to surroundings**

1) Power

$\Delta T_e = 118 - 100 = 18^\circ\mathrm{C}$: nucleate boiling



properties:

$$\mu_l = 279\times10^{-6}\ \mathrm{N\cdot s/m^2}$$

$$h_{fg} = 2257\ \mathrm{kJ/kg}$$

$$\rho_l = 957.9\ \mathrm{kg/m^3}$$

$$\rho_v = 0.5955\ \mathrm{kg/m^3}$$

$$\sigma = 58.9\times10^{-3}\ \mathrm{N/m}$$

$$c_{p,l} = 4.217\ \mathrm{kJ/kg\cdot K}$$

$$\mathrm{Pr}_l = 1.76$$

From Table 10.1

$$C_{s,f} = 0.0128,\ n = 1.0$$

$$q''_s = \mu_l h_{fg}\left[\frac{g(\rho_l-\rho_v)}{\sigma}\right]^{1/2}\left(\frac{c_{p,l}\Delta T_e}{C_{s,f}h_{fg}\mathrm{Pr}_l^n}\right)^3 = 836\ \mathrm{kW/m^2}$$

$$q_s = q''_s A = q''_s\frac{\pi D^2}{4} = 59.1\ \mathrm{kW}$$

2) Evaporation rate

$$q_s = \dot{m}_b h_{fg}$$

$$\dot{m}_b = \frac{q_s}{h_{fg}} = 0.0262 \text{ kg/s} = 94 \text{ kg/h}$$

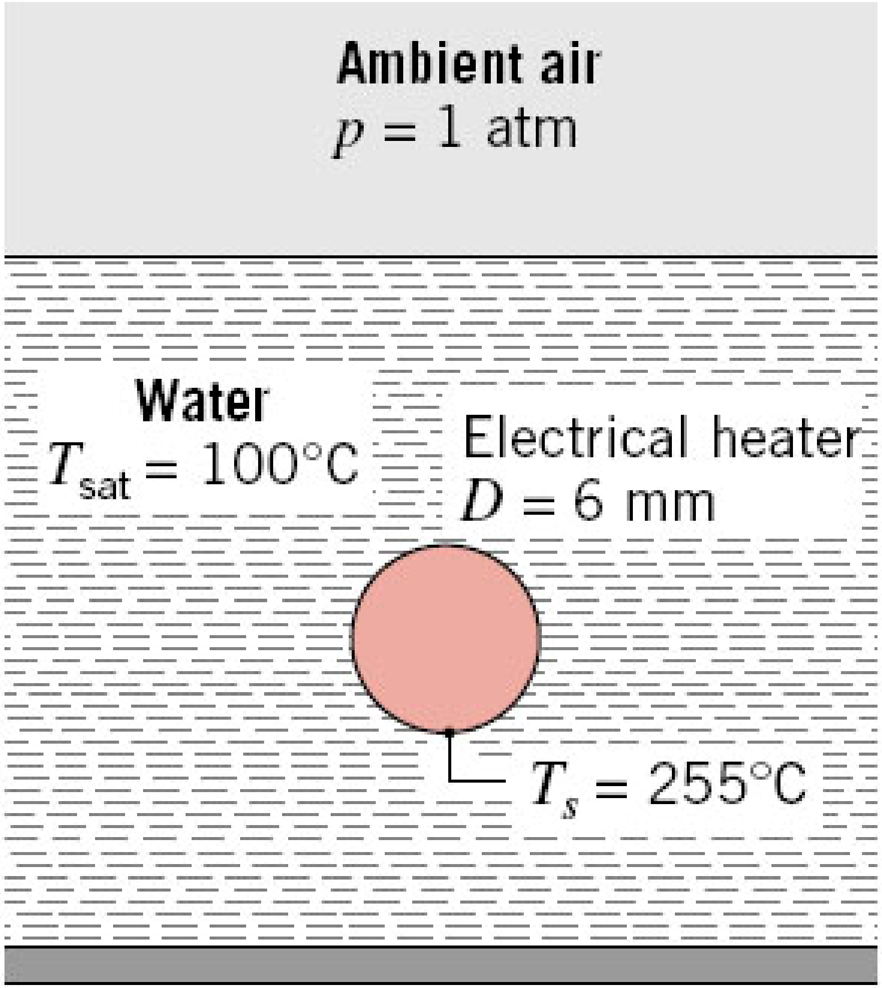
3) Critical heat flux

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

$C = 0.149$ for large horizontal plate

$$q''_{\max} = 1.26 \text{ MW/m}^2$$

Example 10.2

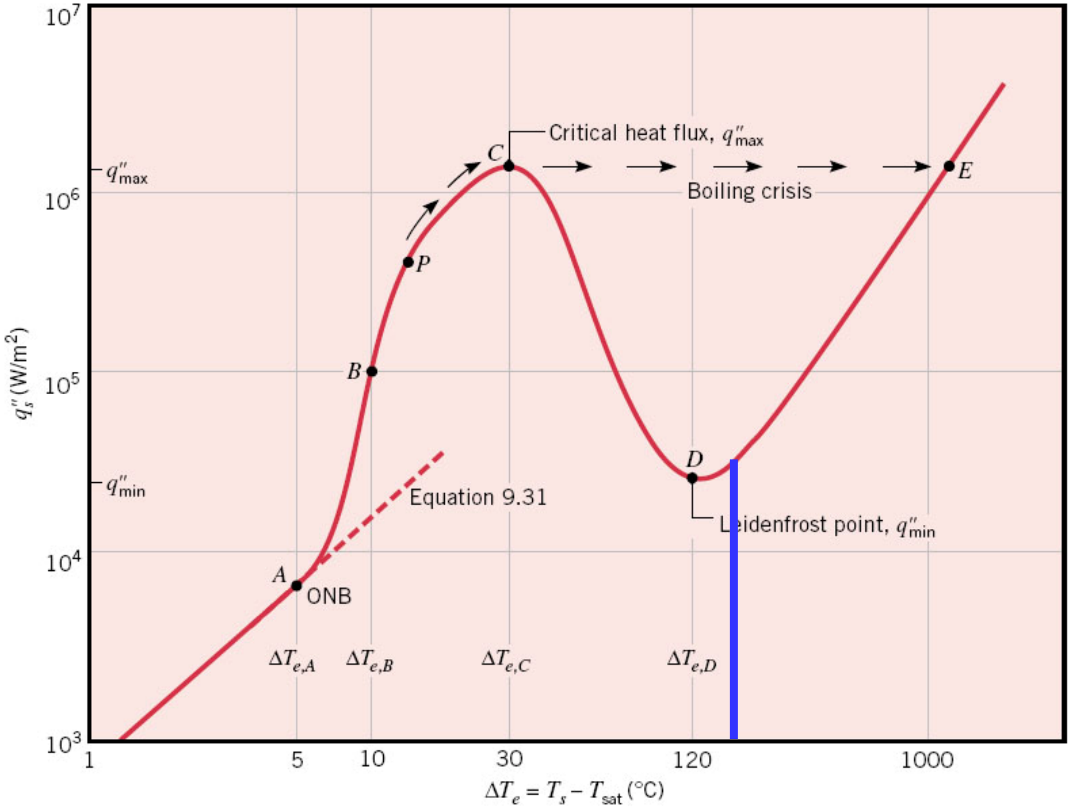


Find: Power dissipation per unit length for the cylinder, q_s'

Assumption:

