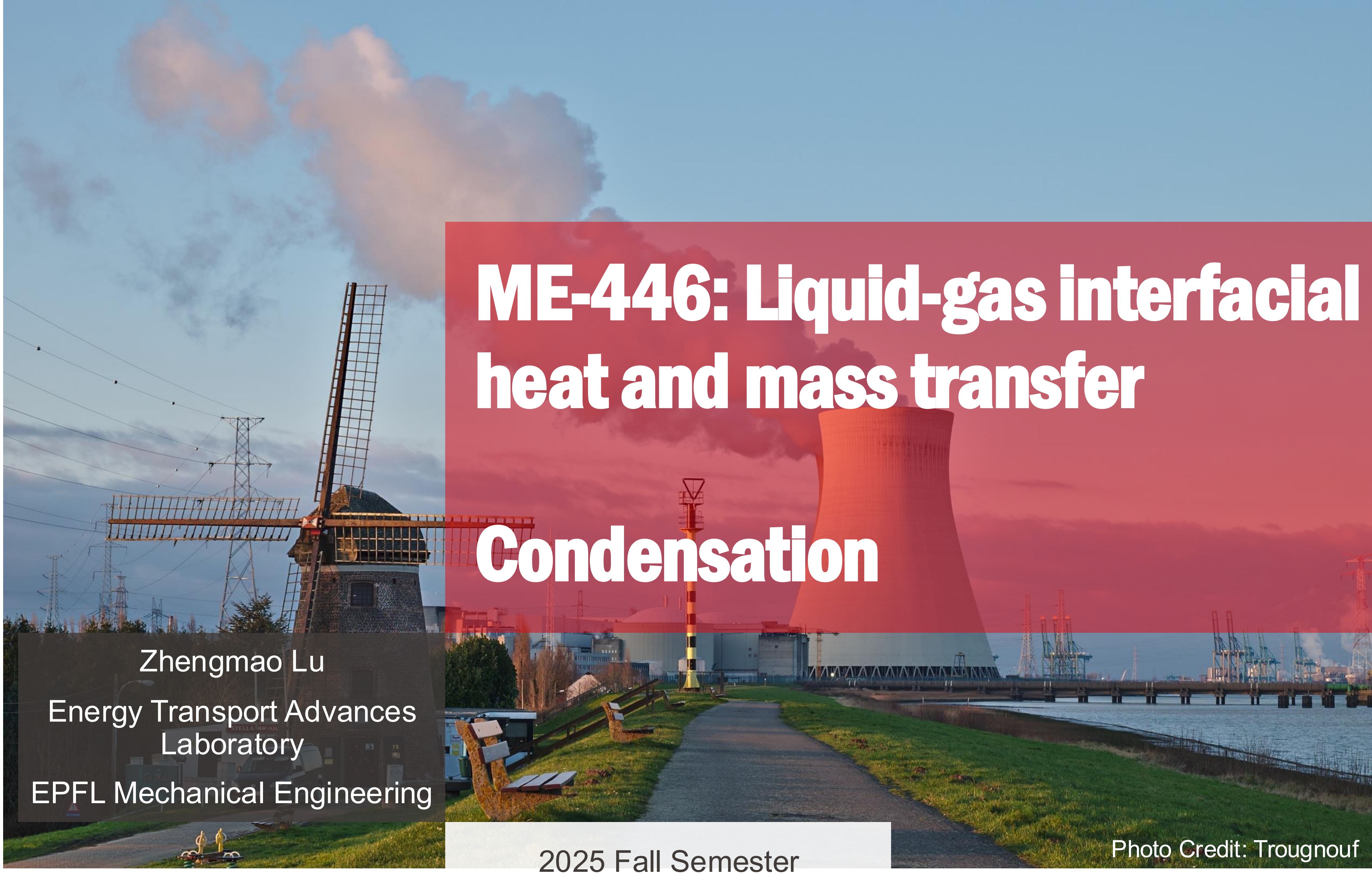


ME-446: Liquid-gas interfacial heat and mass transfer

Condensation

Zhengmao Lu

Energy Transport Advances Laboratory

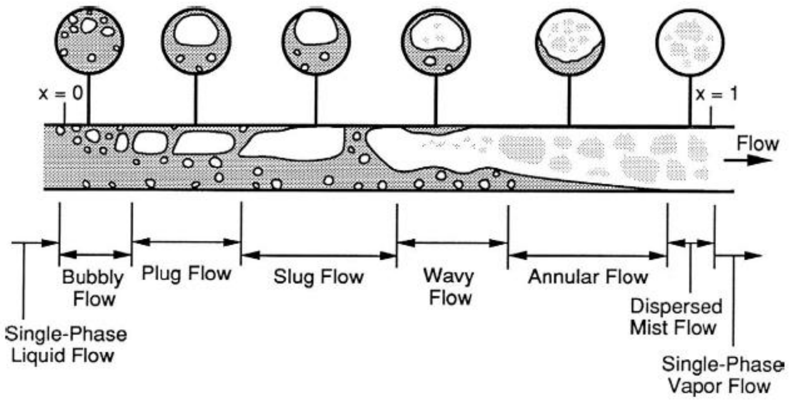
EPFL Mechanical Engineering

2025 Fall Semester

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)

Bubble Confined in Microchannels

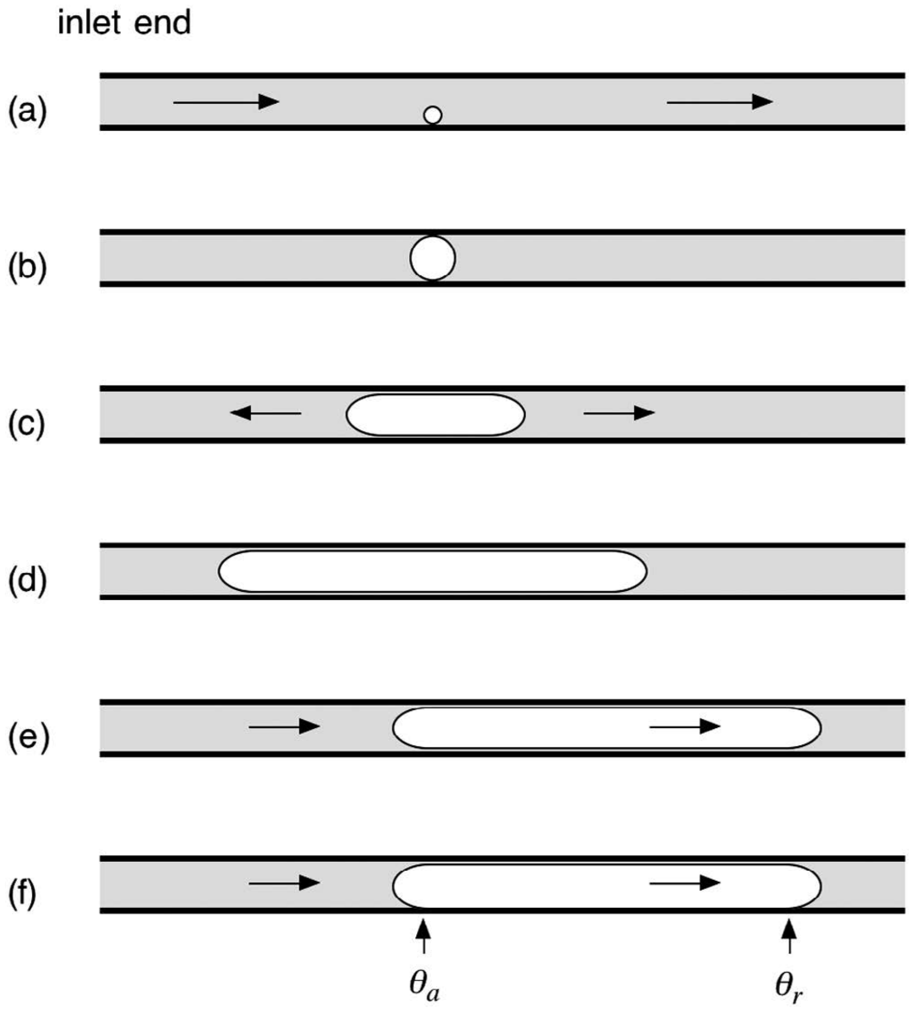


Fig. 12.31 in Carey

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

Microchannel Flow Boiling HTC

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

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

$$h_{nb} = h_0\left(\frac{q''}{q_0''}\right)\left(\frac{R_p}{R_{p0}}\right)^{0.133}\left[1.73p_r^{0.27} + \left(6.1 + \frac{0.68}{1-p_r}\right)p_r^2\right]$$

