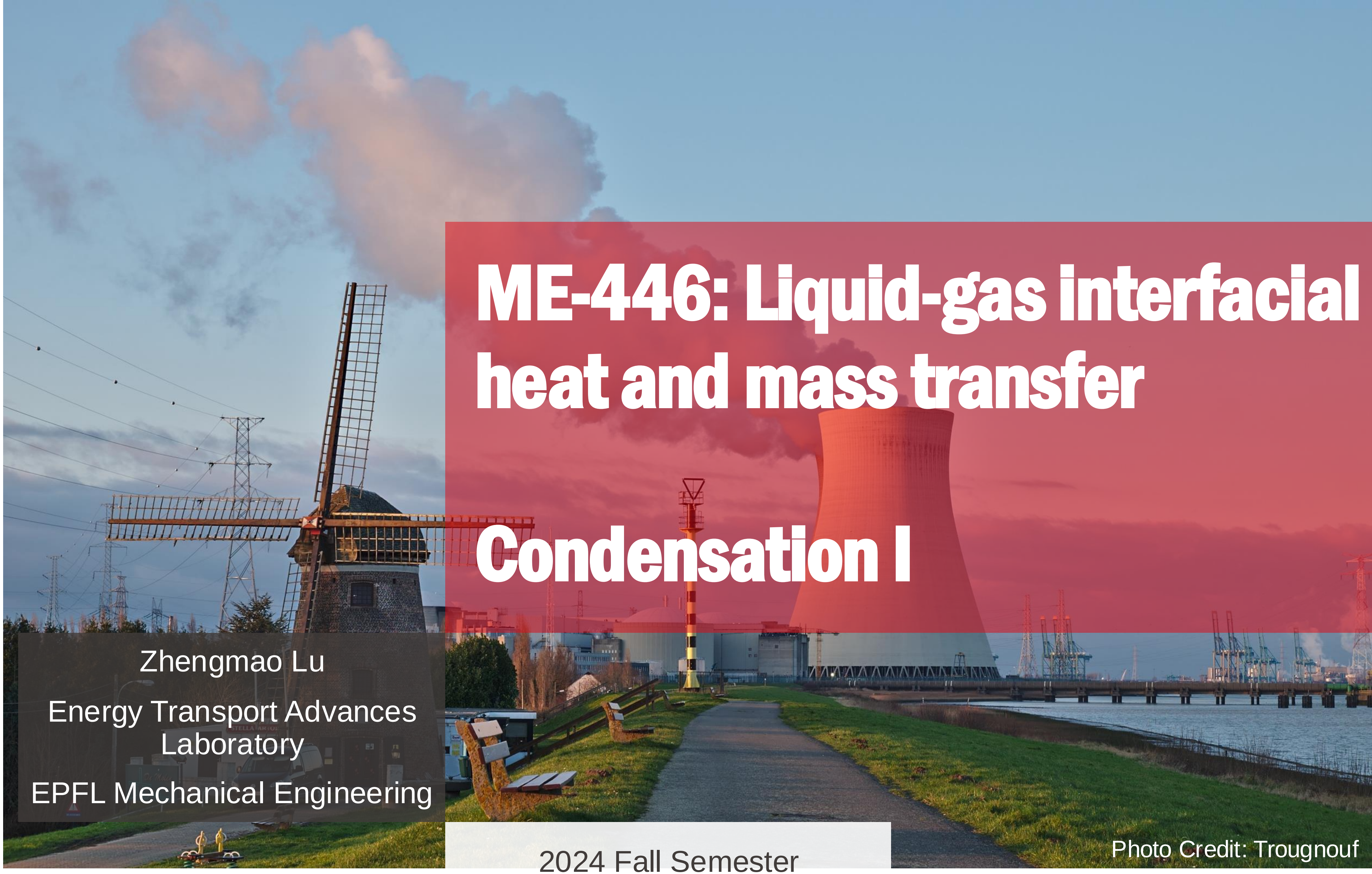
EPFL

ETA-Lab
Energy Transport Advances



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

Condensation I

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Energy Transport Advances Laboratory