Steady-state, atmospheric pressure, water at uniform temperature T_{sat} = 100C,

$$\Delta T_e = 255 - 100 = 155^\circ\text{C}$$: film boiling



$$q'_s = q''_s(\pi D)$$

$$= \bar{h}(\pi D)\Delta T_e$$

$$\bar{h}^{4/3} = \bar{h}_{\text{conv}}^{4/3} + \bar{h}_{\text{rad}}^{1/3}$$

$$\bar{h}_{\text{rad}} = \frac{\varepsilon\sigma\left(T_s^4 - T_{\text{sat}}^4\right)}{T_s - T_{\text{sat}}}$$

$$\overline{\text{Nu}}_D = \frac{\bar{h}_{\text{conv}} D}{k_v} = C\left[\frac{g(\rho_l - \rho_v)h'_{fg}D^3}{\nu_v k_v (T_s - T_{\text{sat}})}\right]^{1/4},$$

$$h'_{fg} = h_{fg} + 0.80 c_{p,v}(T_s - T_{\text{sat}})$$

properties:

$$\rho_l = 1/v_f = 957.9\ \text{kg/m}^3,\ h_{fg} = 2257\ \text{kJ/kg},\ \rho_v = 0.4902\ \text{kg/m}^3,$$

$$c_{p,v} = 1.980\ \text{kJ/kg}\cdot\text{K},\ k_v = 0.0299\ \text{W/m}\cdot\text{K},\ \mu_v = 279\times10^{-6}\ \text{N}\cdot\text{s/m}^2$$

$$\bar{h}_{\text{conv}} = \frac{k_v}{D}C\left[\frac{g\left(\rho_l - \rho_v\right)h'_{fg}D^3}{\nu_v k_v\left(T_s - T_{\text{sat}}\right)}\right]^{1/4} = 238\ \text{W/m}^2\cdot\text{K}$$

$$\bar{h}_{\text{rad}} = \frac{\varepsilon\sigma\left(T_s^4 - T_{\text{sat}}^4\right)}{T_s - T_{\text{sat}}} = 21.3\ \text{W/m}^2\cdot\text{K}$$

$$\bar{h}^{4/3} = 238^{4/3} + 21.3^{1/3}$$

$$\bar{h} = 254.1\ \text{W/m}^2\cdot\text{K}$$

$$q'_s = \bar{h}\left(\pi D\right)\Delta T_e = 742\ \text{W/m}$$

Forced Convection Boiling

- **External flow**
- **Internal flow: Two-phase flow**

- **External forced convection boiling**

effect of forced convection and subcooling:

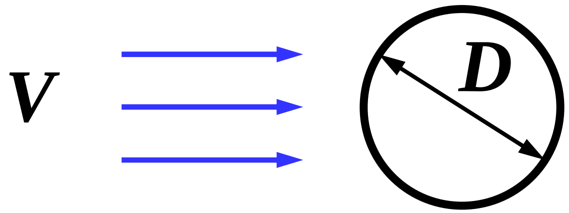
increase the critical heat flux

Ex) water at 1 atm

pool boiling: 1.3 MW/m^2

convection boiling: 35 MW/m^2

for a crossflow over a cylinder of diameter D



low velocity: $$\frac{q''_{\max}}{\rho_v h_{fg} V} = \frac{1}{\pi}\left[1 + \left(\frac{4}{\mathrm{We}_D}\right)^{1/3}\right]$$

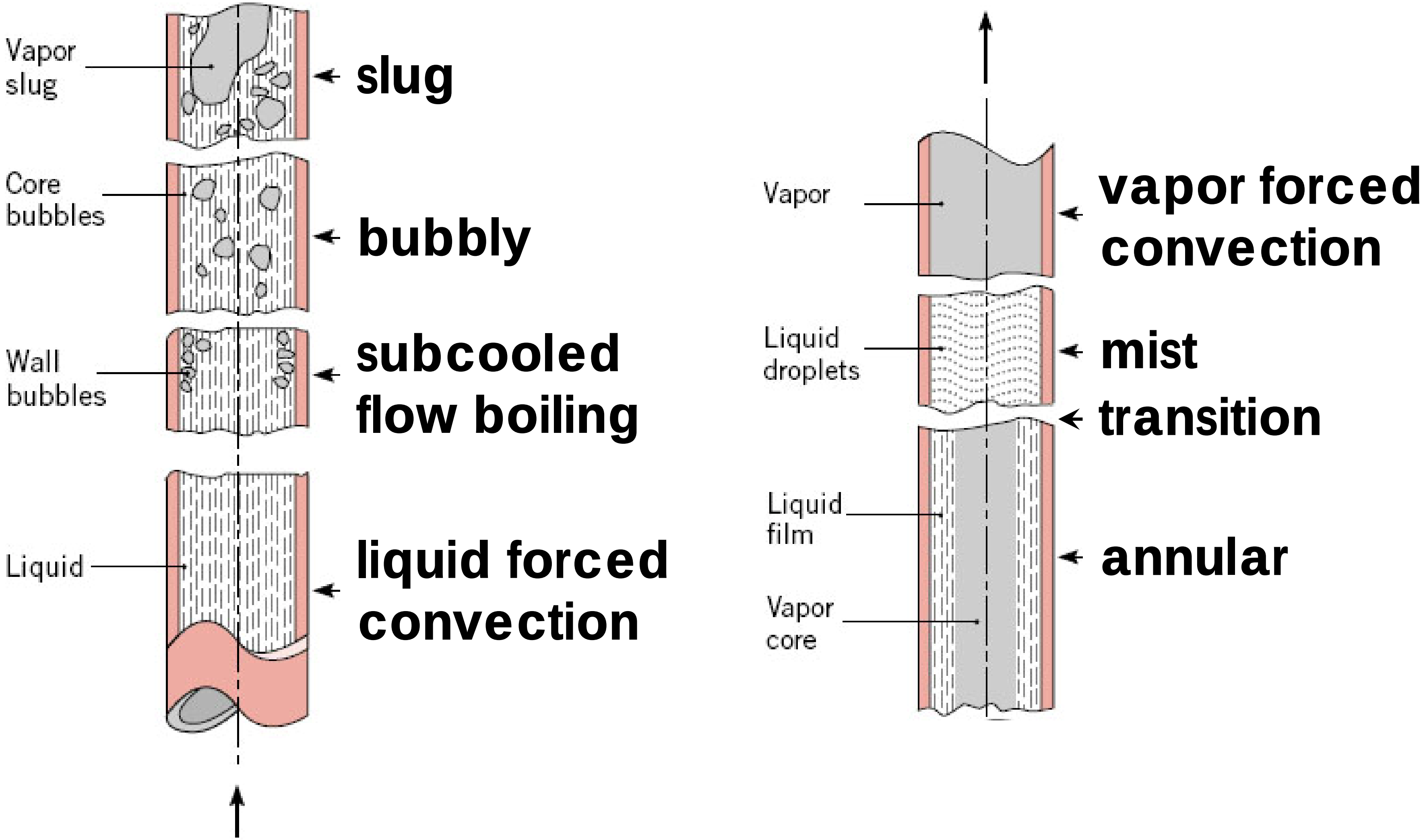
high velocity: $$\frac{q''_{\max}}{\rho_v h_{fg} V} = \frac{\left(\rho_l / \rho_v\right)^{3/4}}{169\pi} + \frac{\left(\rho_l / \rho_v\right)^{1/2}}{19.2\pi \mathrm{We}_D^{1/3}}$$