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

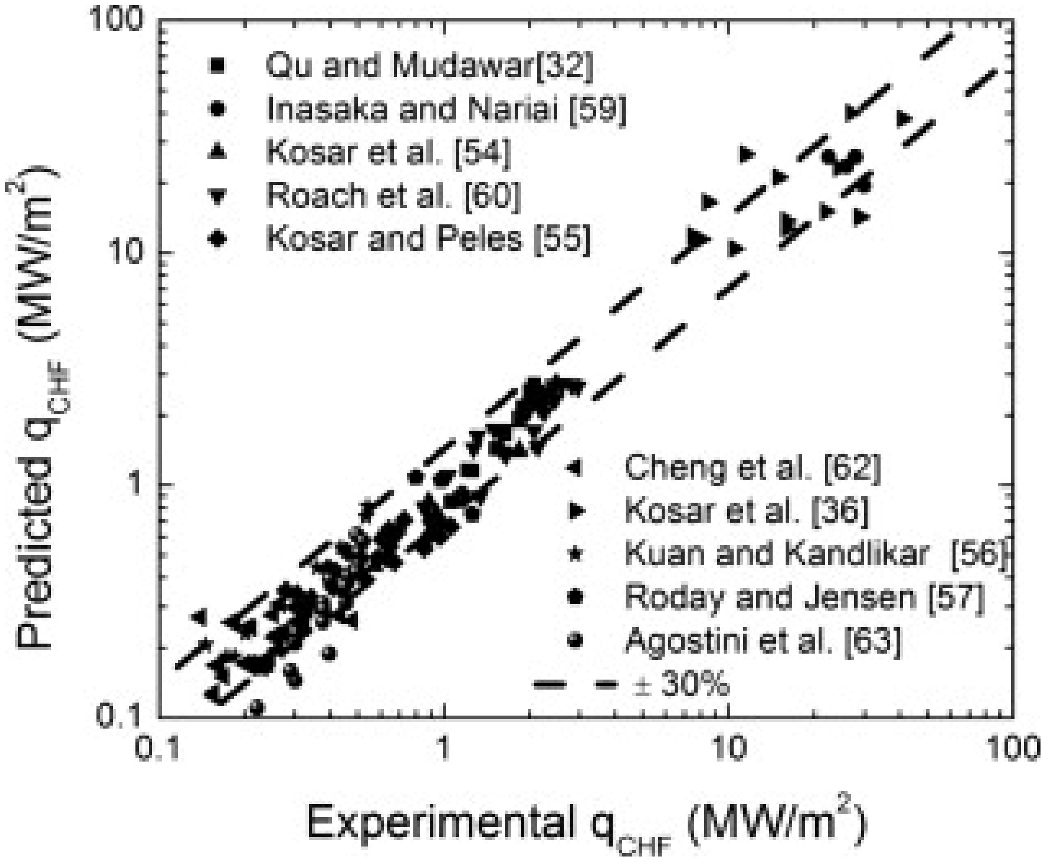
$h_0 = 5600\ \mathrm{W/m^2K}$, $q_0'' = 20\ \mathrm{kW/m^2}$, $R_{p0} = 0.4\ \mathrm{\mu m}$

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

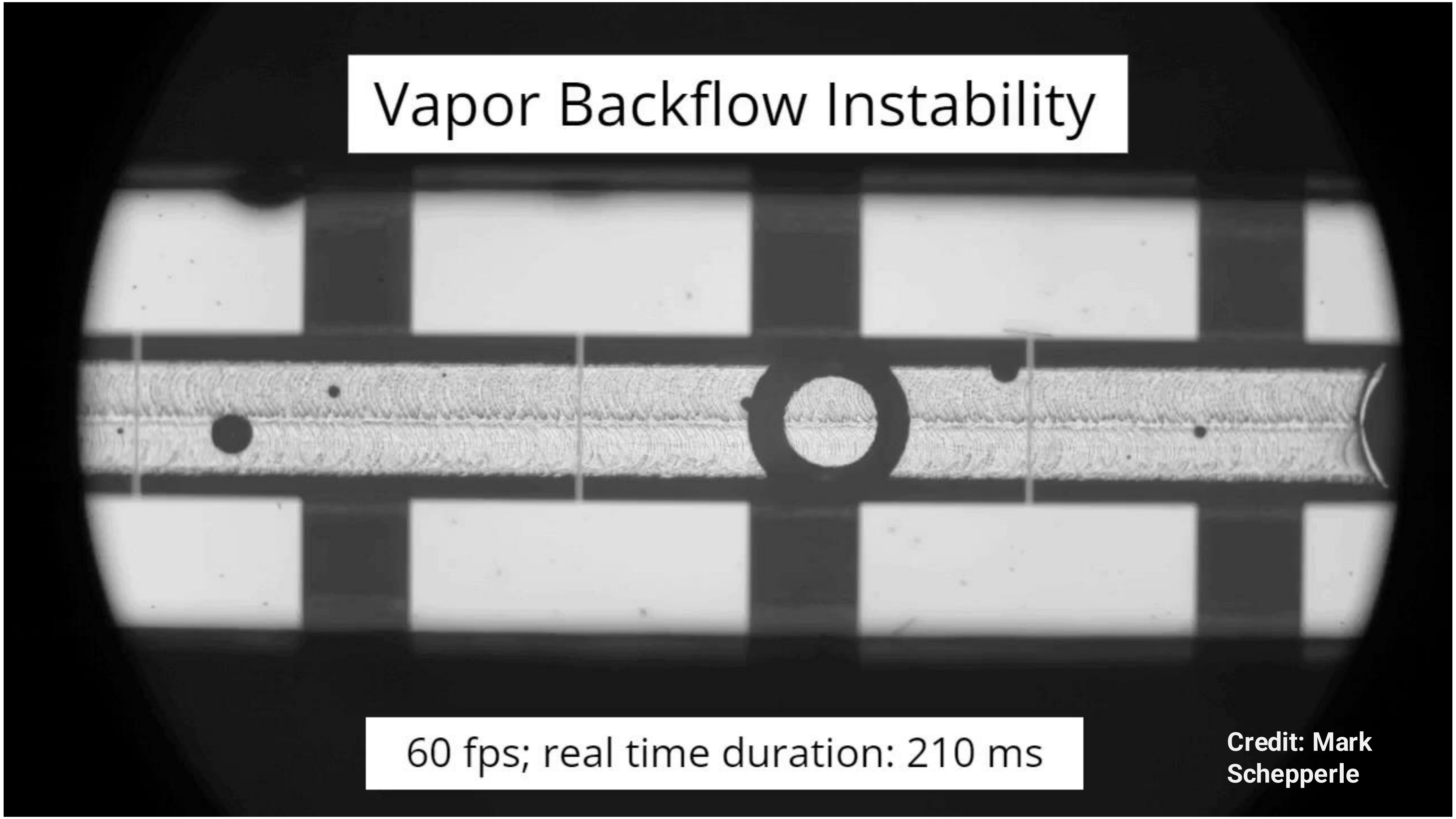
$p_r = P/P_c$ reduced pressure (normalized to critical pressure)

