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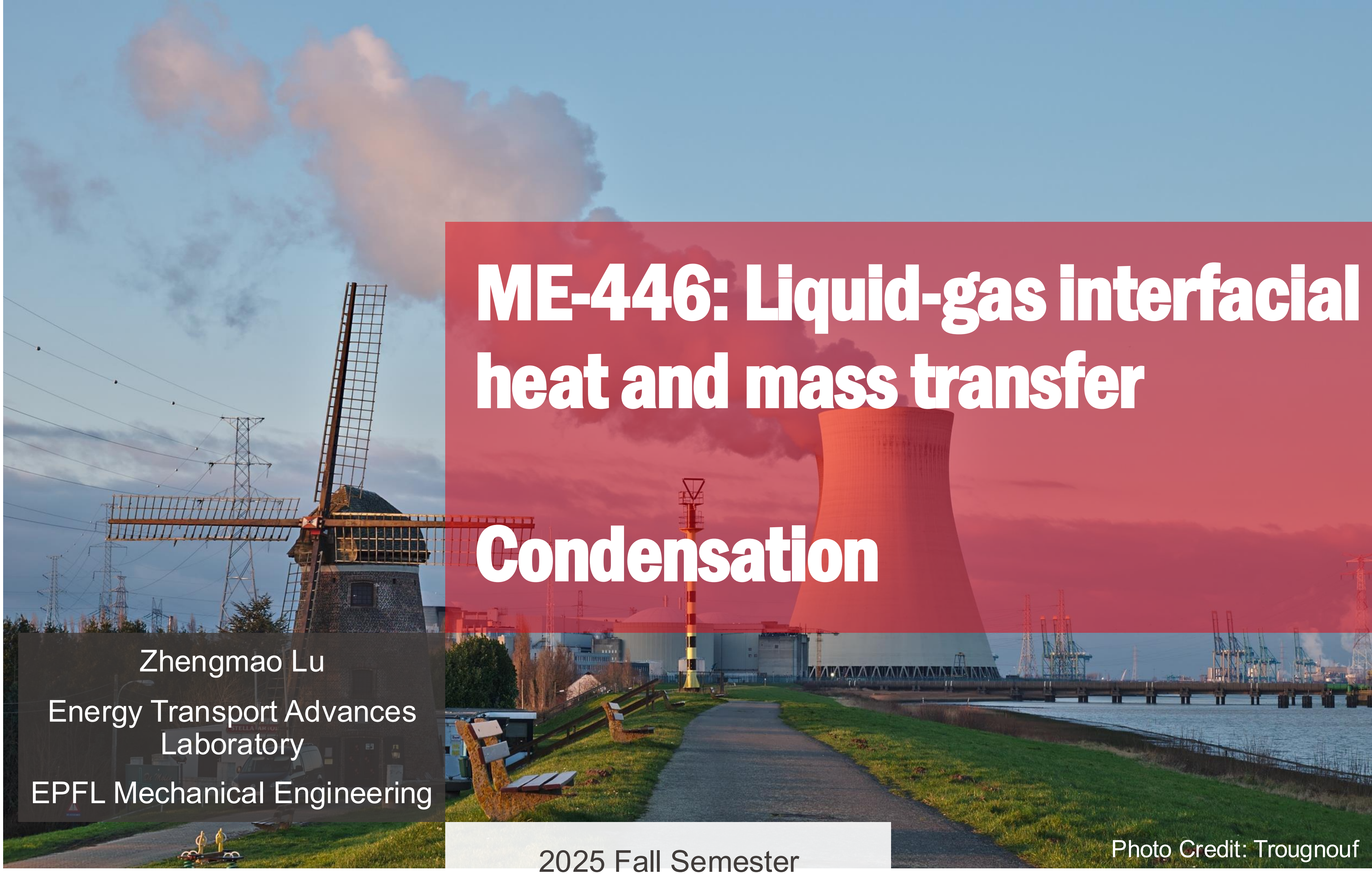
ETA-Lab
Energy Transport Advances



ME-446: Liquid-gas interfacial heat and mass transfer

Condensation

Zhengmao Lu

Energy Transport Advances Laboratory

EPFL Mechanical Engineering

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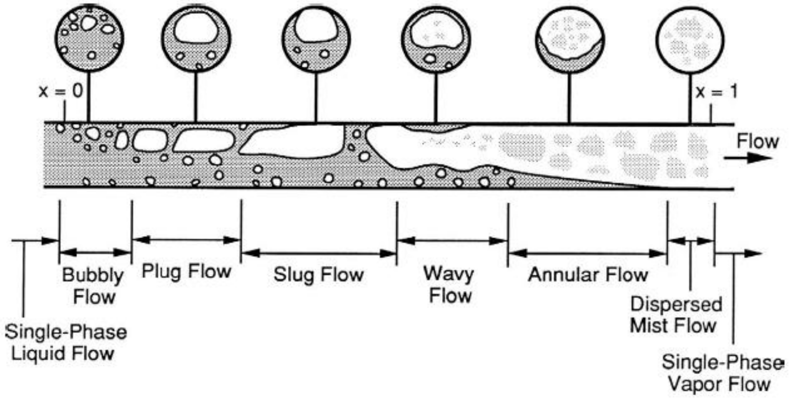
Photo Credit: Trougnouf

Last Time

- How wicking surfaces enhance CHF
- Different flow boiling regimes



- Evaluate ONB, HTC, and CHF in flow boiling with correlations
  - ONB: Sato and Matsumura
  - HTC: Rohsenow's partition (subcooled), Gungor and Winterton (saturated), Kandlikar (saturated)
  - CHF: Celata (subcooled), Groeneveld lookup table (saturated)

Microchannel Flow Boiling : Rationale and Definition

- Miniaturization forces heat dissipation problem into microchannel regime
- Microchannel leads to higher surface-to-volume ratio and lower liquid layer thickness
- How confined the channel needs to be for us to consider it as micro?
(Kew and Cornwell https://doi.org/10.1016/S1359-4311(96)00071-3)

$$Co = \left[\frac{\sigma}{g(\rho_L - \rho_V)D_h^2}\right]^{1/2} > 0.5$$

D_h: hydraulic diameter

Bubble Confined in Microchannels

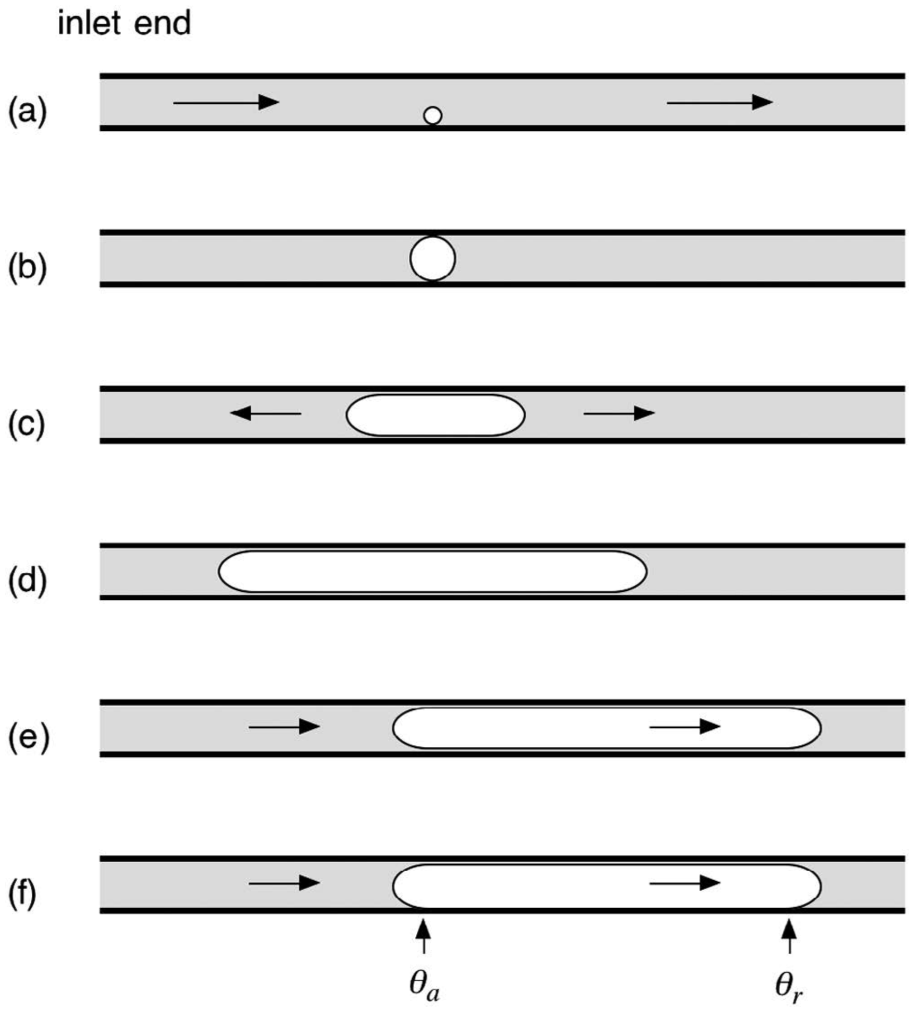


Fig. 12.31 in Carey

Once confinement is reached:

- Bubble elongation dominates
- Thin-film evaporation becomes the key heat transfer mechanism
- Flow patterns collapse to slug–annular regimes
- Macroscale boiling correlations break down

Microchannel Flow Boiling HTC

- Liu and Garimella https://doi.org/10.1115/1.2754944

$$h = h_{sp}F + h_{nb}S$$

$$h_{sp} = 1.86\left(\frac{k_l}{D_h}\right)\left[\frac{\mathrm{Re}_l \mathrm{Pr}_l D}{L}\right]^{1/3}\left(\frac{\mu_l}{\mu_s}\right)^{0.14}$$

$$\mathrm{Re}_l = \frac{G(1-x)D}{\mu_l}$$

μ_s: liquid viscosity at surface temperature

Microchannel Flow Boiling HTC

- Liu and Garimella https://doi.org/10.1115/1.2754944

$$h = h_{sp}F + h_{nb}S$$

$$F = 2\left(\phi_l^2\right)^{0.25}\left(\frac{\mu_{tp}}{\mu_l}\right)^{0.105}\left(\frac{c_{p,tp}}{c_{p,l}}\right)^{0.25}\left(\frac{k_{tp}}{k_l}\right)^{0.75}\mathrm{Pr}_l^{0.167}$$

$$\phi_l^2 = 1 + \frac{5}{X} + \frac{1}{X^2} \qquad X^2 = \left(\frac{1-x}{x}\right)\left(\frac{\rho_v}{\rho_l}\right)\left(\frac{\mu_l}{\mu_v}\right)$$

for laminar flow

Subscript tp: two phase properties $\Psi_{tp} = x\Psi_v + (1-x)\Psi_l$

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Microchannel Flow Boiling HTC

- Liu and Garimella https://doi.org/10.1115/1.2754944

$$h = h_{sp}F + h_{nb}S$$

$$h_{nb} = h_0 \left(\frac{q''}{q''_0}\right)\left(\frac{R_p}{R_{p0}}\right)^{0.133}\left[1.73p_r^{0.27} + \left(6.1 + \frac{0.68}{1-p_r}\right)p_r^2\right]$$

$$S = \exp\left\{36.57 - \frac{55746}{\mathrm{Re}_l\mathrm{F}^3} - 3.4\ln(\mathrm{Re}_l F^3)\right\}$$

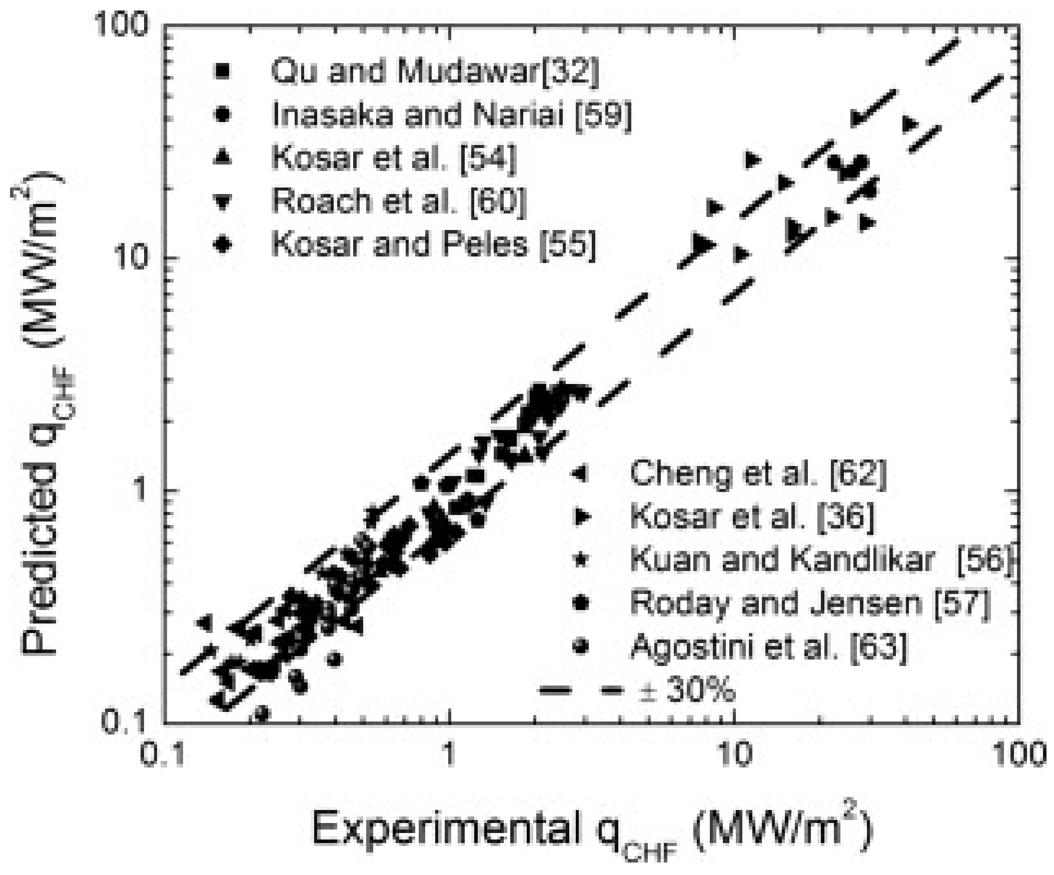
$h_0 = 5600\ \mathrm{W/m^2K}$, $q''_0 = 20\ \mathrm{kW/m^2}$, $R_{p0} = 0.4\ \mu\mathrm{m}$

R_p: surface roughness (set as $1\ \mu\mathrm{m}$ by Liu and Garimella)

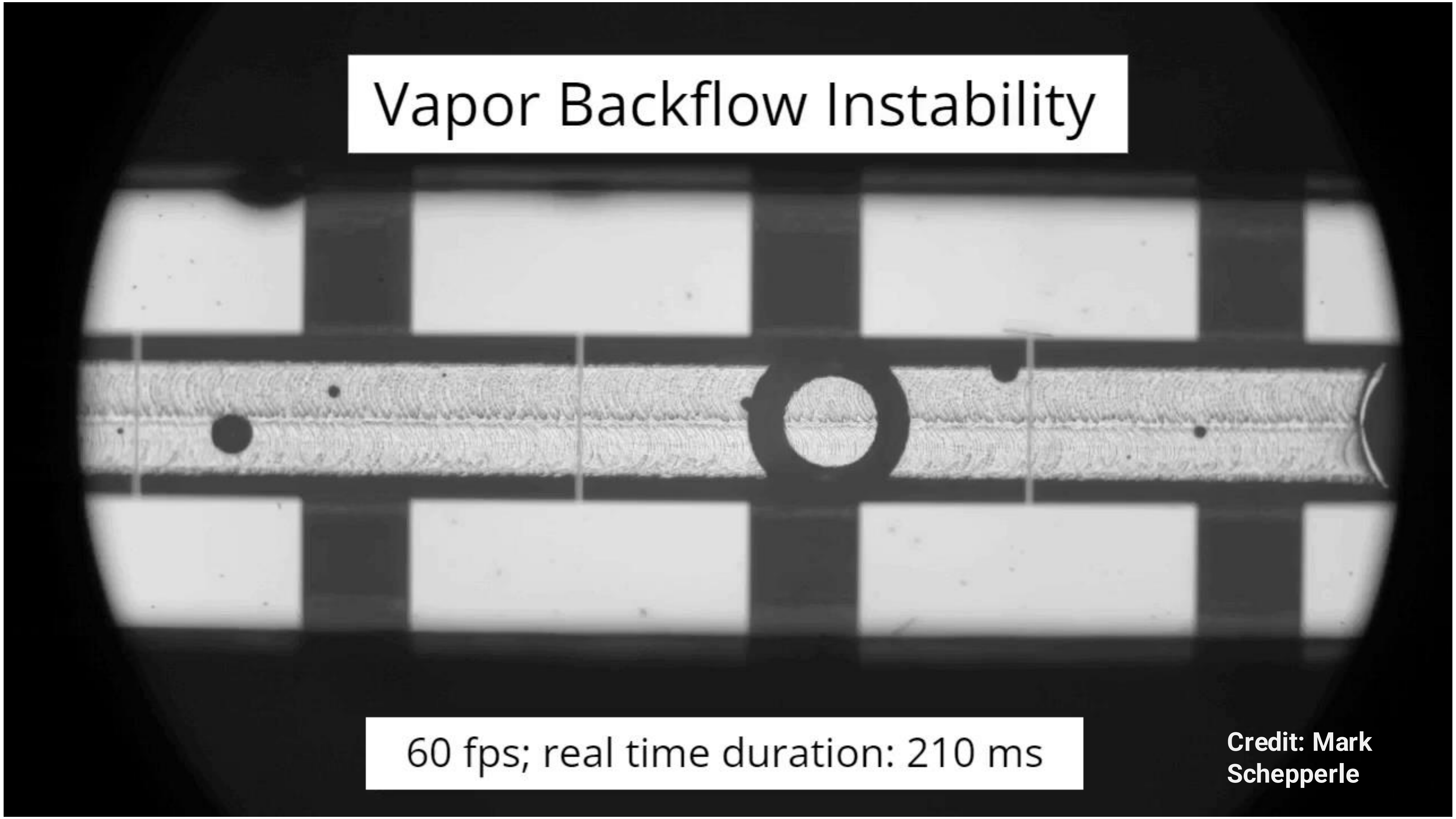
$p_r = P/P_c$ reduced pressure (normalized to critical pressure)