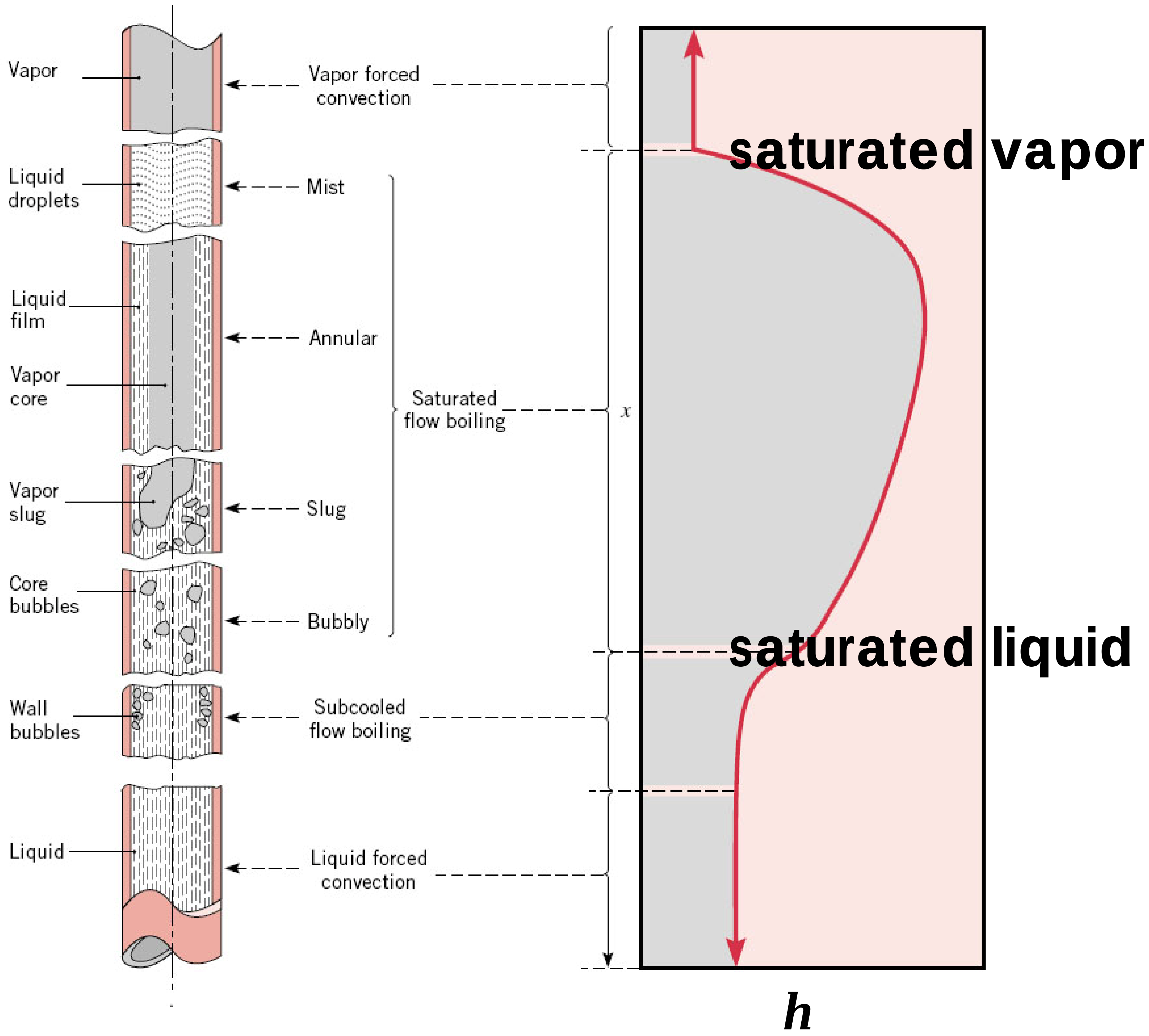
Weber number: $$\mathrm{We}_D = \frac{\rho_v V^2 D}{\sigma} = \frac{\text{inertia force}}{\text{surface tension}}$$

high and low velocity region: $$\frac{q''_{\max}}{\rho_v h_{fg} V} \gtrless \frac{0.275}{\pi}\left(\frac{\rho_l}{\rho_v}\right)^{1/2} + 1$$

- **Two-phase flow**

vertical tube subjected to a constant heat flux





Vapor
Liquid droplets
Liquid film
Vapor core
Vapor slug
Core bubbles
Wall bubbles
Liquid
Vapor forced convection
Mist
Annular
Slug
Bubbly
Saturated flow boiling
Subcooled flow boiling
Liquid forced convection
x
saturated vapor
saturated liquid
h

for saturated boiling region in smooth circular tube

choose larger values of *h* $0 < \bar{X} \le 0.8$

$$\frac{h}{h_{sp}} = 0.6683\left(\frac{\rho_l}{\rho_v}\right)^{0.1} \bar{X}^{0.16}\left(1-\bar{X}\right)^{0.64} f(\mathrm{Fr}) + 1058\left(\frac{q_s''}{\dot{m}''h_{fg}}\right)^{0.7}\left(1-\bar{X}\right)^{0.8} G_{s,f}$$

$$\frac{h}{h_{sp}} = 1.136\left(\frac{\rho_l}{\rho_v}\right)^{0.45} \bar{X}^{0.72}\left(1-\bar{X}\right)^{0.0.08} f(\mathrm{Fr}) + 667.2\left(\frac{q_s''}{\dot{m}''h_{fg}}\right)^{0.7}\left(1-\bar{X}\right)^{0.8} G_{s,f}$$

h_{sp}: associated with liquid forced convection region

$$\dot{m}'' = \dot{m} / A_c$$

$$\mathrm{Nu}_D = \frac{h_{sp}D}{k_l} = \frac{(f/8)(\mathrm{Re}_D - 1000)\mathrm{Pr}}{1 + 12.7(f/8)^{1/2}\left(\mathrm{Pr}^{2/3} - 1\right)}$$

all properties: at saturation temperature

$$\bar{X} \equiv \frac{\int_{A_c} \rho u(r,x) X dA_c}{\dot{m}}$$

X: time average mass fraction of vapor in fluid

For negligible changes in fluid's kinetic and potential energy, and negligible work

$$\bar{X}(x) = \frac{q_s'' \pi D x}{\dot{m} h_{fg}}$$

$G_{s,f}$: Surface-liquid combination

Values of $G_{s,f}$ for various surface-liquid combination

Fluid in Commercial Copper Tubing	$G_{s,f}$
Kerosene	0.488
Refrigerant R-134a	1.63
Refrigerant R-152a	1.10
Water	1.00
For stainless steel tubing, use $G_{s,f} = 1$.	

$f(\mathrm{Fr})$: stratification parameter

Froude number: $\mathrm{Fr} = \dfrac{\left(\dot{m}'' / \rho_l\right)^2}{gD}$

$f(\mathrm{Fr}) = 1$: for vertical tubes and for horizontal tubes with $\mathrm{Fr} \geq 0.04$

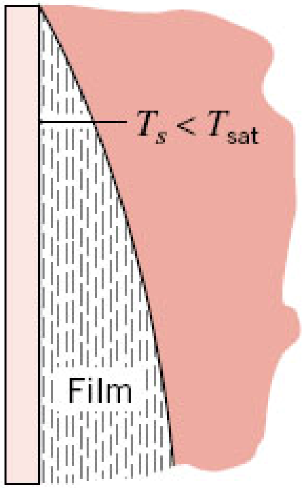
$f(\mathrm{Fr}) = 2.63\mathrm{Fr}^{0.3}$ for horizontal tubes with $\mathrm{Fr} \leq 0.04$

Applicable when channel dimension is large relative to bubble diameter

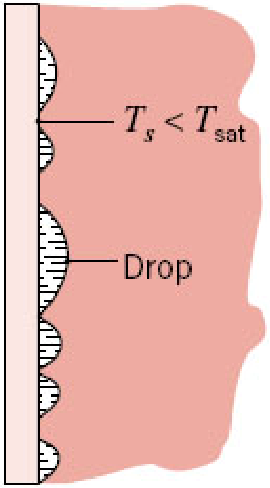
$$\mathrm{Co} = \sqrt{\frac{\sigma / g\left(\rho_l - \rho_v\right)}{D_h}} \leq \frac{1}{2}$$