Microchannel Flow Boiling CHF

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

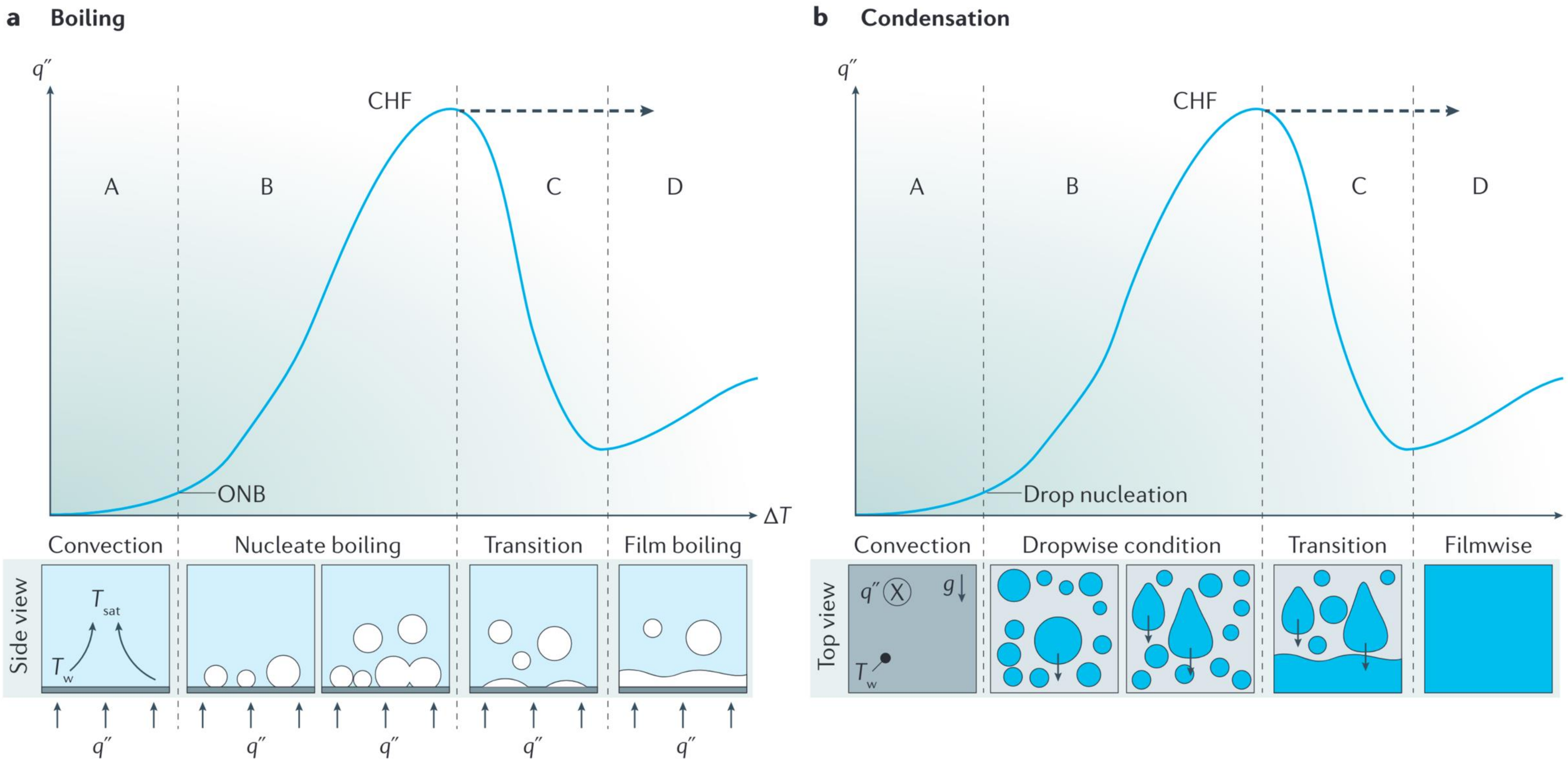


Oscillations in Microchannels



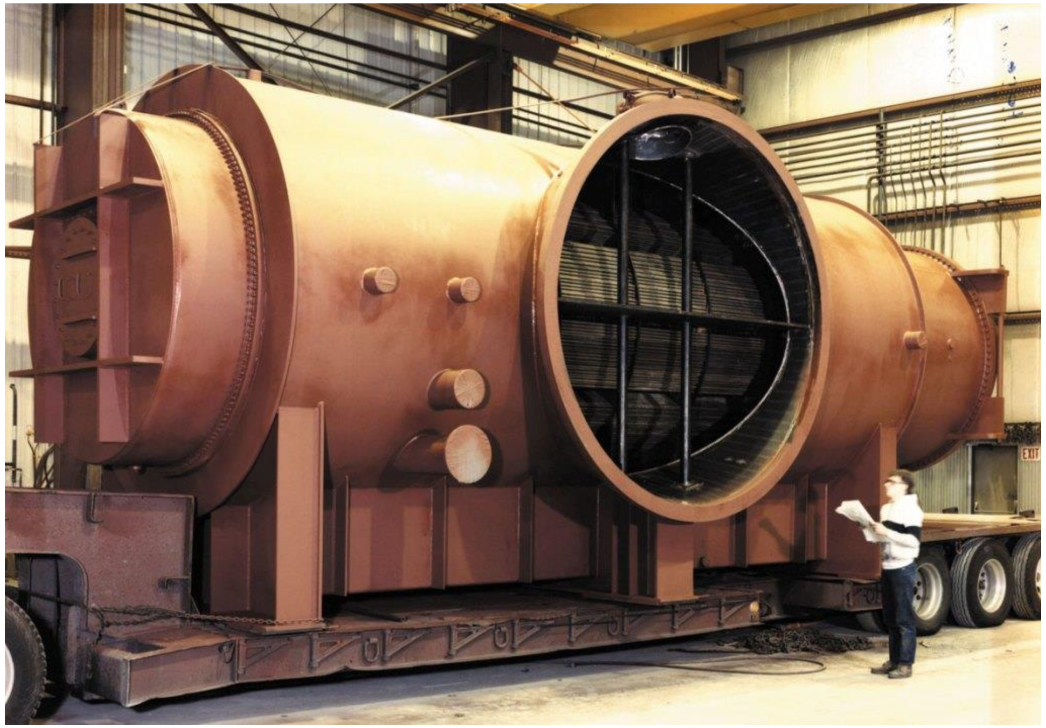
Credit: Mark Schepperle

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

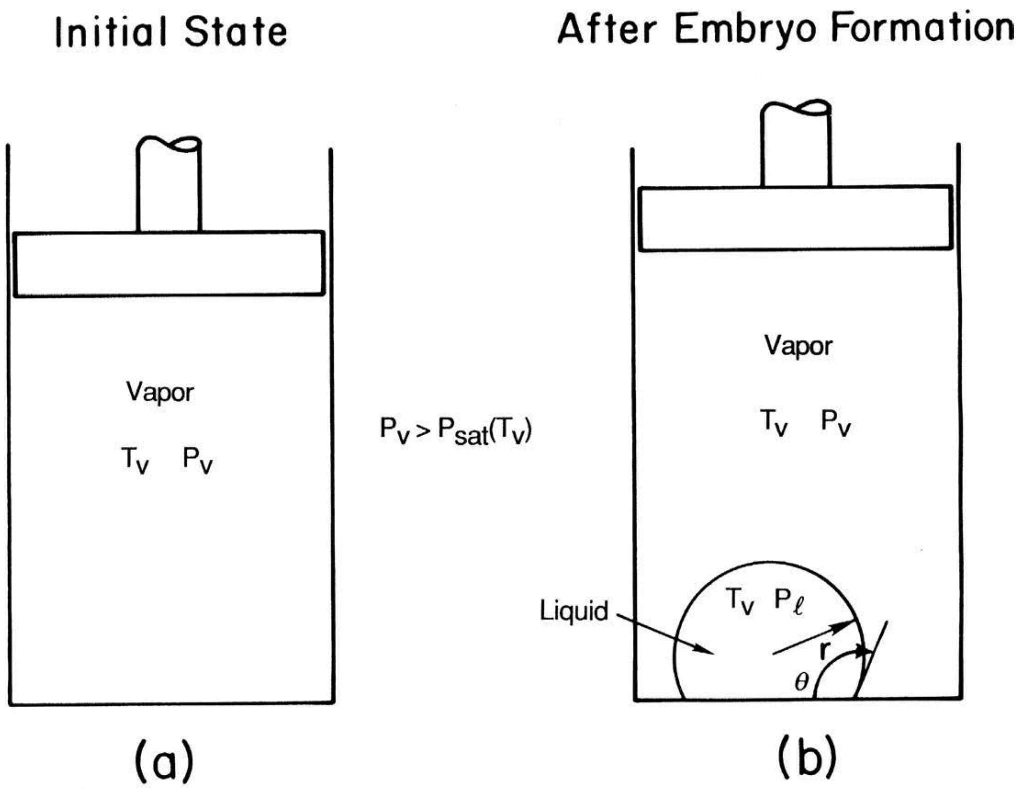
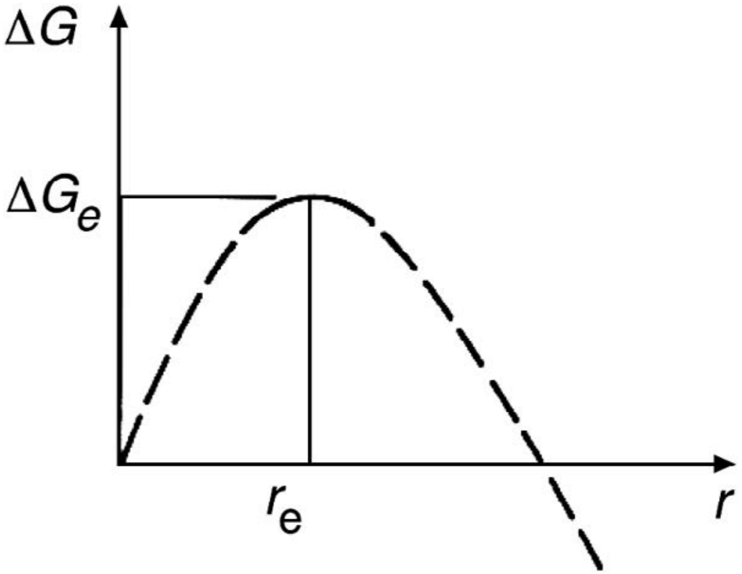


Figure 9.2 in Carey

(b) – (a)