Microchannel Flow Boiling CHF

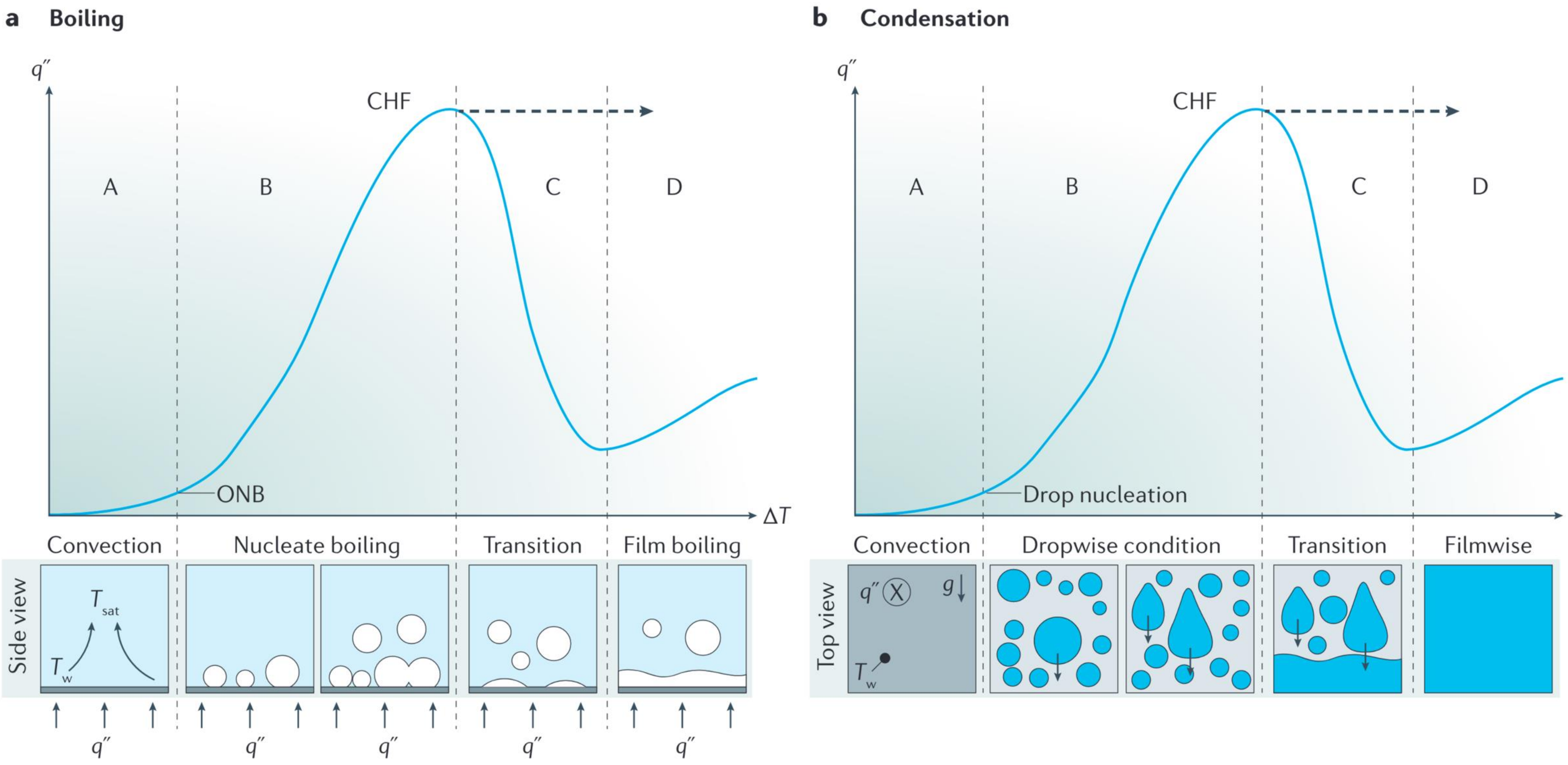
CHF model by Kandlikar https://doi.org/10.1115/1.4001124



Oscillations in Microchannels

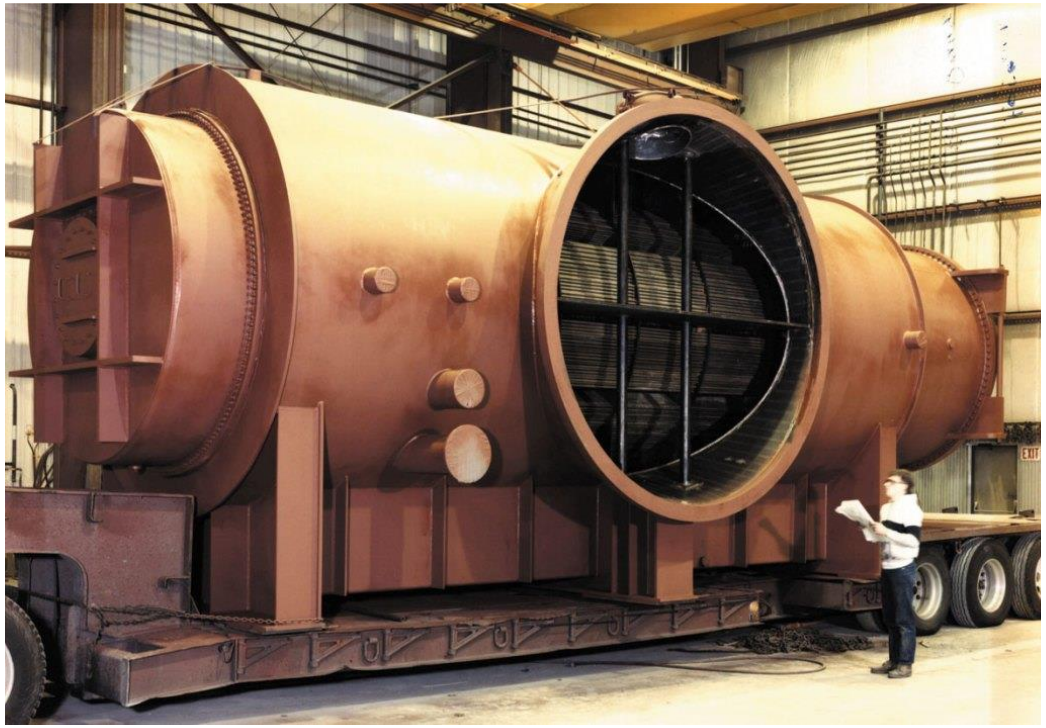


Boiling vs Condensation



DOI: 10.1038/natrevmats.2016.92

Why Condensation Matters



Condenser in Power Plants, Holtec

Condenser in Cooling Systems, STACK

Intended Learning Objectives

- Nucleation in condensation
- Rose’s analysis of dropwise condensation
- Nusselt’s analysis of filmwise condensation