Co: Confinement number

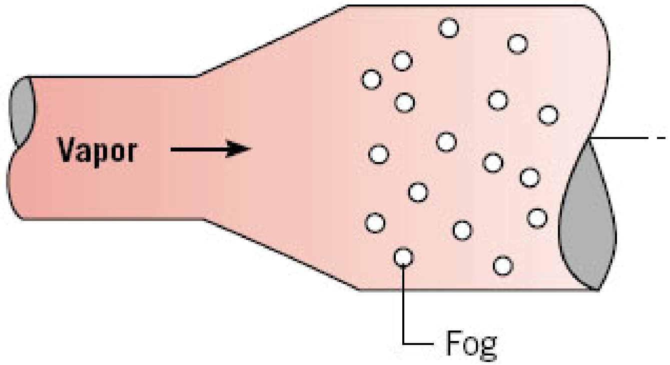
Condensation



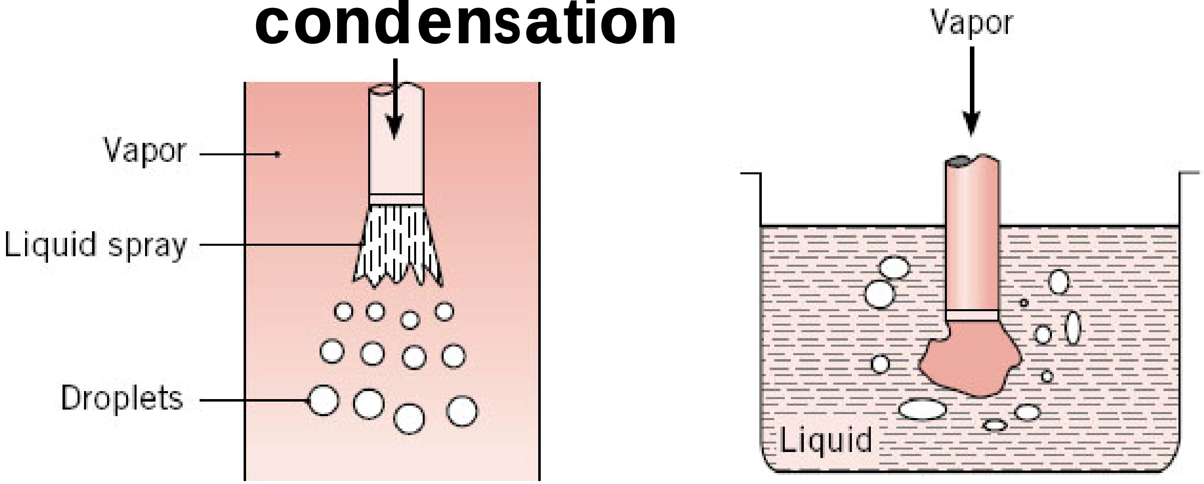
film



Dropwise condensation



Homogeneous condensation



Direct contact condensation

- **Condensation thickness: thermal resistance between vapor and surface**

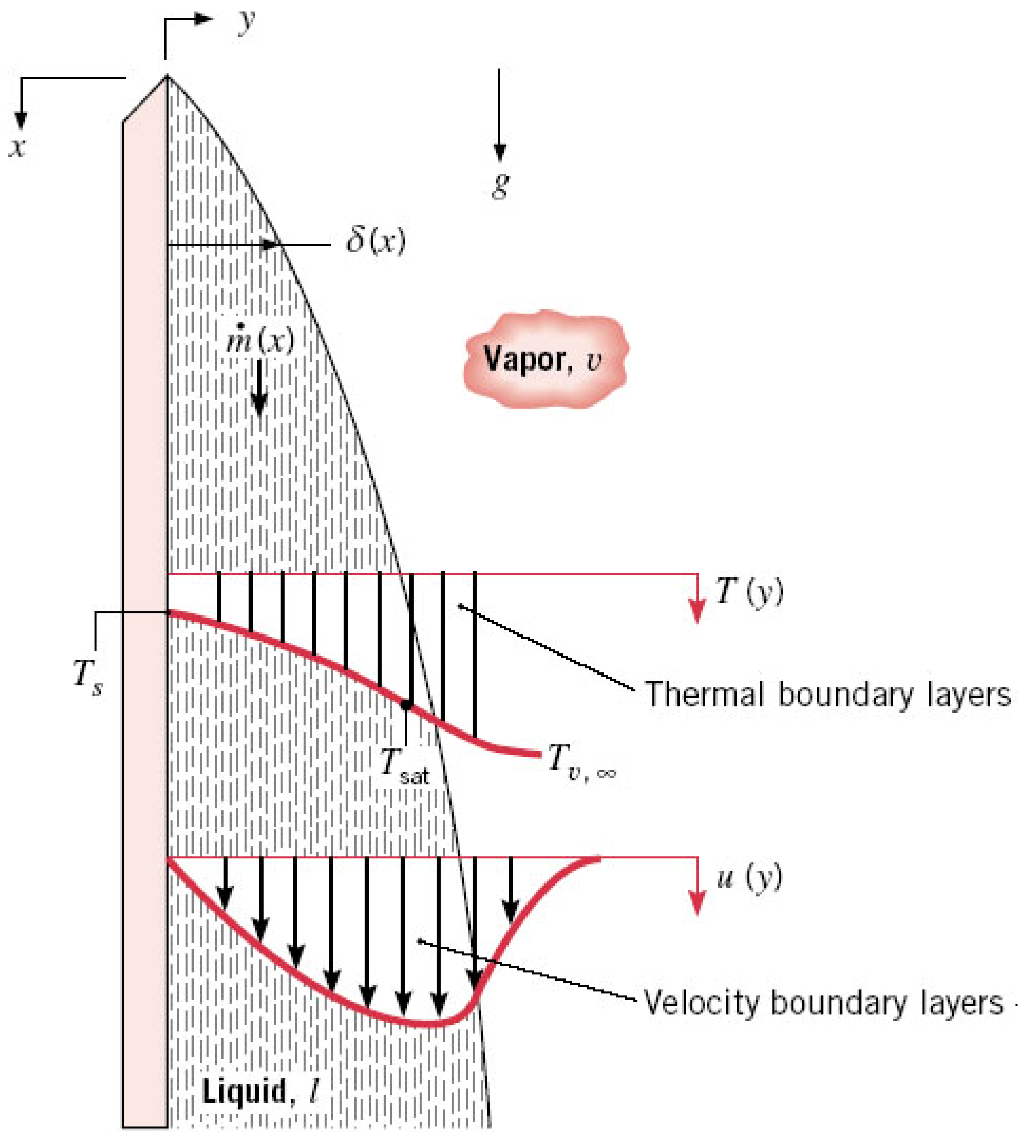
  → horizontal tube bundles preferred

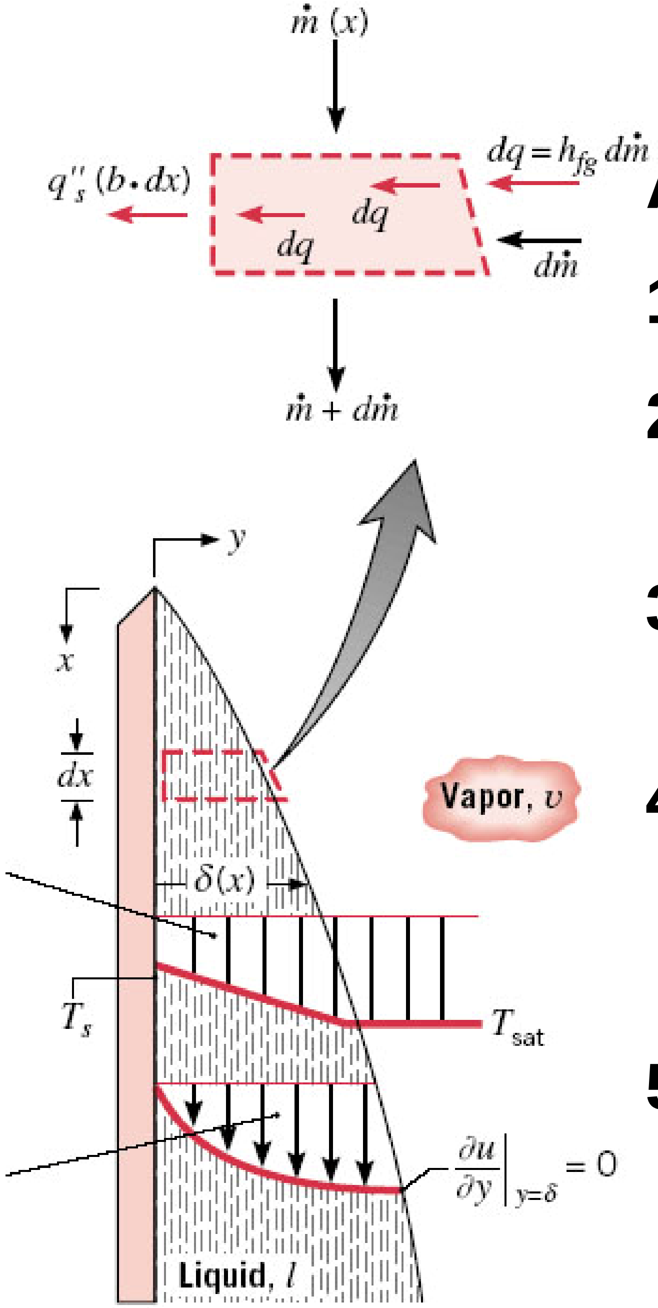
- **Dropwise condensation: favorable to heat transfer**