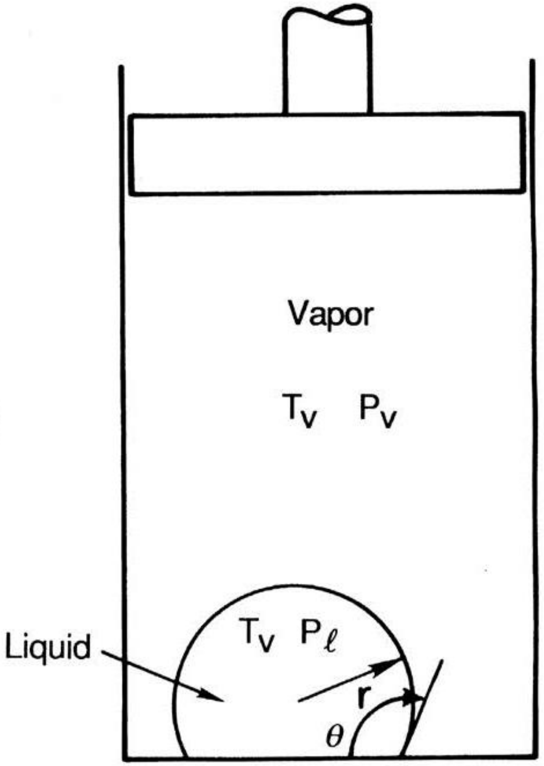


If $r < r_e$, the droplet collapses
If $r > r_e$, the droplet grows

Equilibrium Droplet Radius

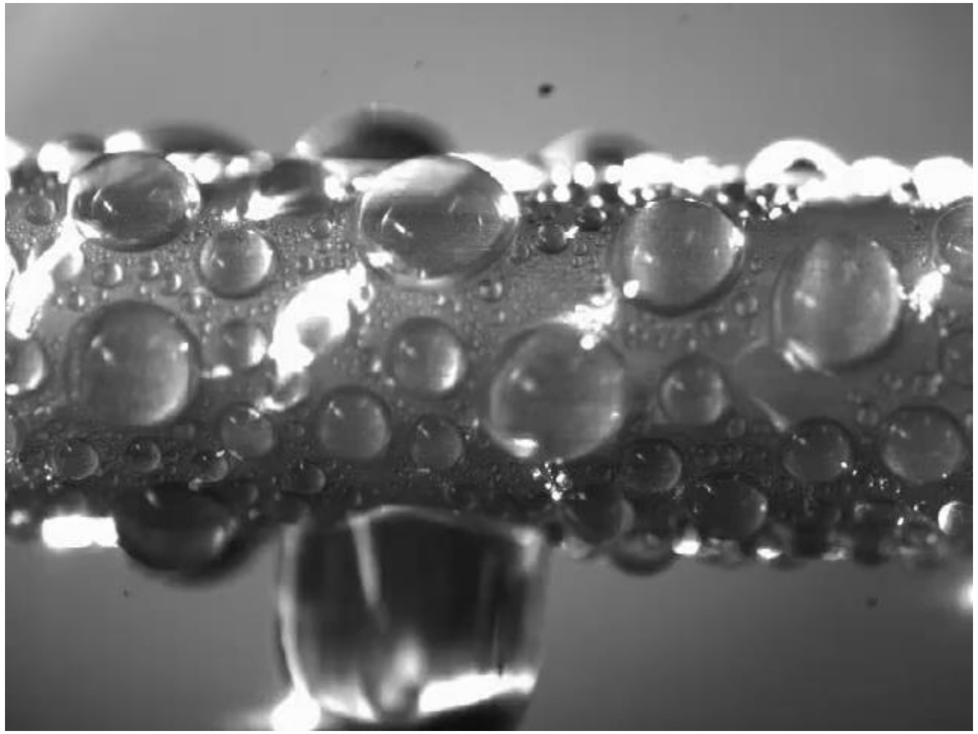
After Embryo Formation

$P_v > P_{sat}(T_v)$



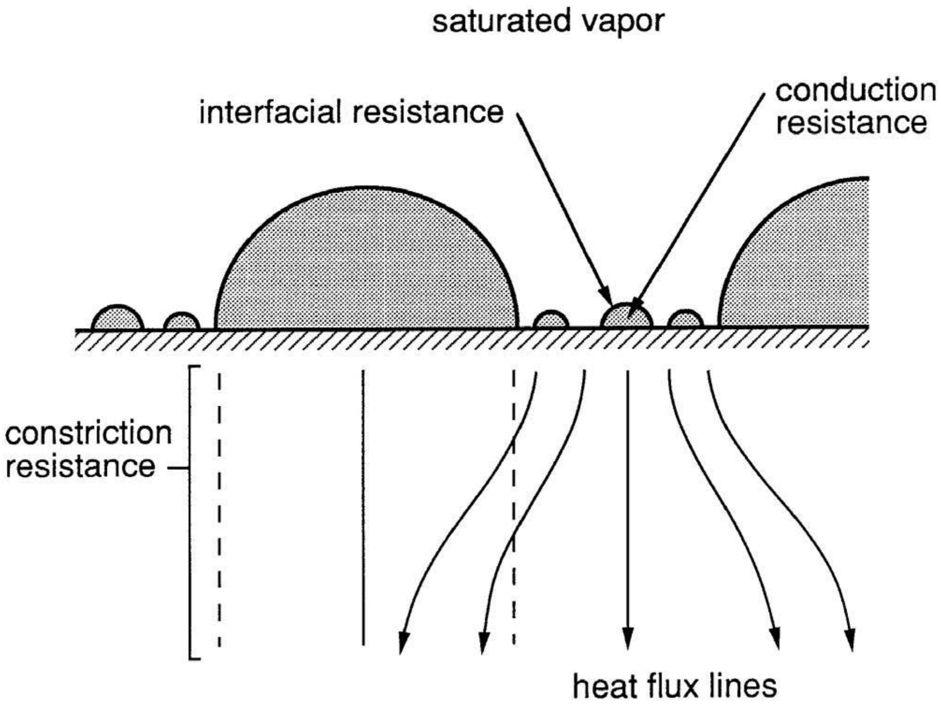
(b)

Dropwise Condensation



https://doi.org/10.1021/nl303835d

Overall Droplet Resistance

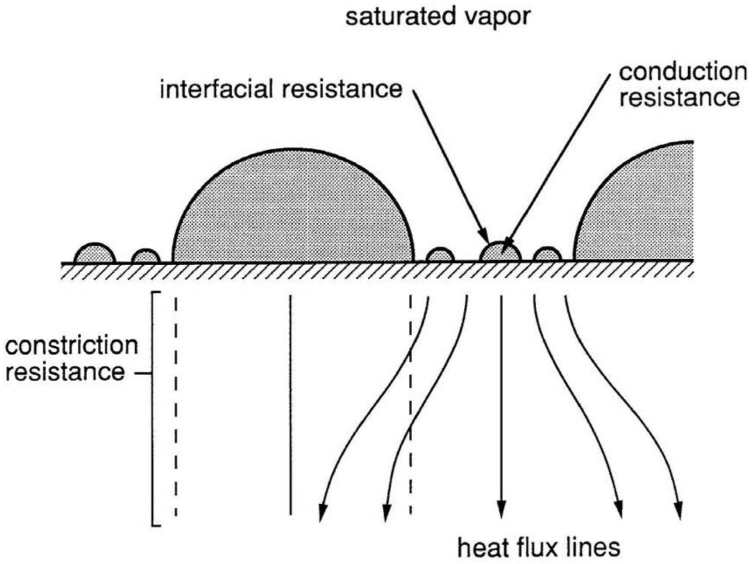


- Interfacial resistance
- Curvature induced resistance
- Conduction through droplet
- Constriction resistance

Interfacial Resistance

- Schrage equation (condensation)

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



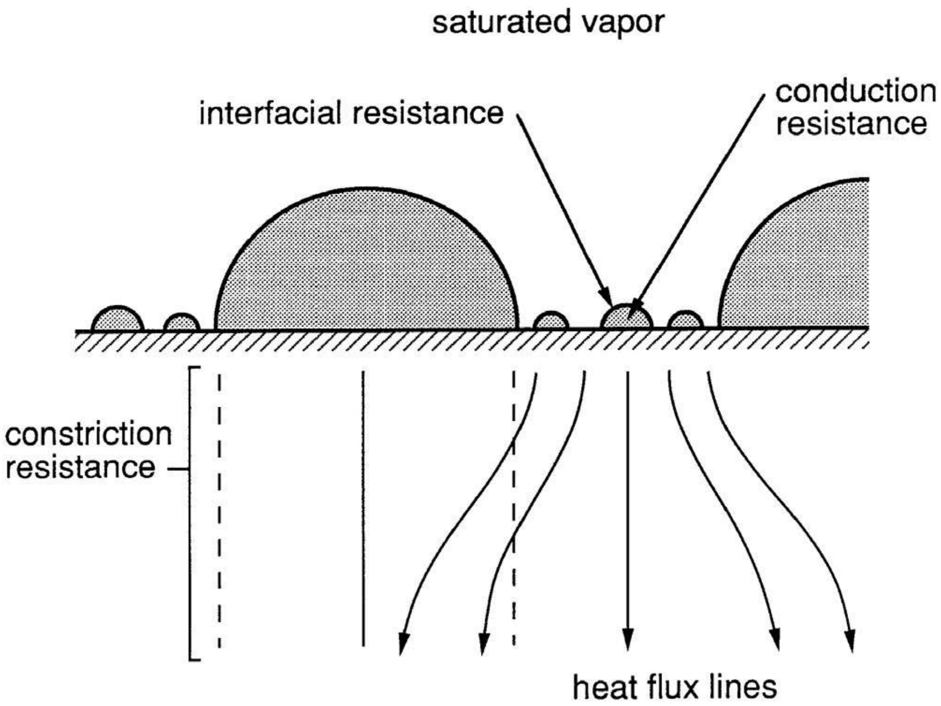
Curvature-Induced Resistance

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

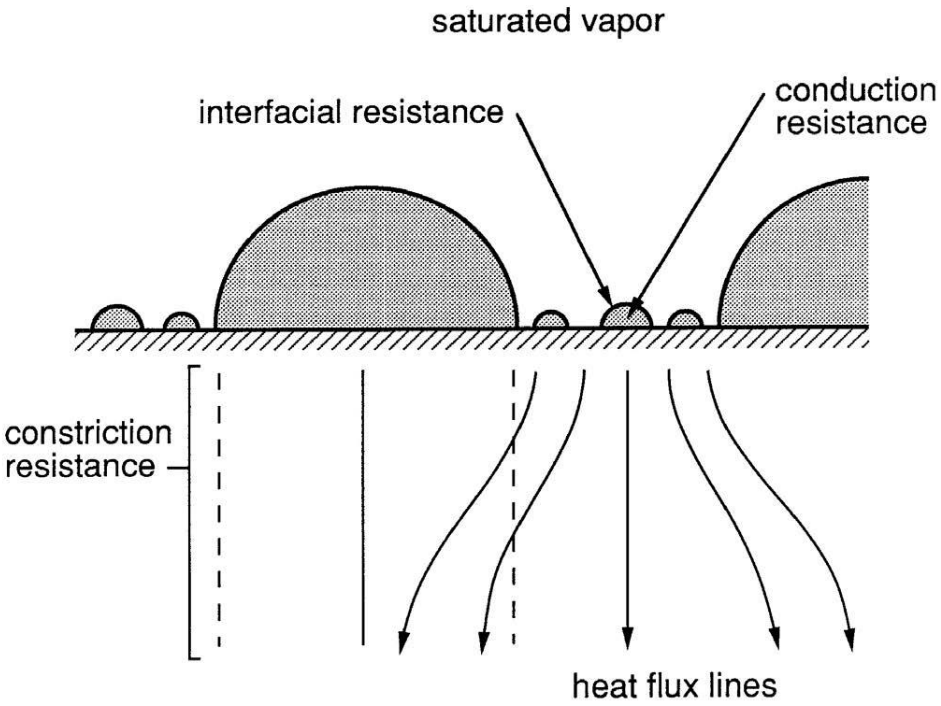
$$r \approx \frac{2\sigma}{\frac{RT_{eq}}{v_l}\ln\left(\frac{P_v}{P_{sat}(T_{eq})}\right)}$$