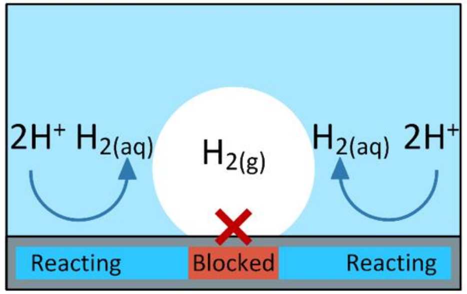
EPFL Mechanical Engineering

2024 Fall Semester

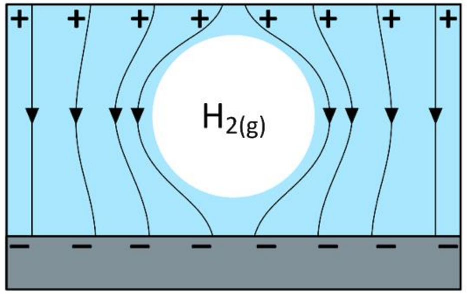
Photo Credit: Trougnouf

Last Time

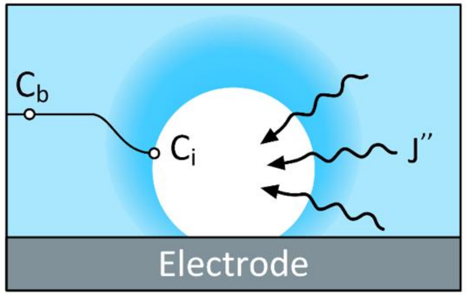
Bubbles and electrochemical reactions



Blocking reaction area



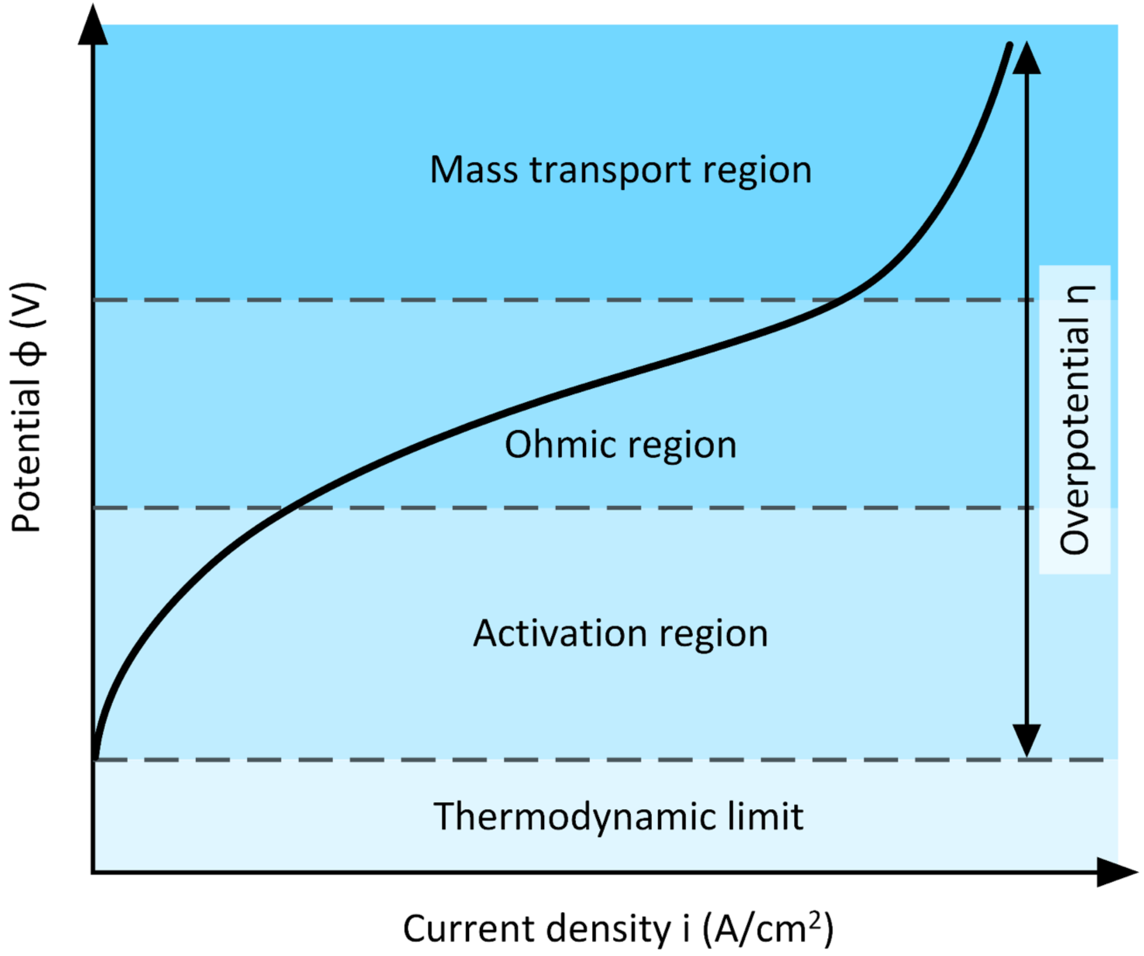