  → surface coatings to inhibit wetting

- **Condensation design: often based on film condensation**

- **Laminar film condensation on a vertical plate**





Nusselt (1916)

Assumptions

1) Laminar flow, constant properties

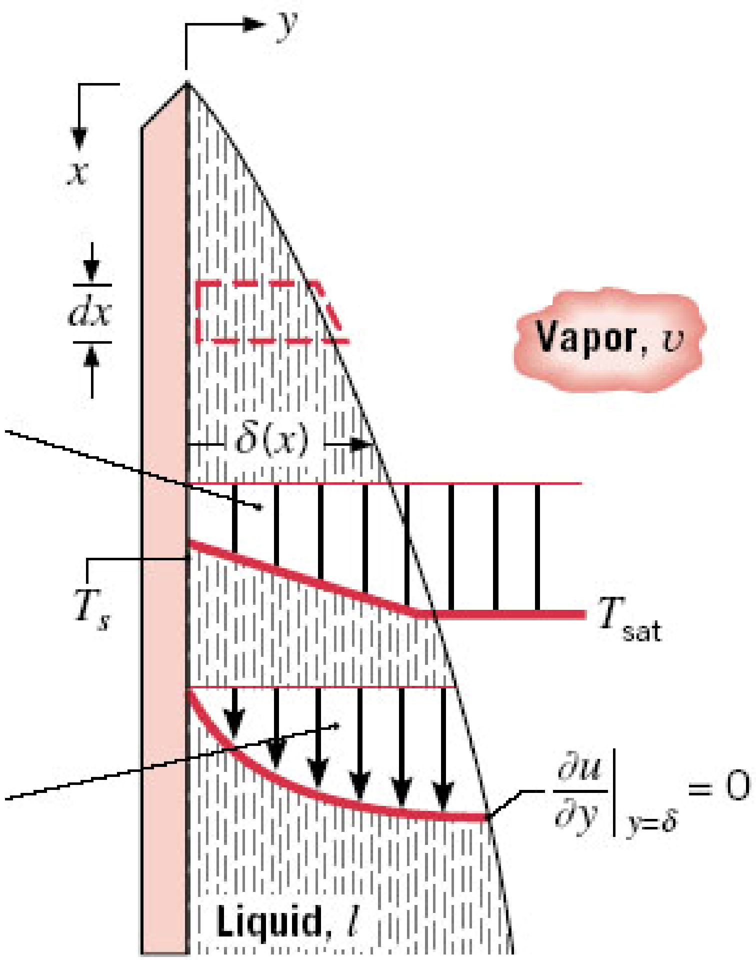
2) Gas: pure vapor and uniform temperature at T_{sat}

3) Heat transfer only by condensation (neglect conduction)

4) Negligible Momentum and energy transfer by advection (low film flow velocity)

5) $\left.\frac{\partial u}{\partial y}\right)_{y=\delta} = 0$

Momentum and energy conservation



x- momentum equation

$$0 = \mu_l \frac{\partial^2 u}{\partial y^2} - \frac{dp}{dx} + \rho_l g$$

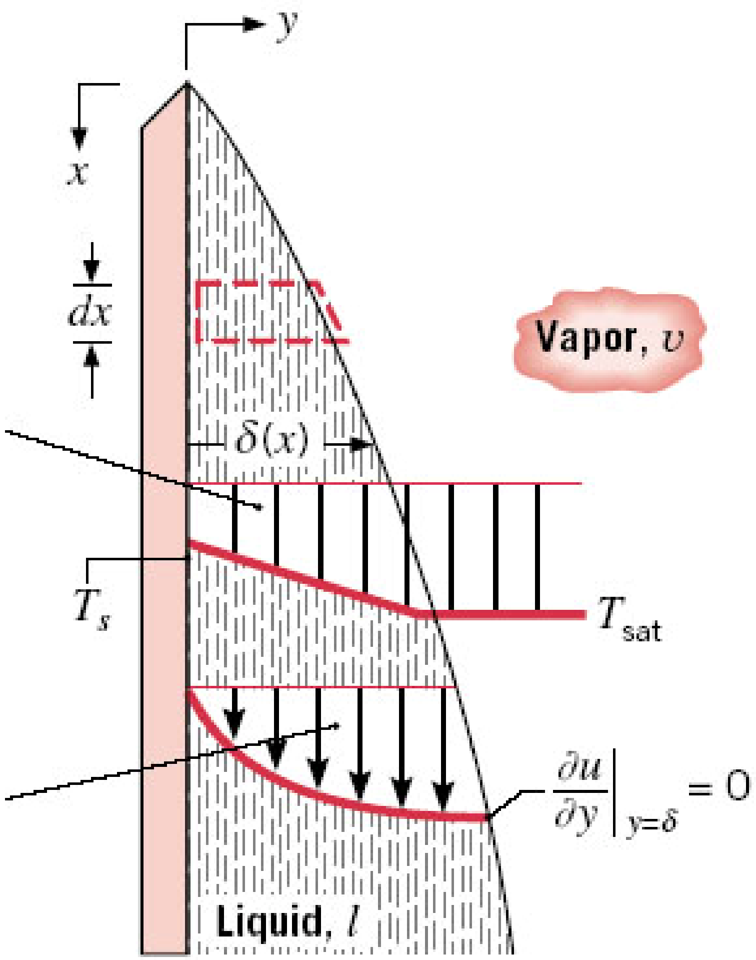
$$\frac{dp}{dx} = \rho_v g$$

$$\frac{\partial^2 u}{\partial y^2} = -\frac{g}{\mu_l}\left(\rho_l - \rho_v\right)$$

viscous force ~ buoyancy force

$$u(0) = 0, \left.\frac{\partial u}{\partial y}\right)_{y=\delta} = 0$$

$$u(x,y)=\frac{g(\rho_l-\rho_v)\delta^2}{\mu_l}\left[\frac{y}{\delta}-2\left(\frac{y}{\delta}\right)^2\right]$$