Carey, Chapter 9

Droplet Embryo

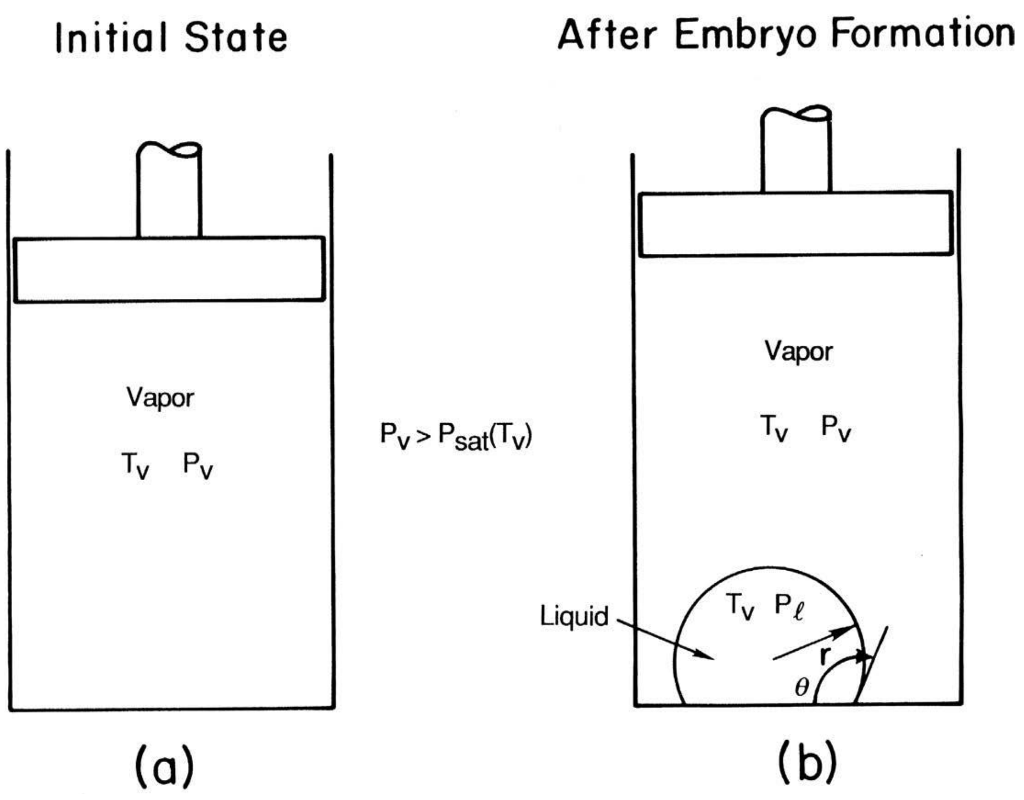
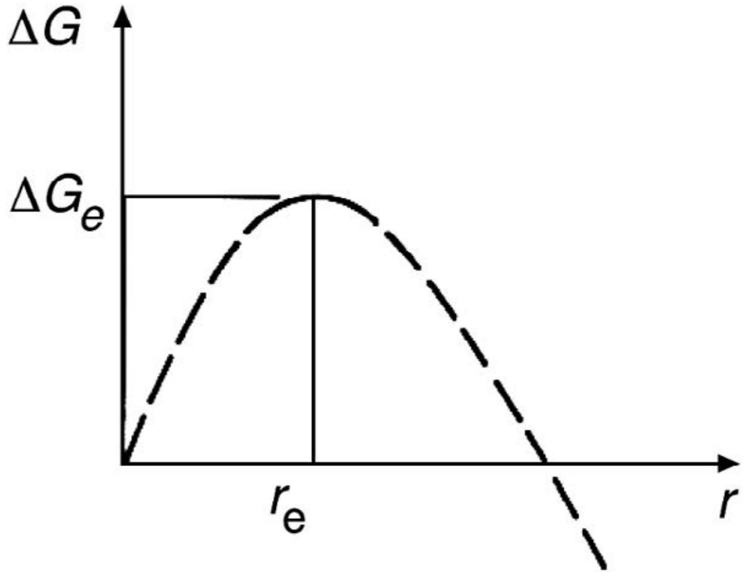


Figure 9.2 in Carey

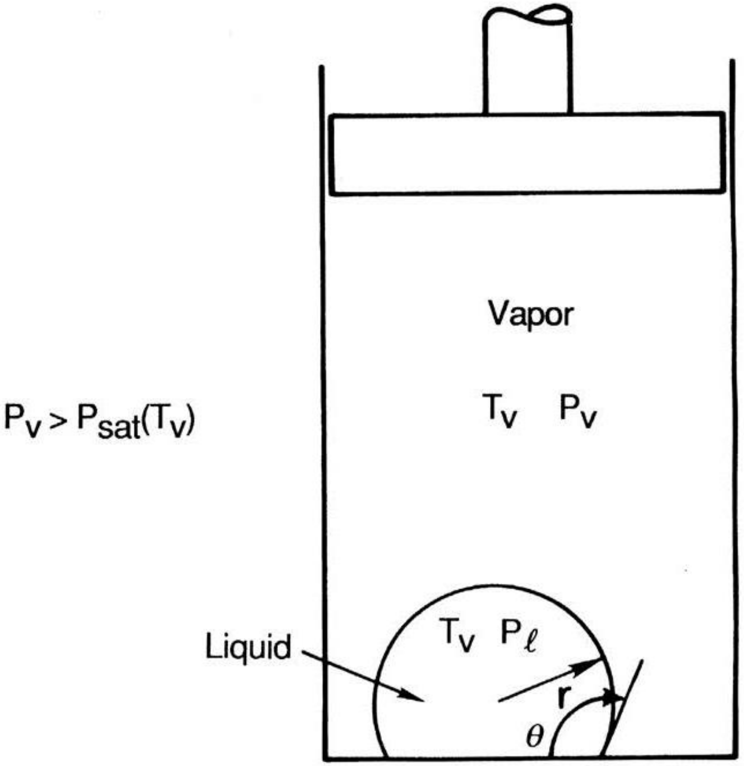
(b) – (a)



If $r < r_e$, the droplet collapses
If $r > r_e$, the droplet grows

Equilibrium Droplet Radius

After Embryo Formation



(b)

$$g_{sat,l}(T_v, P_{sat}) = g_{sat,v}(T_v, P_{sat}) = g_{sat}$$

$$g_v - g_{sat} = \int_{P_{sat}}^{P_v} v_v dP = \int_{P_{sat}}^{P_v} \frac{RT_v}{P} dP = RT_v \ln\left(\frac{P_v}{P_{sat}}\right)$$

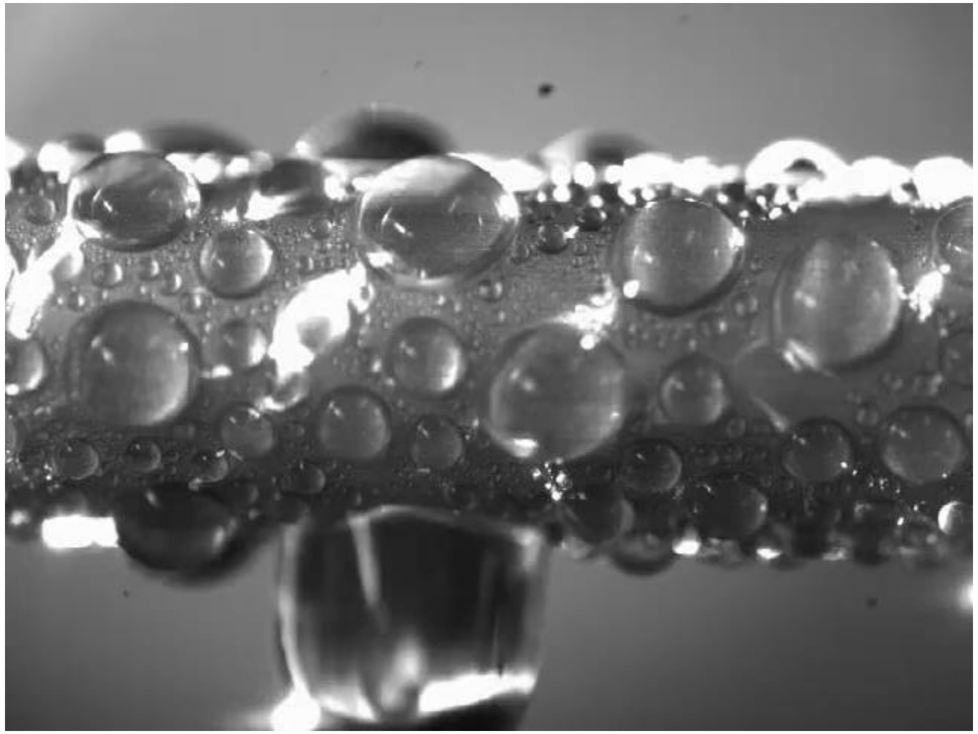
$$g_l - g_{sat} = \int_{P_{sat}}^{P_l} v_l dP = v_l(P_l - P_{sat})$$

$$P_l - P_v = 2\sigma/r_e$$

$$r_e = \frac{2\sigma}{\frac{RT_v}{v_l}\ln\left(\frac{P_v}{P_{sat}}\right) + P_{sat} - P_v} \approx \frac{2\sigma}{\frac{RT_v}{v_l}\ln\left(\frac{P_v}{P_{sat}}\right)}$$