Additional resistance for ion transport



Additional diffusion resistance

Bubble-induced convection

Impact on Electrochemical Overpotentials

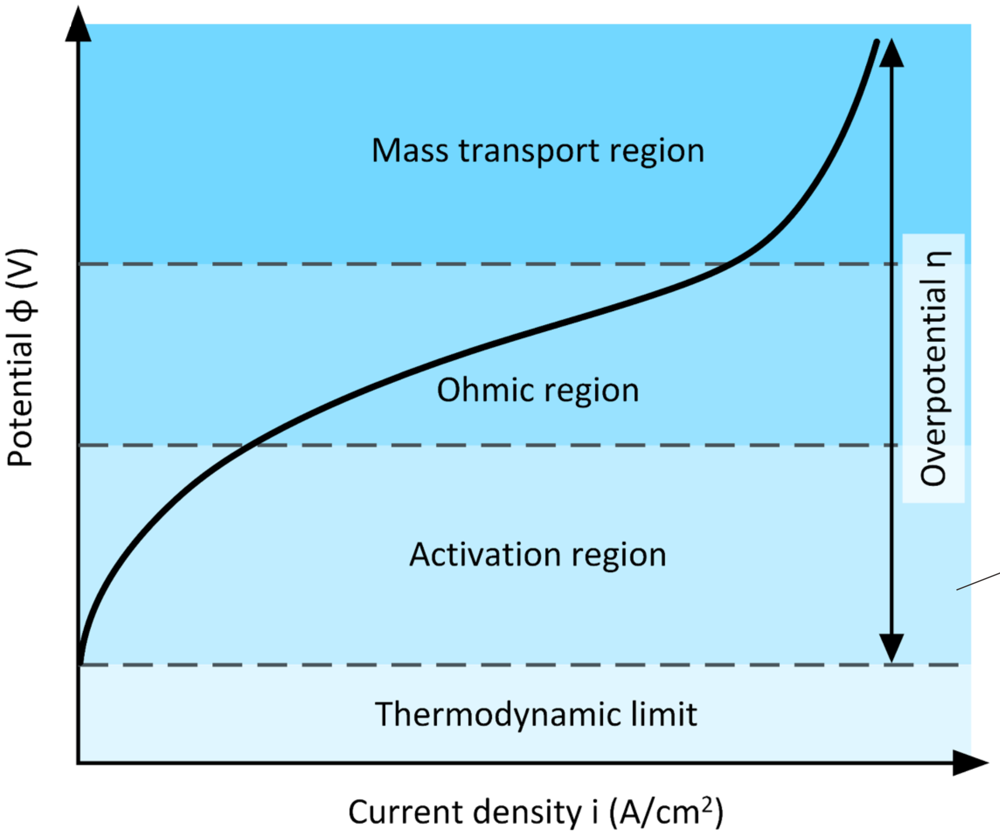


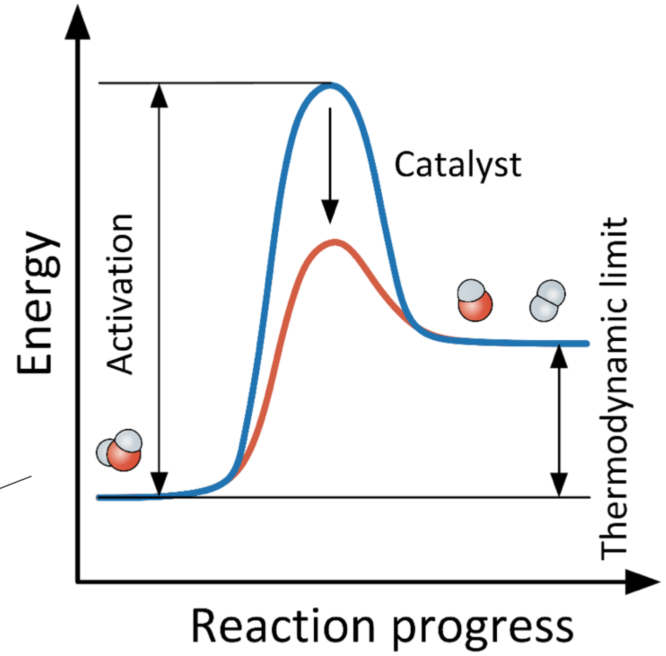
Overpotential (η) is the additional voltage required to drive the electrochemical process over the thermodynamic limit ϕ_{th}