Clausius-Clapeyron $$\frac{dP_{sat}}{dT} = \frac{\rho_v h_{lv}}{T}$$

Conduction Resistance



Overall Droplet Resistance



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

Distribution of Droplet Radii

- Cumulative distribution function (postulated form)

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

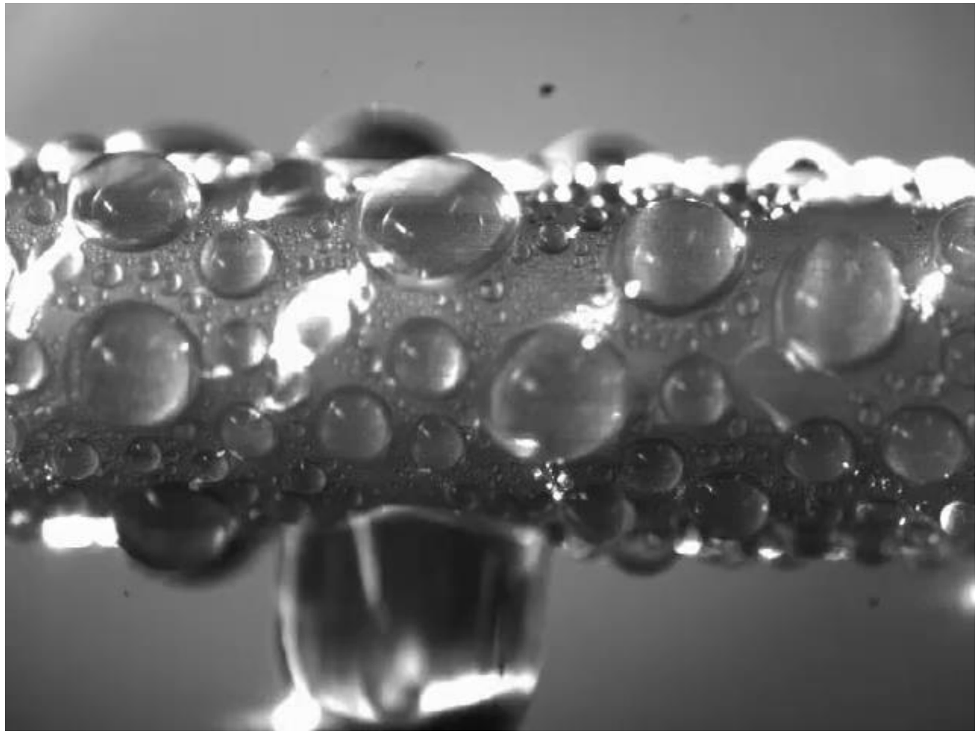
Dropwise Condensation Heat Transfer

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

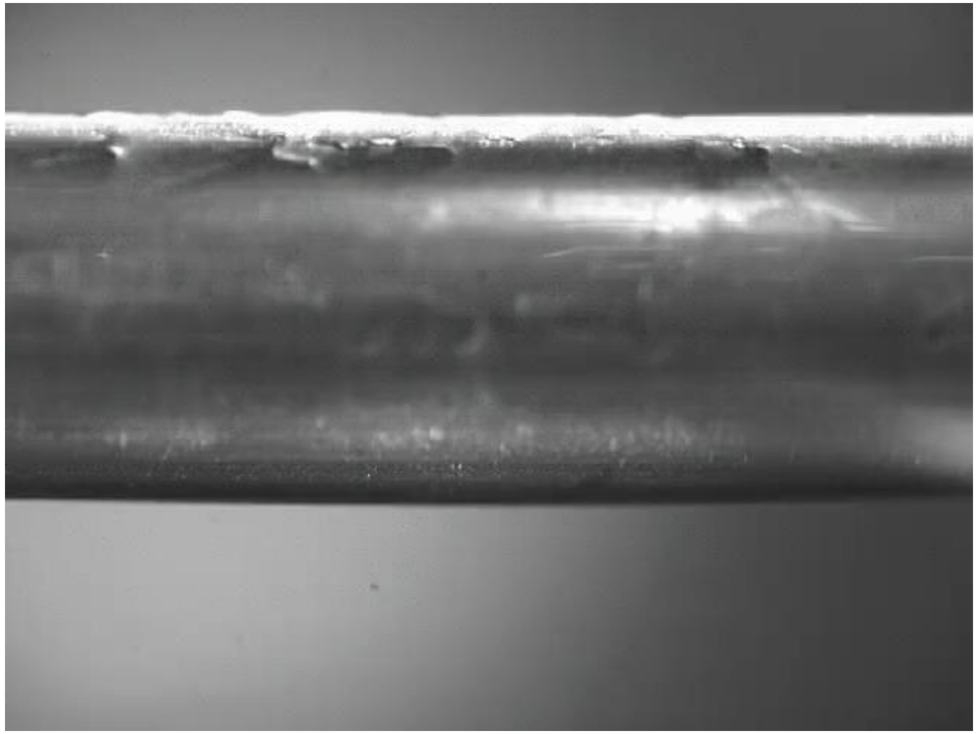
$$h_{dc} = T_v^{0.8}[5 + 0.3(T_{sat} - T_w)]$$ Eq. 9.42 in Carey