$r_e \sim$ 1 nm, for water vapor with $T_v = 100°\text{C}$ and $P_v = P_{sat}(110°\text{C})$

Dropwise Condensation



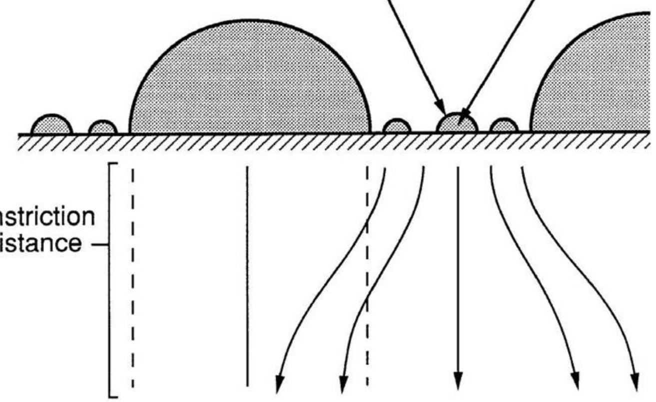
https://doi.org/10.1021/nl303835d

Interfacial Resistance

- Schrage equation (condensation)

$$q_i'' = \left(\frac{2\hat{\sigma}}{2-\hat{\sigma}}\right) h_{lv} \sqrt{\frac{1}{2\pi R}} \left(\frac{P_v}{\sqrt{T_v}} - \frac{P_l}{\sqrt{T_l}}\right)$$

$$\approx \left(\frac{2\hat{\sigma}}{2-\hat{\sigma}}\right) \frac{\rho_v h_{lv}^2}{T_v} \sqrt{\frac{1}{2\pi R T_v}} \left(1 - \frac{P_v}{2\rho_v h_{lv}}\right) \Delta T_i = h_i \Delta T_i$$



$$\frac{d\left(\frac{P_{sat}}{\sqrt{T}}\right)}{dT} = \frac{\rho_v h_{lv} - \frac{P_v}{2}}{T^{3/2}}$$

Clausius-Clapeyron

$$\frac{dP_{sat}}{dT} \approx \frac{\rho_v h_{lv}}{T}$$

Assuming hemispherical droplet $q_i'' = \frac{q_d}{2\pi r^2}$ $\Delta T_i = \frac{q_d}{2\pi r^2 h_i}$ q_d [W]

Curvature-Induced Resistance

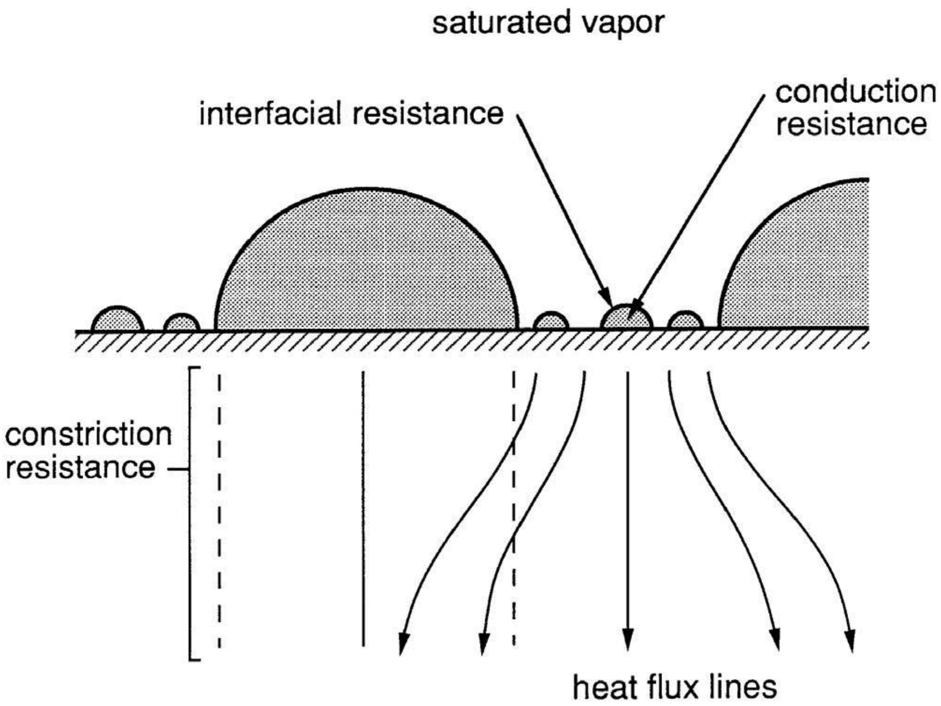
Given a droplet radius *r*, the equilibrium droplet temperature at the interface should follow

$$r \approx \frac{2\sigma}{\frac{RT_{eq}}{v_l}\ln\left(\frac{P_v}{P_{sat}(T_{eq})}\right)}$$

Clausius-Clapeyron $$\frac{dP_{sat}}{dT} = \frac{\rho_v h_{lv}}{T} \approx \frac{P_{sat}}{RT^2} h_{lv}$$

$$r \approx \frac{2\sigma v_l T_{sat}(P_v)}{h_{lv}\left(T_{sat}(P_v) - T_{eq}\right)} \qquad \Delta T_{cap} = \frac{2\sigma v_l T_{sat}(P_v)}{h_{lv} r}$$

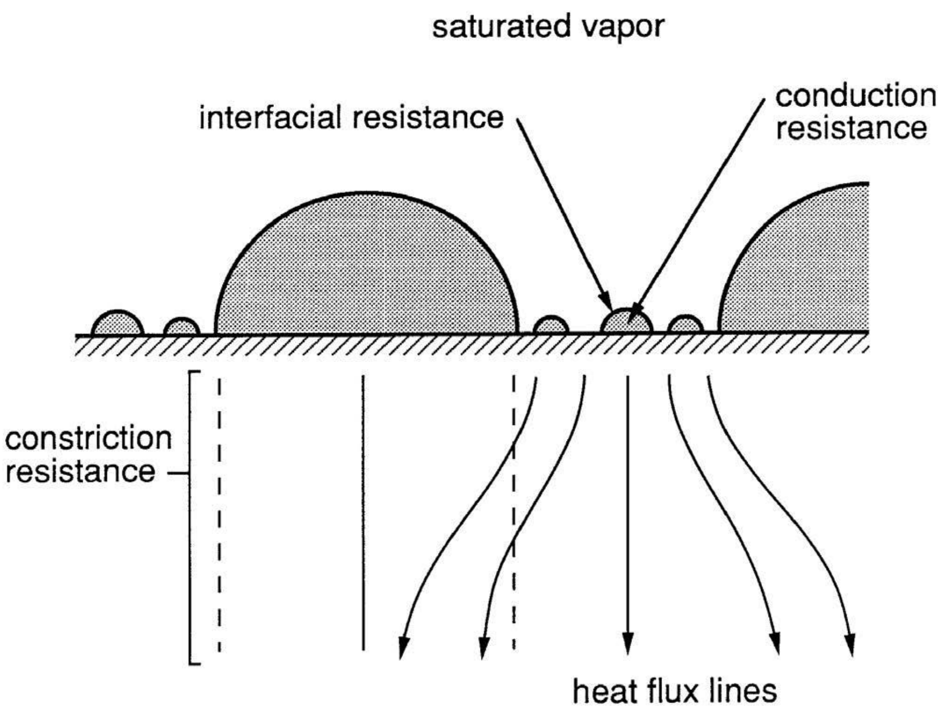
Conduction Resistance



$$q_d \approx \frac{k_l \Delta T_{con}}{r/2} \cdot 2\pi r^2$$

$$\Delta T_{con} \approx \frac{q_d}{4\pi k_l r}$$

Overall Droplet Resistance



- Interfacial resistance
- Curvature induced resistance
- Conduction through droplet
- Constriction resistance

$$\Delta T_t = \Delta T_i + \Delta T_{cap} + \Delta T_{con} = \frac{q_d}{2\pi r^2 h_i} + \frac{2\sigma T_{sat}(P_v)}{h_{lv} r} + \frac{q_d}{4\pi k_l r}$$