Energy efficiency of an electrolytic cell

$$\epsilon = \frac{\phi_{\mathrm{th}}}{\eta + \phi_{\mathrm{th}}}$$

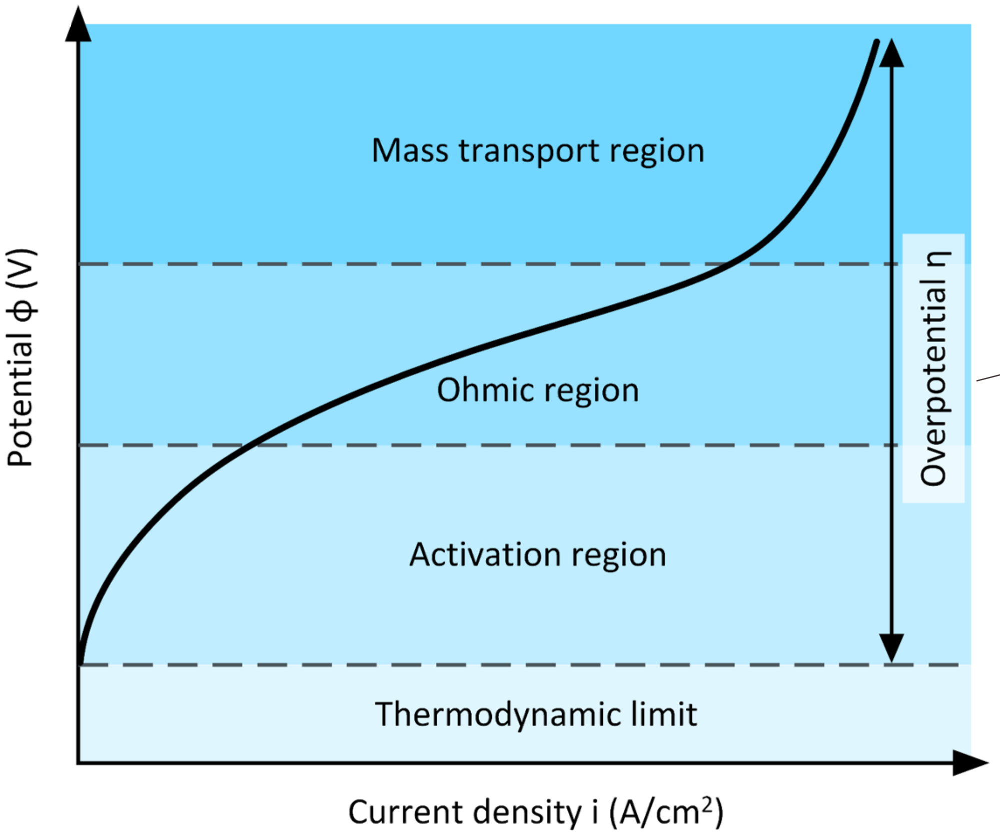
Activation Overpotentials

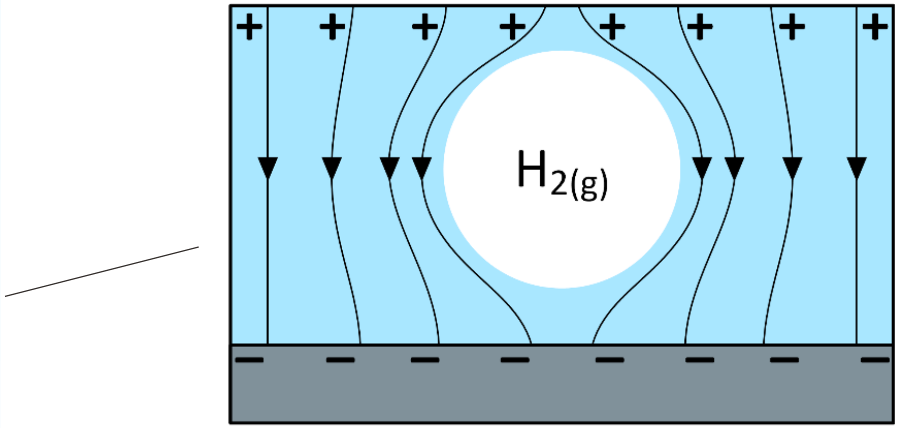




Activation overpotential η_{act} depends on the performance of the electrocatalyst