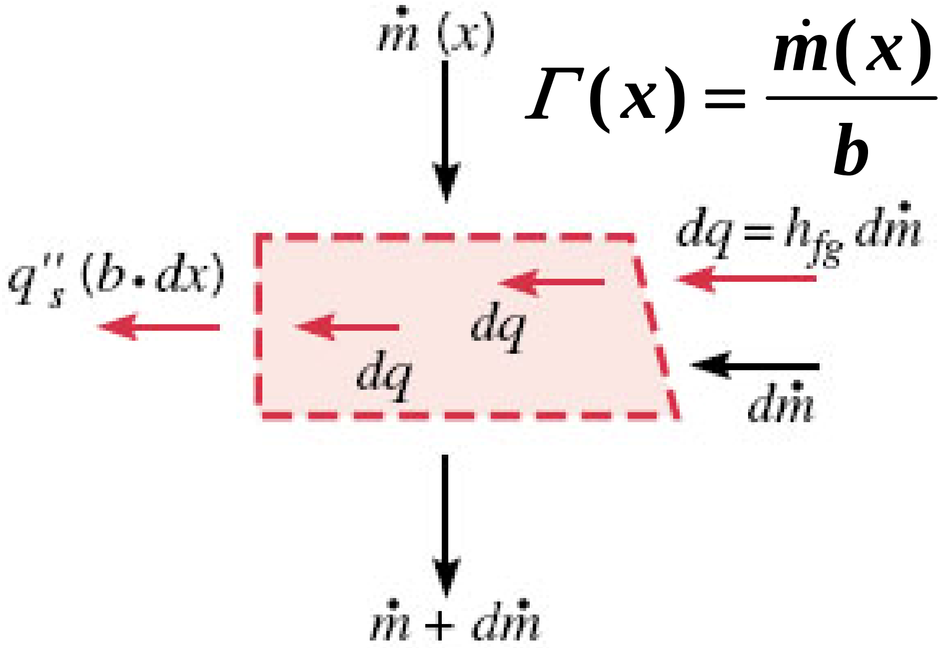


condensate mass flow rate per unit width

$$\frac{\dot{m}(x)}{b}=\Gamma(x)=\int_0^{\delta(x)}\rho_l u(x,y)dy$$

Then,

$$\Gamma(x)=\frac{g\rho_l(\rho_l-\rho_v)\delta^3}{3\mu_l}$$



$$\Gamma(x)=\frac{\dot m(x)}{b}$$

energy conservation

$$dq=h_{fg}d\dot m=q_s''\left(bdx\right)$$

$$q_s''=\frac{k_l\left(T_{sat}-T_s\right)}{\delta}$$

$$q_s''=h_{fg}\frac{1}{b}\frac{d\dot m}{dx}=h_{fg}\frac{d}{dx}\left(\frac{\dot m}{b}\right)=h_{fg}\frac{d\Gamma}{dx}\rightarrow\frac{d\Gamma}{dx}=\frac{q_s''}{h_{fg}}$$

$$\frac{d\Gamma}{dx}=\frac{k_l\left(T_{sat}-T_s\right)}{\delta h_{fg}}\qquad\left[\Gamma(x)=\frac{g\rho_l\left(\rho_l-\rho_v\right)\delta^3}{3\mu_l}\right]$$

$$\frac{d\Gamma}{dx}=\frac{k_l\left(T_{sat}-T_s\right)}{\delta h_{fg}}=\frac{g\rho_l\left(\rho_l-\rho_v\right)\delta^2}{\mu_l}\frac{d\delta}{dx}$$

$$\frac{g\rho_l\left(\rho_l-\rho_v\right)\delta^2}{\mu_l}\frac{d\delta}{dx}=\frac{k_l\left(T_{\mathrm{sat}}-T_s\right)}{\delta h_{fg}}$$

$$\delta^3 d\delta=\frac{k_l\mu_l\left(T_{\mathrm{sat}}-T_s\right)}{g\rho_l\left(\rho_l-\rho_v\right)h_{fg}}dx$$

$$\delta(x)=\left[\frac{4k_l\mu_l\left(T_{\mathrm{sat}}-T_s\right)x}{g\rho_l\left(\rho_l-\rho_v\right)h_{fg}}\right]^{1/4}$$

sensible heat transfer correction

$$h'_{fg}=h_{fg}\left(1+0.68\mathrm{Ja}\right),\quad \mathrm{Ja}=\frac{c_p\Delta T}{h_{fg}}$$

$$q_s'' = h_x\left(T_{\text{sat}} - T_s\right) = \frac{k_l\left(T_{\text{sat}} - T_s\right)}{\delta} \rightarrow h_x = \frac{k_l}{\delta}$$

$$\delta(x) = \left[\frac{4k_l\mu_l\left(T_{\text{sat}} - T_s\right)x}{g\rho_l\left(\rho_l - \rho_v\right)h_{fg}}\right]^{1/4}$$

$$h_x = \left[\frac{g\rho_l\left(\rho_l - \rho_v\right)k_l^3 h'_{fg}}{4\mu_l\left(T_{\text{sat}} - T_s\right)x}\right]^{1/4}, \quad \bar{h}_L = \frac{1}{L}\int_0^L h_x dx = \frac{4}{3}h_L$$

$$\bar{h}_L = 0.943\left[\frac{g\rho_l\left(\rho_l - \rho_v\right)k_l^3 h'_{fg}}{\mu_l\left(T_{\text{sat}} - T_s\right)L}\right]^{1/4}$$

$$\overline{\text{Nu}}_L = \frac{\bar{h}_L L}{k_l} = 0.943\left[\frac{g\rho_l\left(\rho_l - \rho_v\right)h'_{fg}L^3}{\mu_l k_l\left(T_{\text{sat}} - T_s\right)}\right]^{1/4}$$

$$\overline{\mathrm{Nu}}_L = \frac{\bar{h}_L L}{k_l} = 0.943\left[\frac{g\rho_l\left(\rho_l - \rho_v\right)h'_{fg}L^3}{\mu_l k_l\left(T_{\mathrm{sat}} - T_s\right)}\right]^{1/4}$$