Distribution of Droplet Radii

- Cumulative distribution function (postulated form)

$$F(r) = \left(\frac{r}{r_{max}}\right)^{1/3} \text{ for } r_e < r \leq r_{max};$$

- Probability distribution function

$$A(r) = \frac{dF}{dr} = \frac{r^{-2/3}}{3r_{max}^{1/3}}$$

$$r_{max} = K_3\sqrt{\frac{\sigma}{\rho g}}$$

Dropwise Condensation Heat Transfer

$$q'' = \int_{r_e}^{r_{max}} \frac{q_d}{2\pi r^2} A(r)dr$$

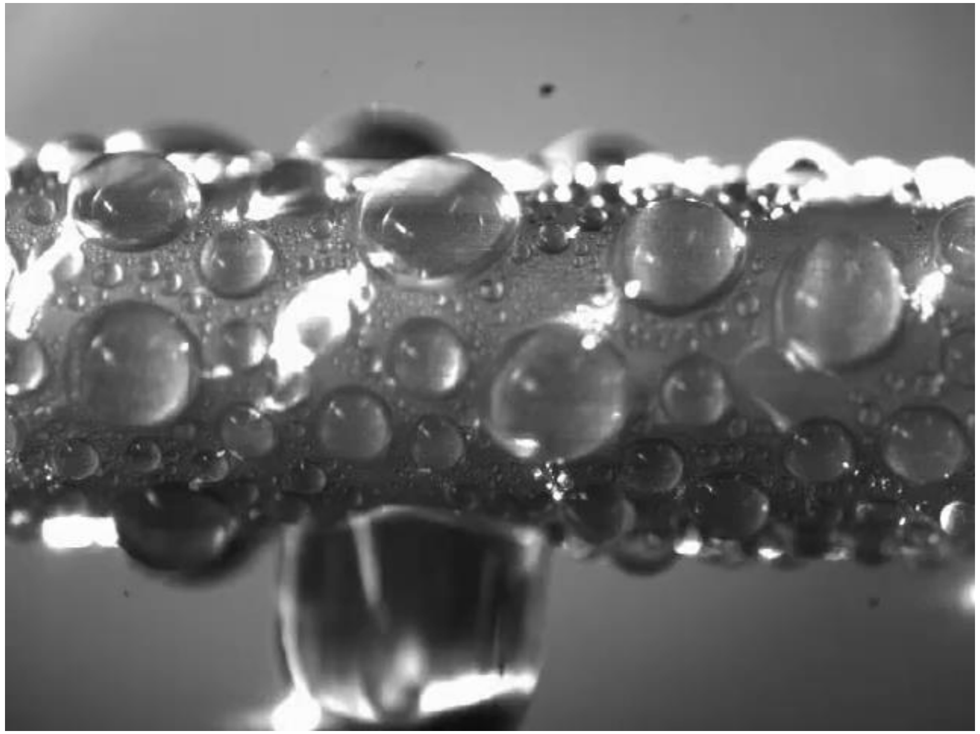
$$h_{dc} = \frac{1}{\Delta T_t} \int_{r_e}^{r_{max}} \frac{q_d}{2\pi r^2} A(r)dr$$

For dropwise condensation of steam at pressures below 1 atm, Rose et al. recommended the following empirical correlation for the heat transfer coefficient

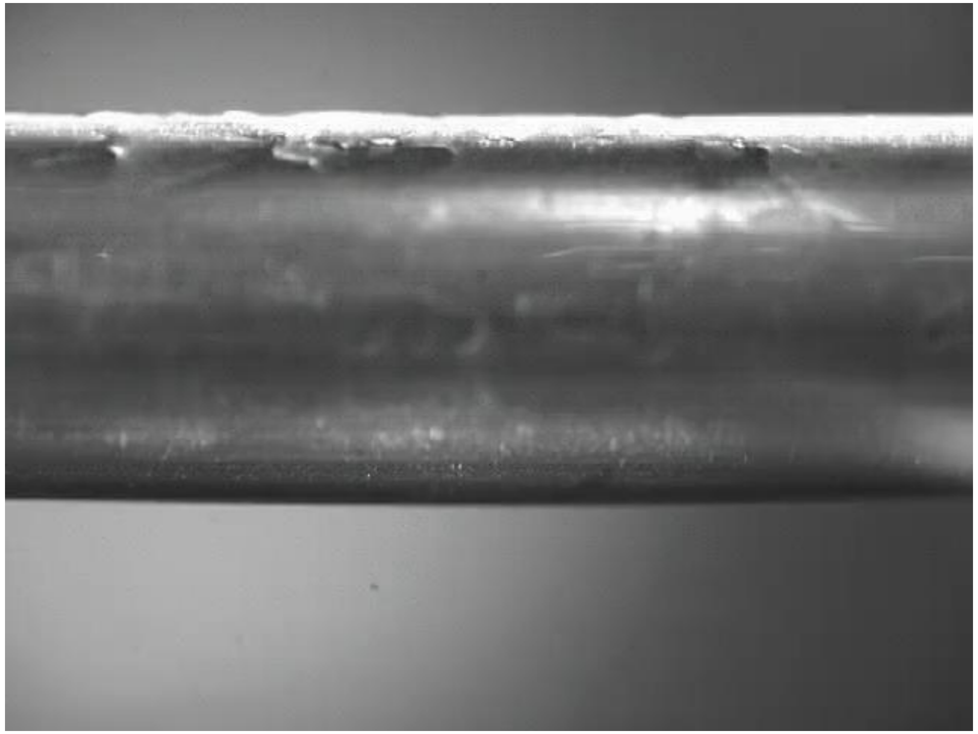
$$h_{dc} = T_v^{0.8}[5 + 0.3(T_{sat} - T_w)]$$ Eq. 9.42 in Carey