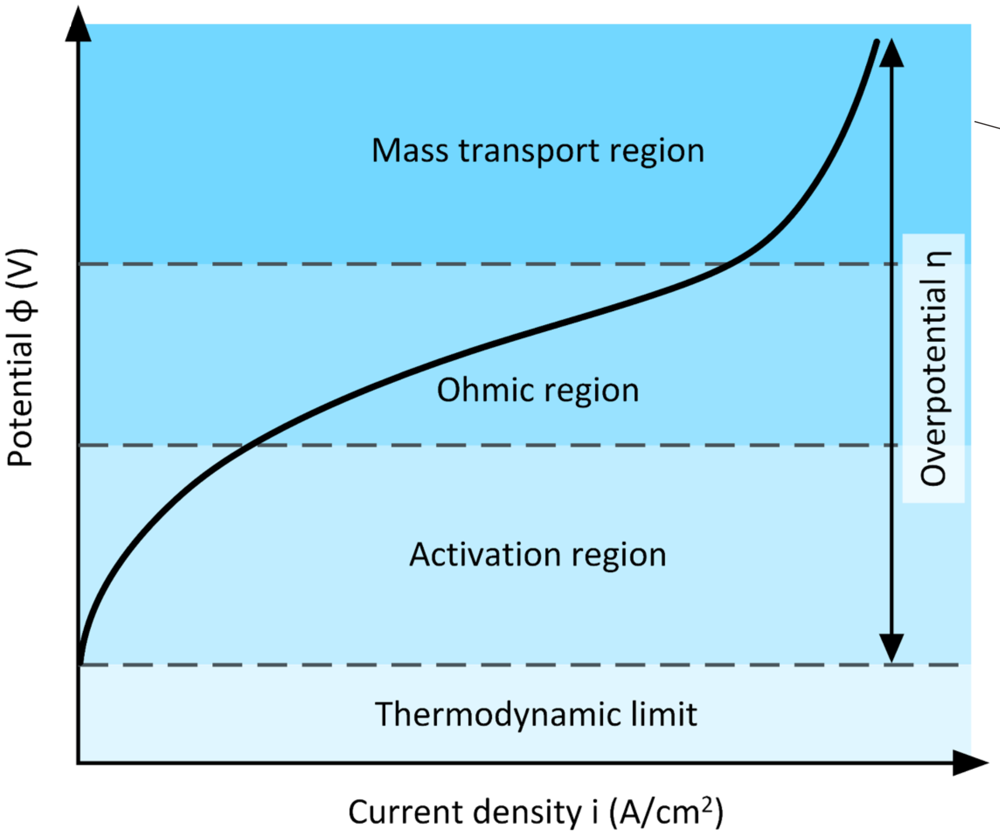
Ohmic Overpotentials

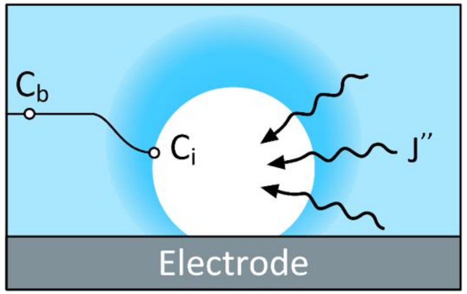




Gas bubbles are electrically insulating, which creates additional resistance for ion transport across the electrolyte