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

Dropwise vs Filmwise Condensation

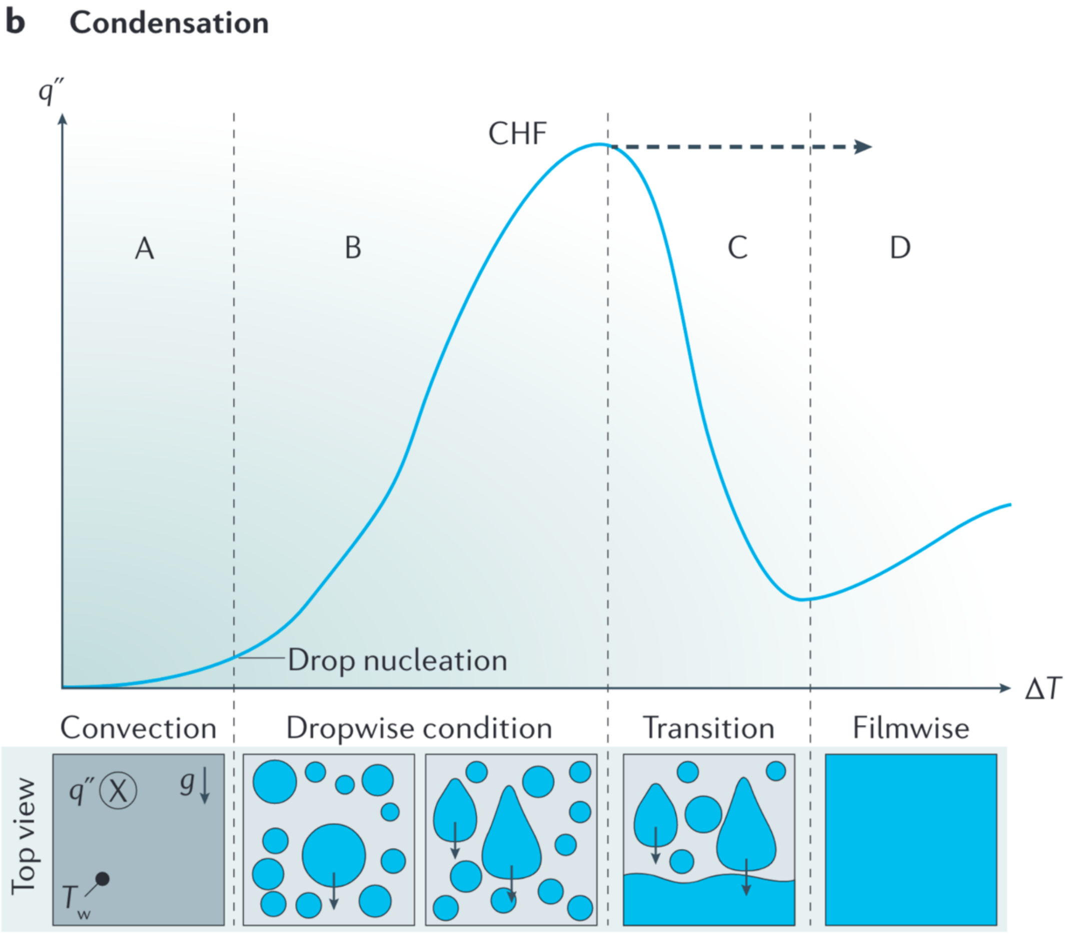


Dropwise condensation



Filmwise condensation