Temperature in Celsius and HTC in kW/m^2K

Dropwise vs Filmwise Condensation

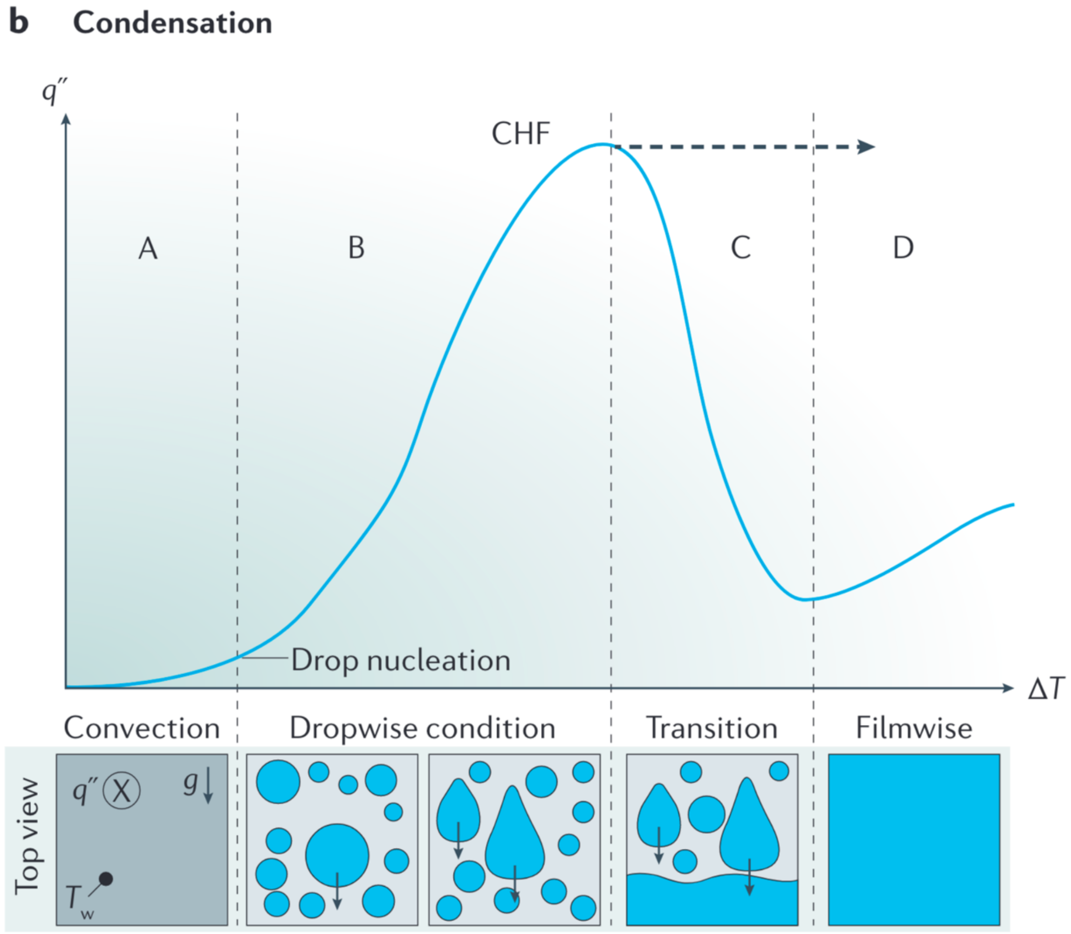


Dropwise condensation



Filmwise condensation

Dropwise vs Filmwise Condensation



Data obtained by Takeyama and Shimizu [9.40] for condensation of steam on a short vertical copper surface.

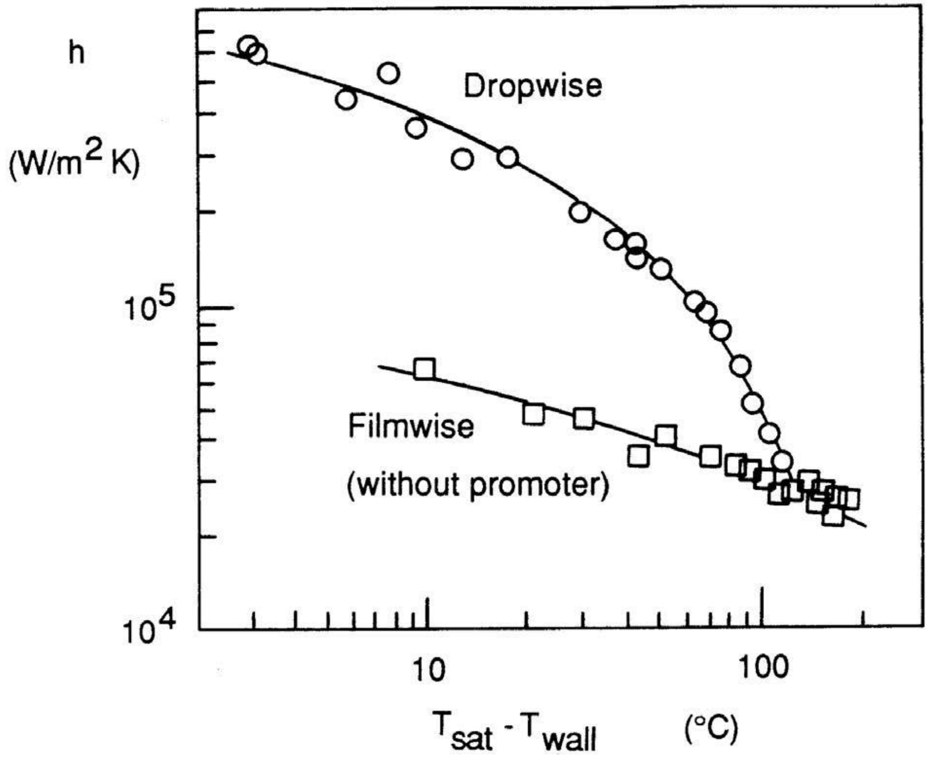
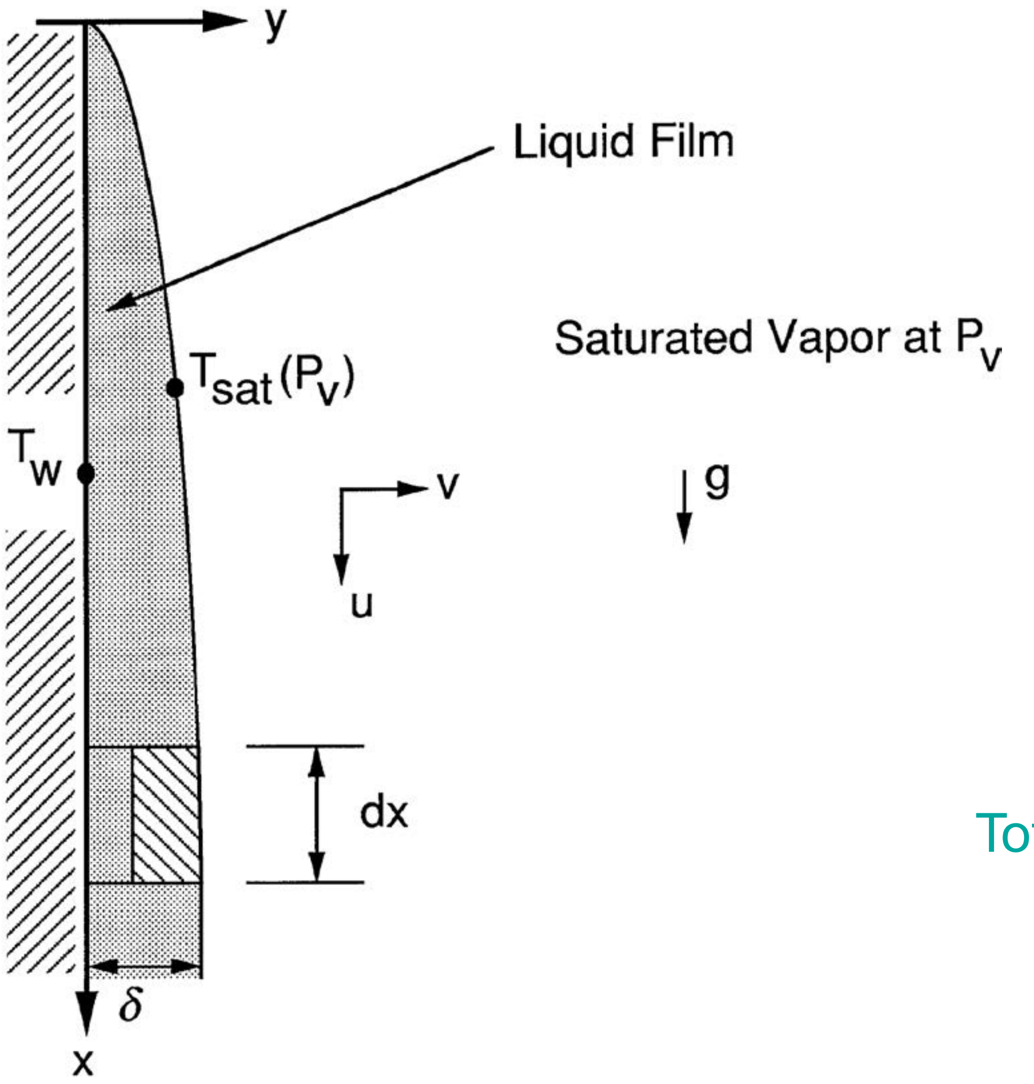