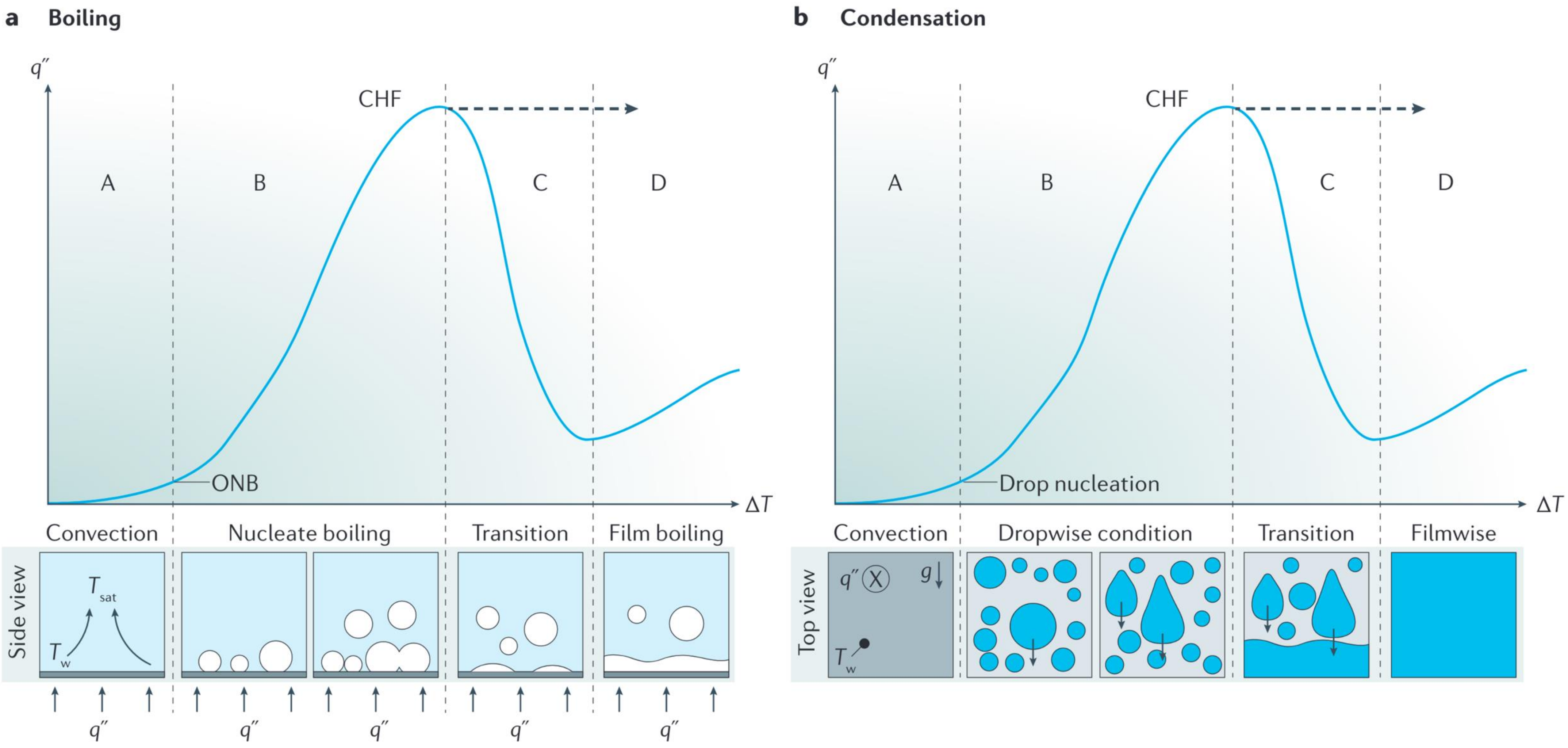
Concentration Overpotentials





At higher current densities, the reaction may be limited by how quickly the reactants and products are transferred to and away from the electrode (not driven by electrical field)