Dropwise vs Filmwise Condensation



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

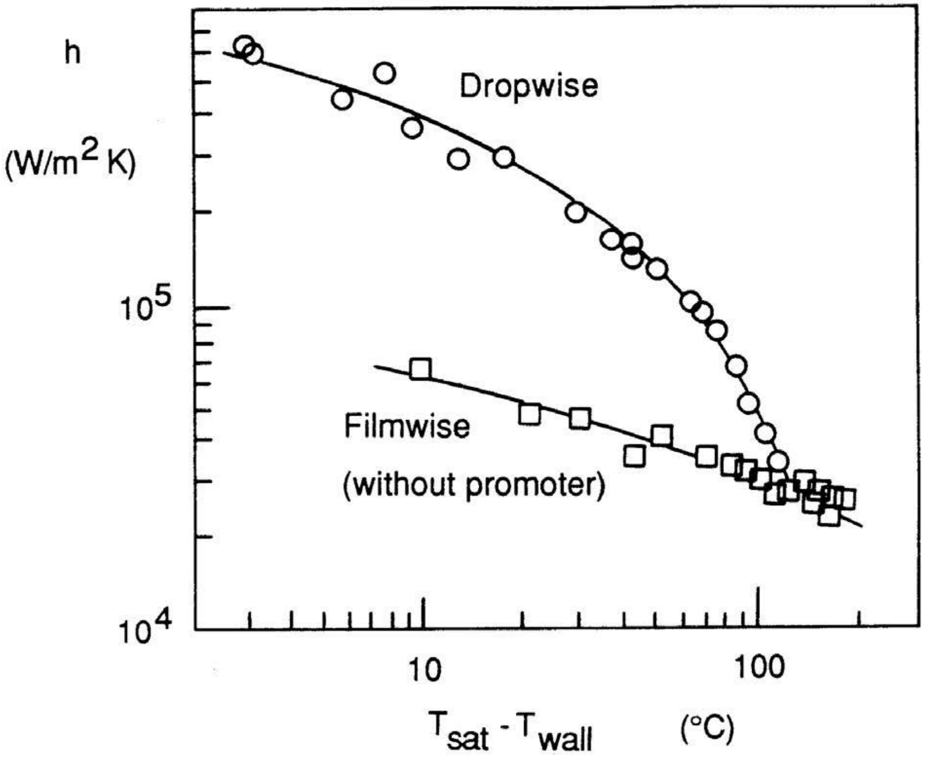
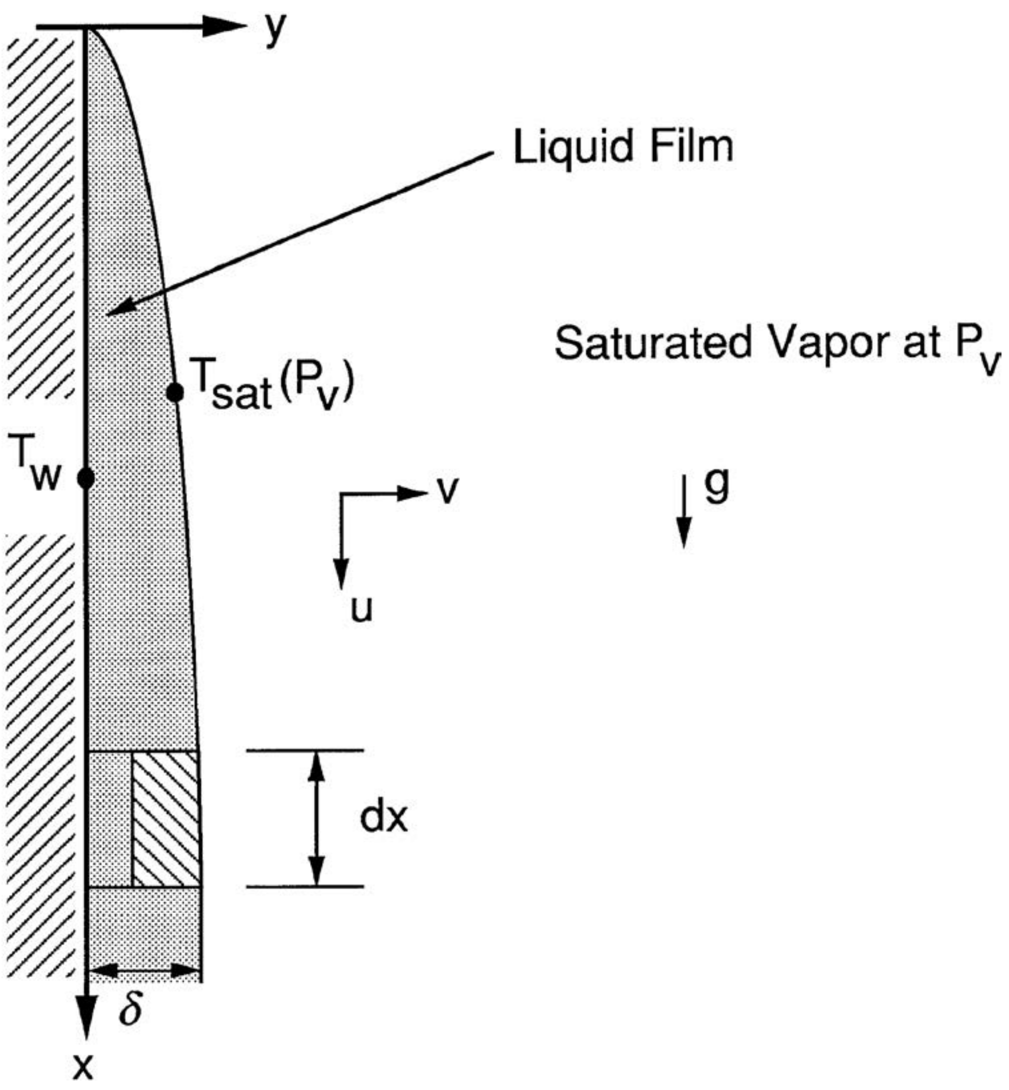
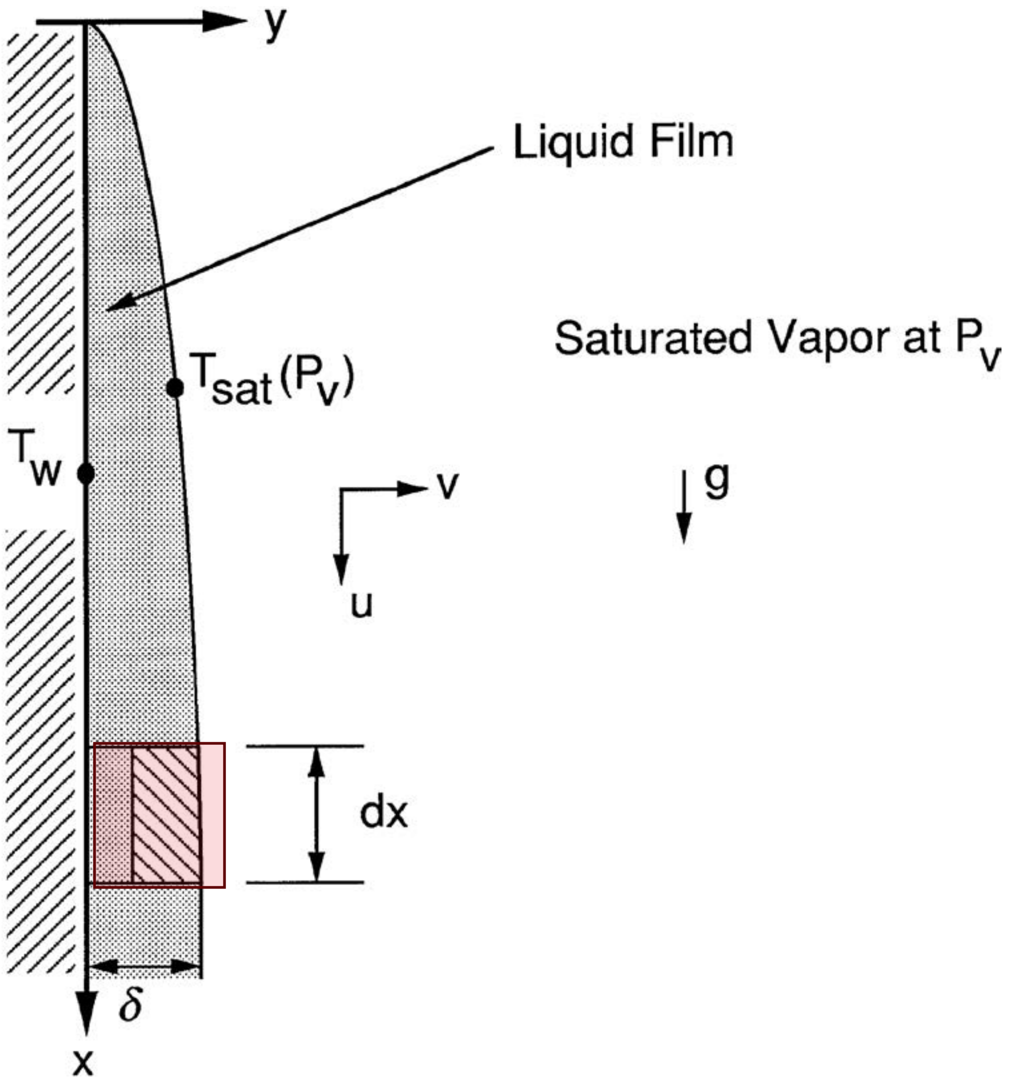