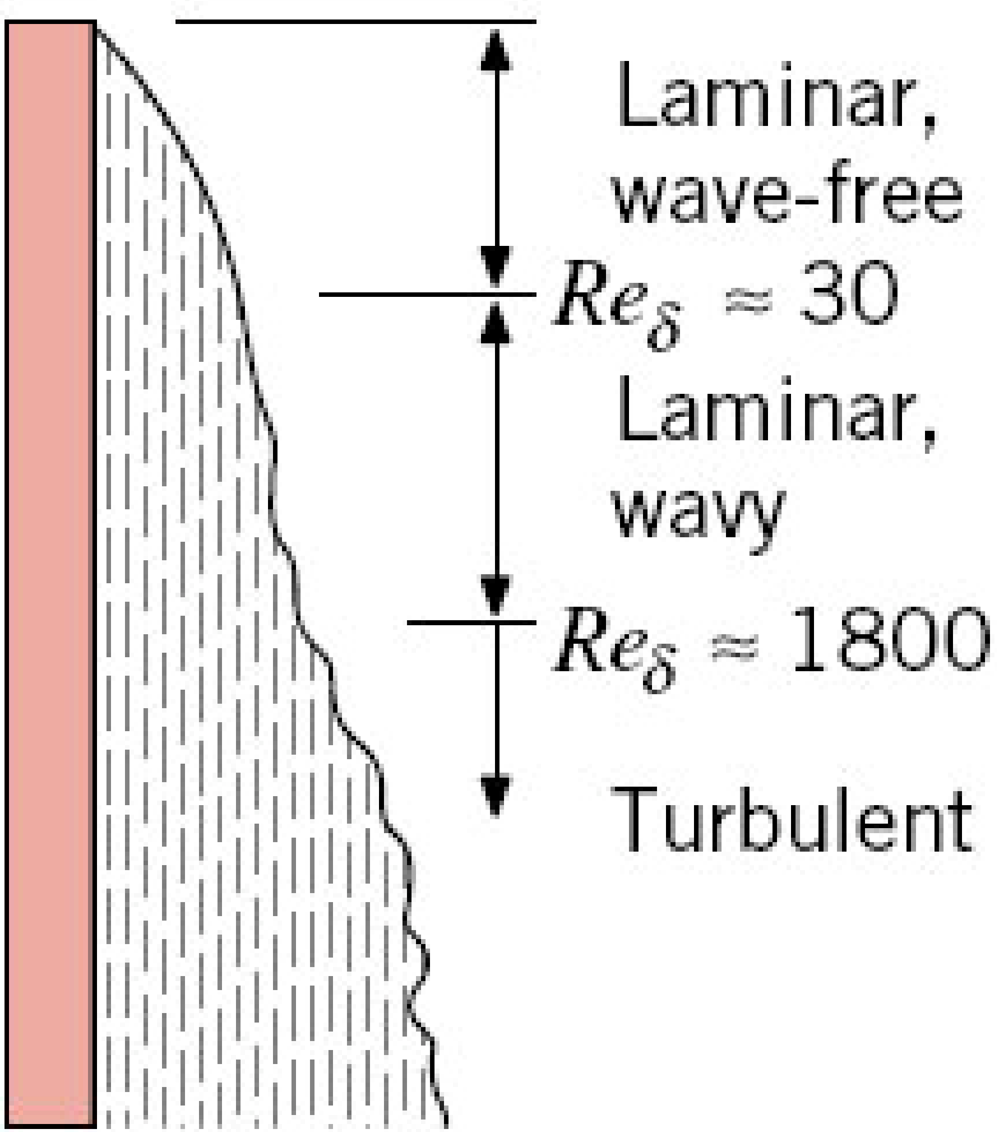
liquid properties at film temperature

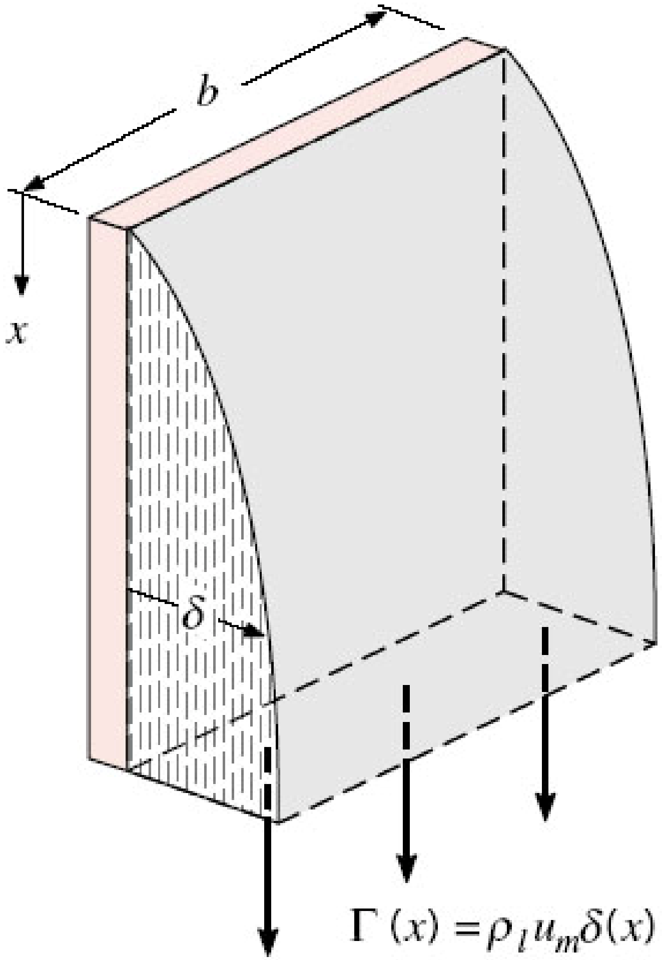
$$T_f = \frac{T_{\mathrm{sat}} + T_s}{2}$$

h_{fg}: at T_{sat}

- inclined plate: $g \to g\cos\theta$
- tube: $R >> \delta$

- **Turbulent film condensation**





mass flow per unit depth

$$\Gamma(x) = \rho_l u_m \delta(x)$$

$$\mathrm{Re}_\delta \equiv \frac{4\Gamma}{\mu_l}$$

- **Wave-free laminar region**

$$\Gamma(x) = \frac{g\rho_l\left(\rho_l - \rho_v\right)\delta^3}{3\mu_l}$$

$$\mathrm{Re}_\delta = \frac{4g\rho_l\left(\rho_l - \rho_v\right)\delta^3}{3\mu_l^2}$$

assuming $\rho_l >> \rho_v$

$$\delta(x) = \left[\frac{4k_l\mu_l\left(T_{\text{sat}} - T_s\right)x}{g\rho_l\left(\rho_l - \rho_v\right)h_{fg}}\right]^{1/4}$$

$$\bar{h}_L = 0.943\left[\frac{g\rho_l\left(\rho_l - \rho_v\right)k_l^3 h'_{fg}}{\mu_l\left(T_{\text{sat}} - T_s\right)L}\right]^{1/4}$$

$$\frac{\bar{h}_L\left(\nu_l^2/g\right)^{1/3}}{k_l} = 1.47\,\text{Re}_\delta^{-1/3} \qquad \left(\text{Re}_\delta \le 30\right)$$

$$\text{Re}_\delta = 3.78\left[\frac{k_l L\left(T_{\text{sat}} - T_s\right)}{\mu_l h'_{fg}\left(\nu_l^2/g\right)^{1/3}}\right]^{3/4}$$

- **Laminar wavy region** $30 \le \mathrm{Re}_\delta \le 1800$

$$\frac{\bar{h}_L \left(\nu_l^2 / g\right)^{1/3}}{k_l} = \frac{\mathrm{Re}_\delta}{1.08\,\mathrm{Re}_\delta^{1.22} - 5.2}$$

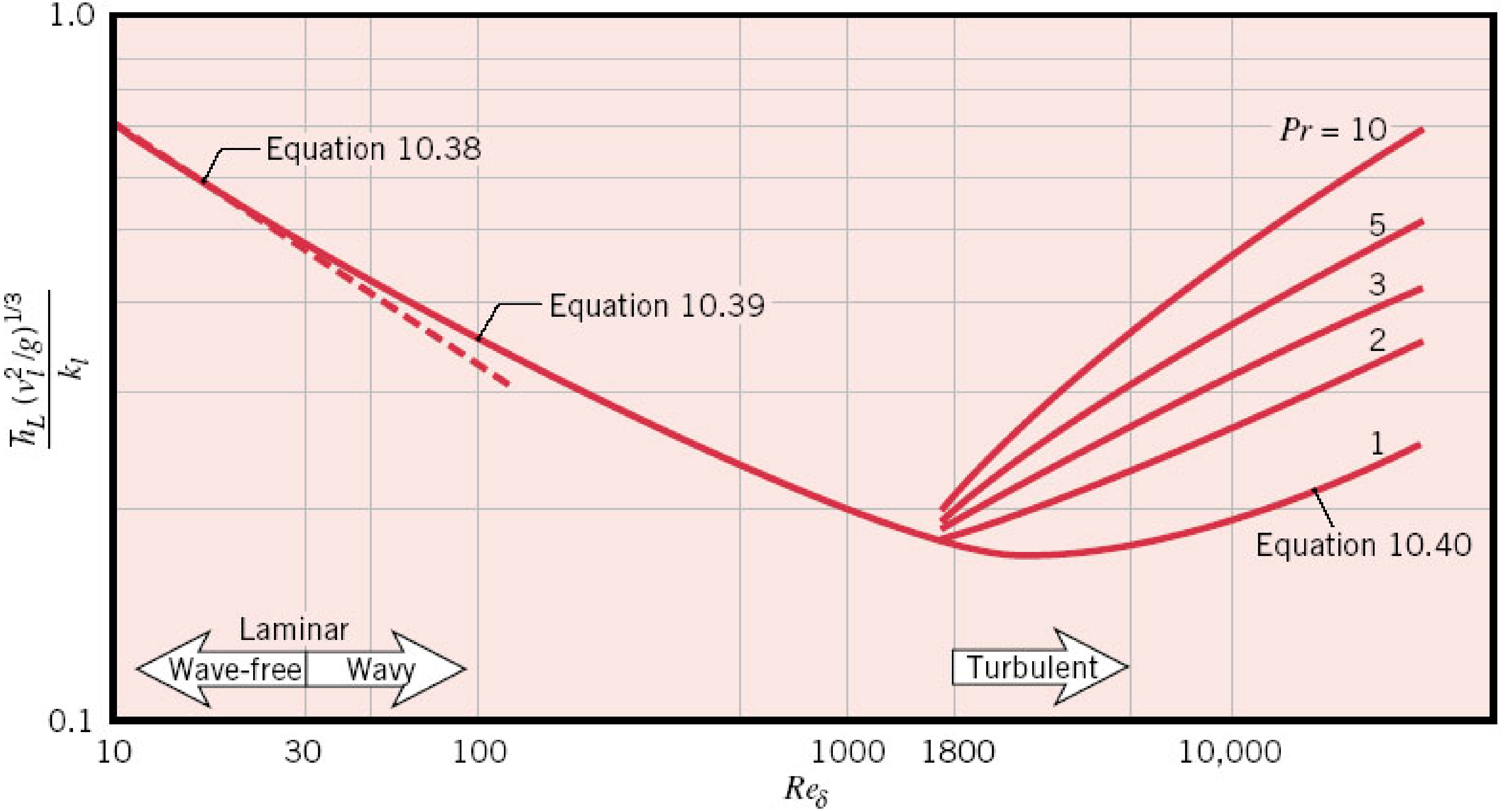
$$\mathrm{Re}_\delta = \left[\frac{3.70 k_l L \left(T_{\mathrm{sat}} - T_s\right)}{\mu_l h'_{fg} \left(\nu_l^2 / g\right)^{1/3}} + 4.8\right]^{0.82}$$