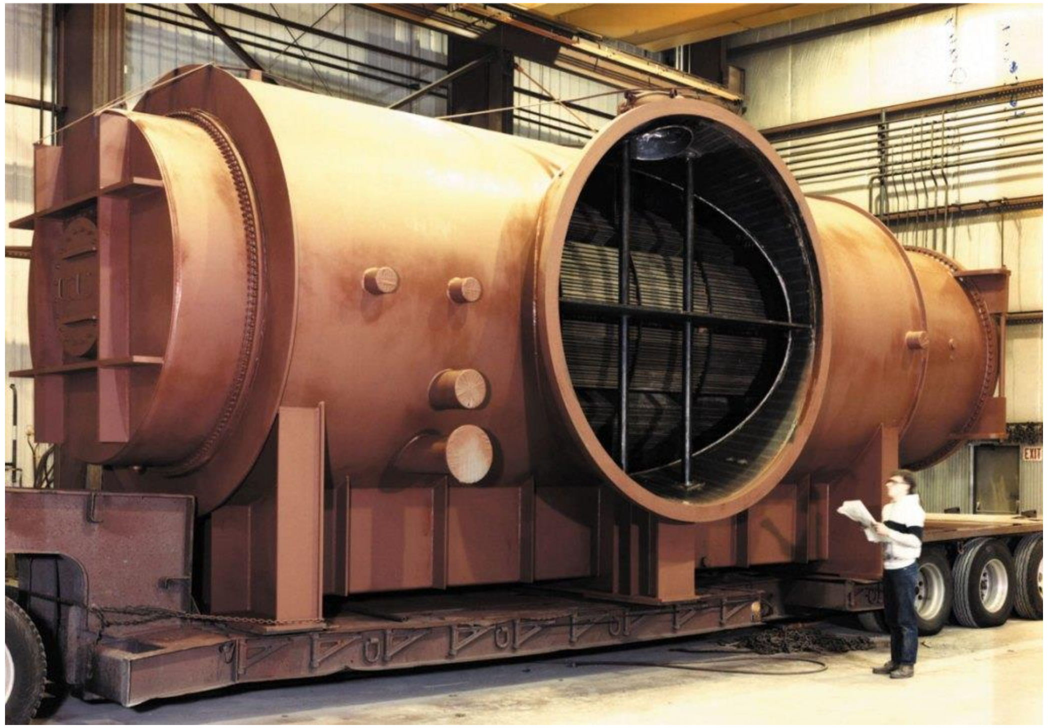
Boiling vs Condensation



DOI: 10.1038/natrevmats.2016.92

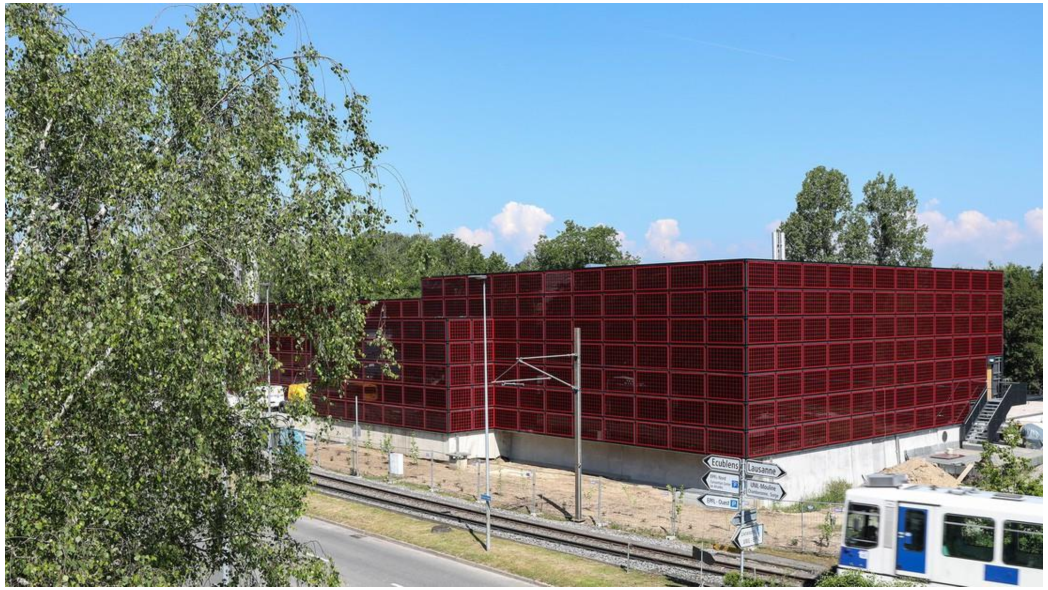
Why Condensation Matters

Ashalim Solar Power Station



Condenser, Holtec

Why Condensation Matters



EPFL Data Center

Condensers, STACK

Intended Learning Objectives

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

Carey, Chapter 9

Droplet Embryo

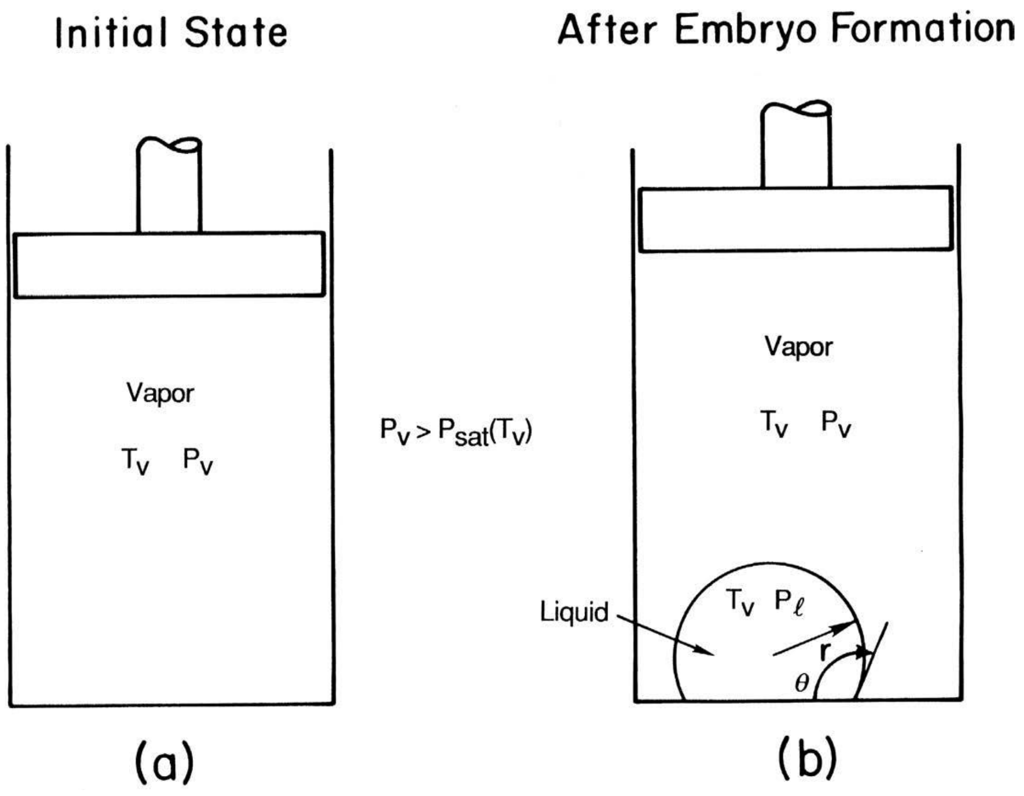


Figure 9.2 in Carey

(b) – (a)