Figure 9.6 in Carey

Filmwise Condensation on a Flat Vertical Surface



Force balance on the shaded film element

$$(\delta - y)dx(\rho_l - \rho_v)g = \mu_l\left(\frac{du}{dy}\right)dx$$

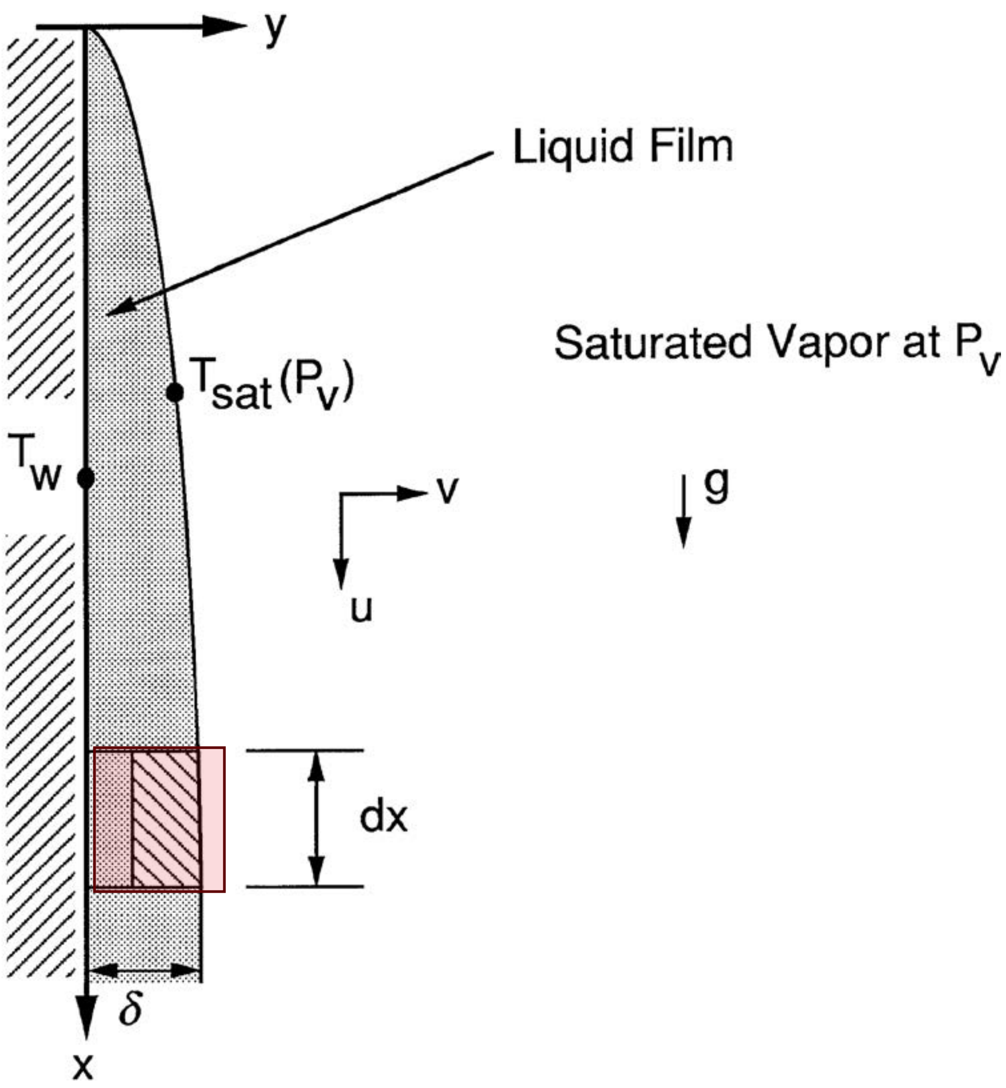
Integrating this equation w.r.t. *y*

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

Total mass flow rate per unit depth in y-direction

$$\dot{m}' = \rho_l \int_0^\delta u dy = \frac{\rho_l(\rho_l - \rho_v)g\delta^3}{3\mu_l}$$

Energy Balance



$$dq = \frac{k_l \Delta T}{\delta} dx \qquad \Delta T = T_{sat} - T_w$$

$$dq = h_{lv} d\dot{m}'$$

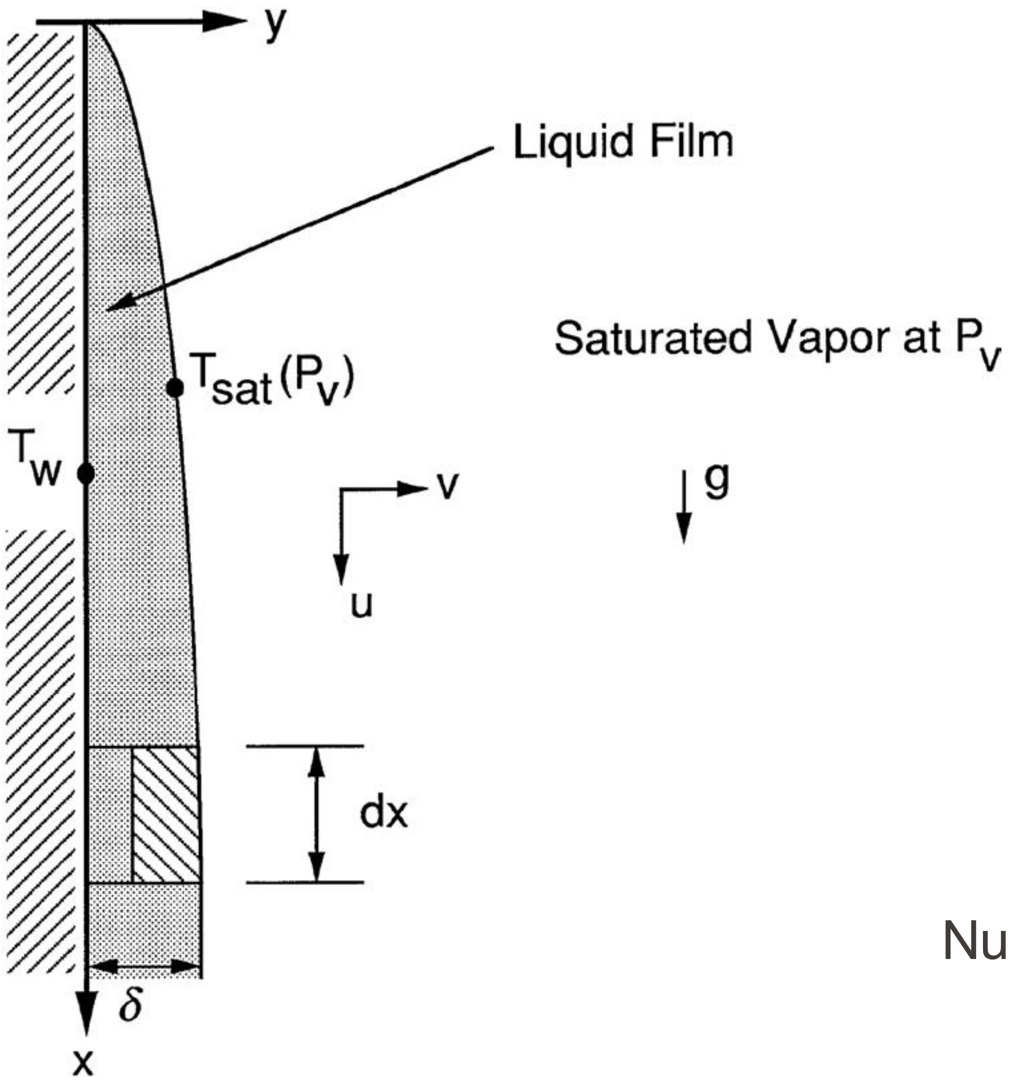
$$\frac{k_l \Delta T}{\delta} = \frac{h_{lv} d\dot{m}'}{dx}$$

$$\frac{d\delta}{dx} = \frac{k_l \mu_l \Delta T}{\rho_l(\rho_l - \rho_v) g h_{lv} \delta^3}$$

Using $\delta = 0$ at $x = 0$

$$\delta = \left[\frac{4 k_l \mu_l x \Delta T}{\rho_l(\rho_l - \rho_v) g h_{lv}}\right]^{1/4}$$

Filmwise Condensation HTC



$$h_l = \frac{k_l}{\delta} = k_l\left[\frac{\rho_l(\rho_l-\rho_v)gh_{lv}}{4k_l\mu_l x\Delta T}\right]^{1/4}$$

$$\bar{h}_l = \frac{1}{x_e}\int_0^{x_e}\frac{k_l}{\delta}dx = \frac{4}{3}k_l\left[\frac{\rho_l(\rho_l-\rho_v)gh_{lv}}{4k_l\mu_l x\Delta T}\right]^{1/4}$$

$$\overline{Nu}_{xe} = \frac{\bar{h}_l x_e}{k_l} = \frac{4}{3}\left[\frac{\rho_l(\rho_l-\rho_v)gh_{lv}x^3}{4k_l\mu_l\Delta T}\right]^{1/4}$$

Nusselt equation for filmwise condensation

Additional Comments

- Filmwise condensation still the most common operation mode in industry
  - Not as bad as film boiling as liquid is much more conductive than vapor

- Dropwise condensation requires strong hydrophobicity at high supersaturation (droplets must roll off the surface quickly before flooding occurs). However, maintaining strong hydrophobicity over extended period is challenging.