- **Turbulent region** $\mathrm{Re}_\delta \ge 1800$

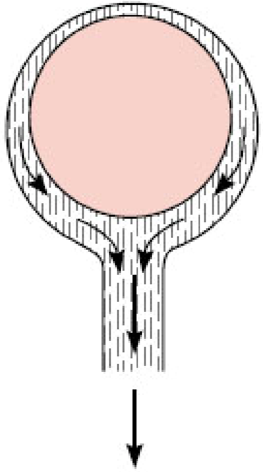
$$\frac{\bar{h}_L \left(\nu_l^2 / g\right)^{1/3}}{k_l} = \frac{\mathrm{Re}_\delta}{8750 + 58\,\mathrm{Pr}^{-0.5}\left(\mathrm{Re}_\delta^{0.75} - 253\right)}$$

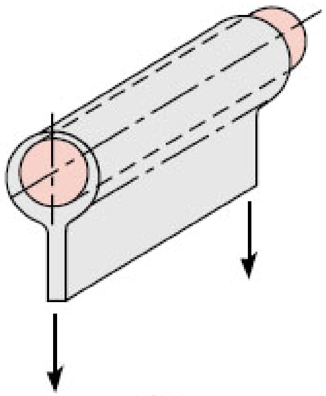
$$\mathrm{Re}_\delta = \left[\frac{0.069 k_l L \left(T_{\mathrm{sat}} - T_s\right)}{\mu_l h'_{fg} \left(\nu_l^2 / g\right)^{1/3}} \mathrm{Pr}_l^{0.5} - 151\,\mathrm{Pr}_l^{0.5} + 253\right]^{4/3}$$

Modified Nusselt number for condensation on a vertical plate



• Film condensation on radial system

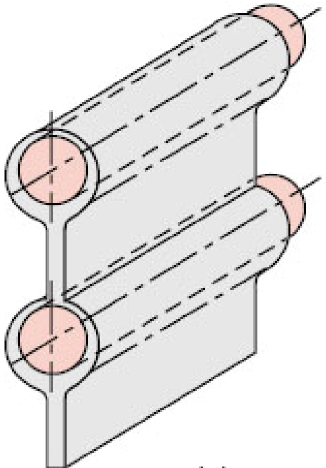

(a)

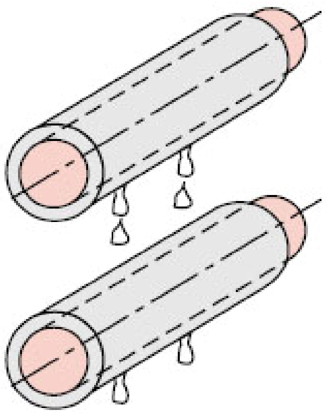

(b)

$$\bar{h}_D = C\left[\frac{g\rho_l(\rho_l-\rho_v)k_l^3 h'_{fg}}{\mu_l(T_{sat}-T_s)D}\right]^{1/4}$$

C = 0.826 for sphere

C = 0.729 for tube


(c)

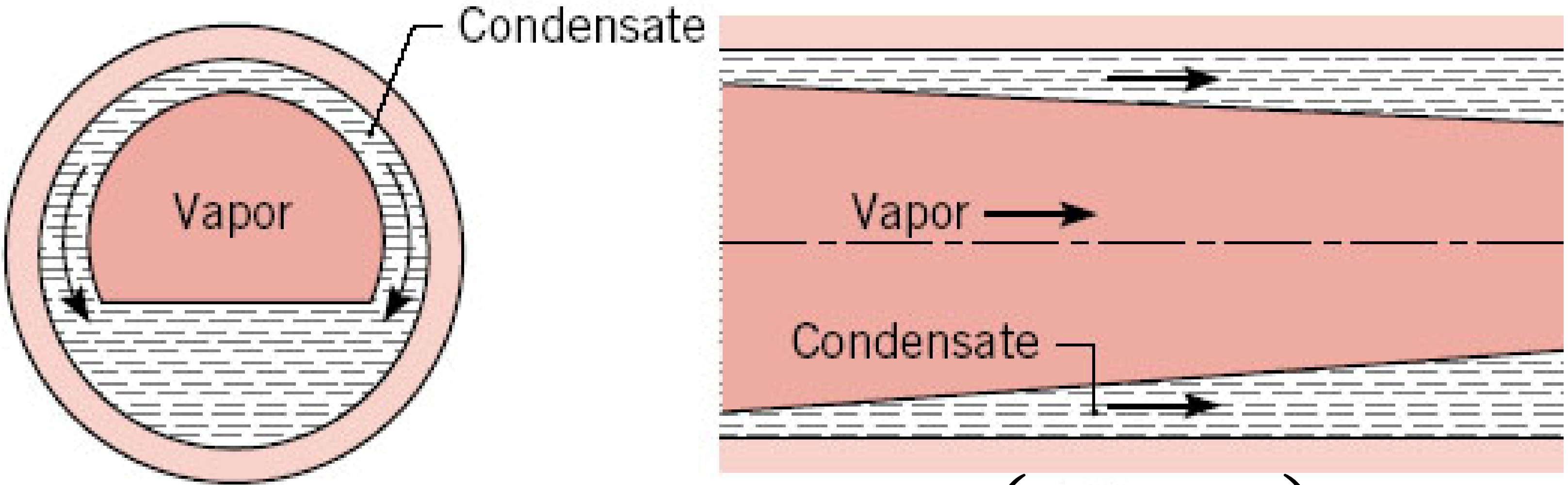

(d)

- a vertical tier of N tubes

$$\bar{h}_{D,N} = 0.729\left[\frac{g\rho_l(\rho_l-\rho_v)k_l^3 h'_{fg}}{N\mu_l(T_{sat}-T_s)D}\right]^{1/4}$$

$$\bar{h}_{D,N} = \bar{h}_D N^{-1/4}$$

- **Film Condensation in Horizontal Tubes**



for low vapor velocities $\mathrm{Re}_{v,i} = \left(\frac{\rho_v u_{m,v} D}{\mu_v}\right) < 35{,}000$

$$\bar{h}_D = 0.555\left[\frac{g\rho_l(\rho_l - \rho_v)k_l^3 h'_{fg}}{\mu_l(T_{\text{sat}} - T_s)D}\right]^{1/4}$$

$$h'_{fg} \equiv h_{fg} + \frac{3}{8}c_{p,l}(T_{\text{sat}} - T_s)$$

- **Dropwise Condensation**

steam condensation on copper surface

$$\bar{h}_{\mathrm{dc}} = 51{,}104 + 2044 T_{\mathrm{sat}}\,(^\circ\mathrm{C}) \qquad 22^\circ\mathrm{C} \le T_{\mathrm{sat}} \le 100^\circ\mathrm{C}$$

$$\bar{h}_{\mathrm{dc}} = 255{,}510 \qquad 100^\circ\mathrm{C} \le T_{\mathrm{sat}}$$