Figure 9.6 in Carey

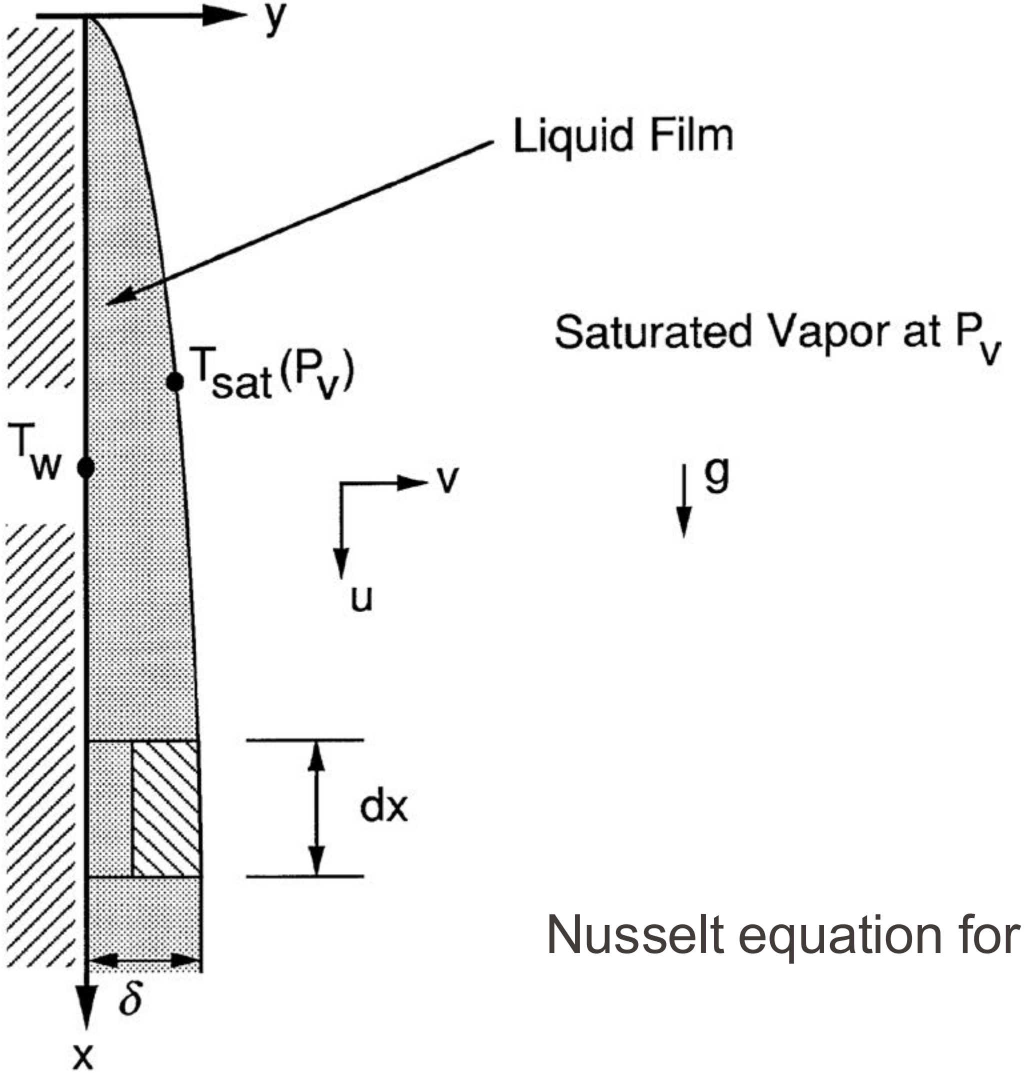
Filmwise Condensation on a Flat Vertical Surface



Energy Balance



Filmwise Condensation HTC



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.