At equilibrium, assume $r = r_e$

$$\hat{g}_v = \hat{g}_l \qquad P_l - P_v = 2\sigma/r_e$$

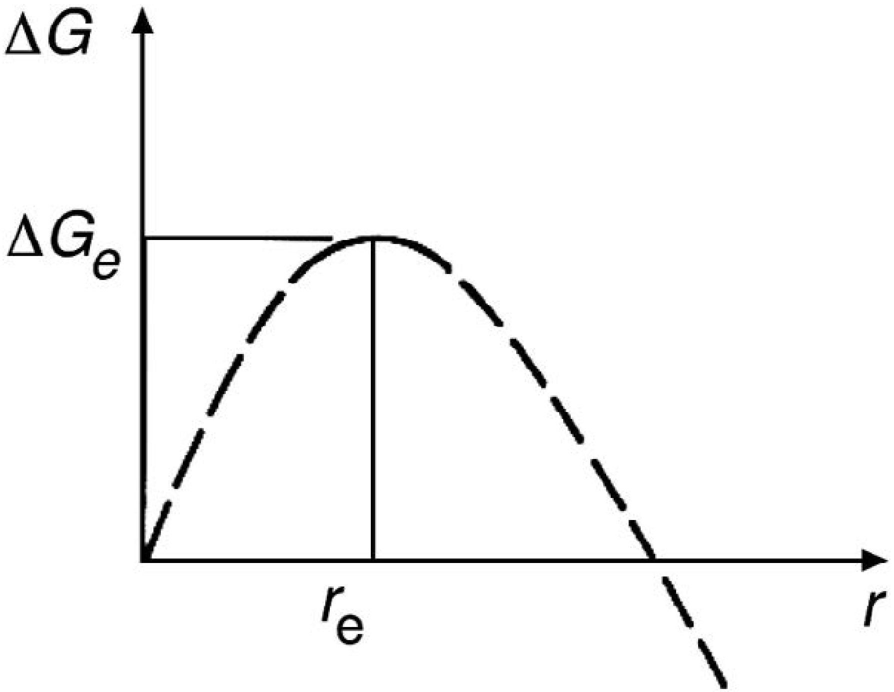
$$\frac{\partial \Delta G}{\partial r} = 0 \Rightarrow \Delta G_e = \frac{4}{3}\pi r_e^2 \sigma_{lv} F_\theta$$

$$F_\theta = 2 - 3\cos\theta + \cos^3\theta$$

Droplet Embryo

- Tailor expansion of ΔG near r_e

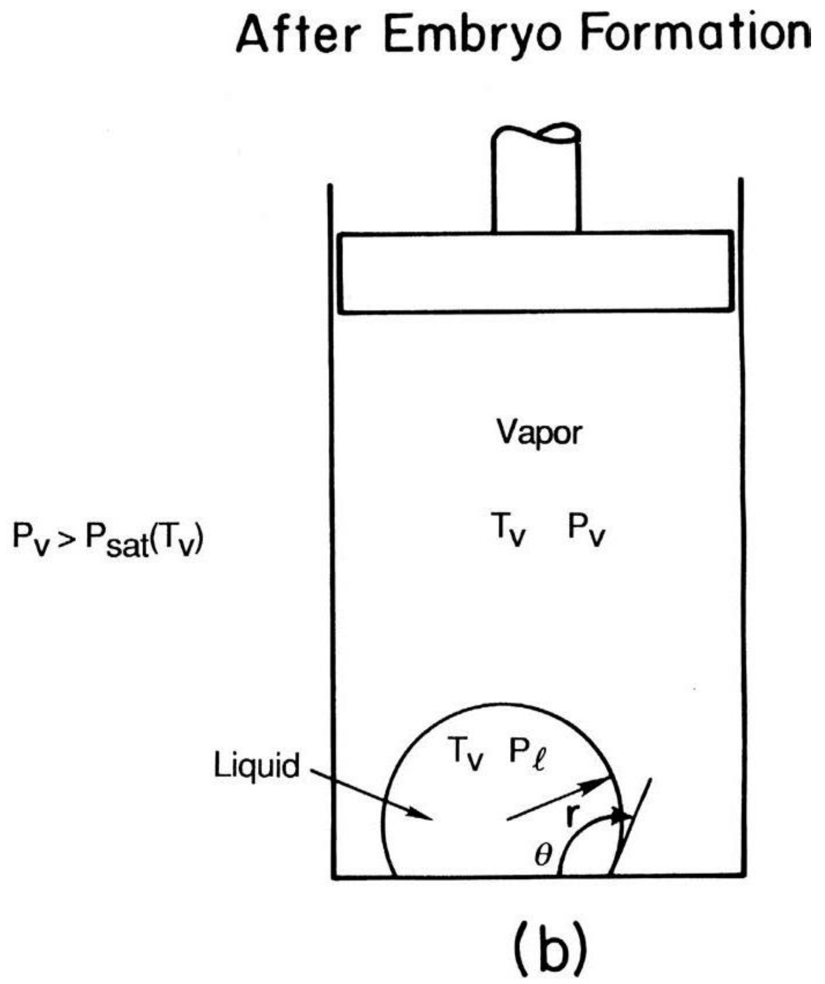
$$\Delta G = \Delta G_e - 4\pi\sigma_{lv}F_\theta(r - r_e)^2 + \cdots$$



Density fluctuation in supercooled vapor produces droplets of random r

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

Equilibrium Droplet Radius



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

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

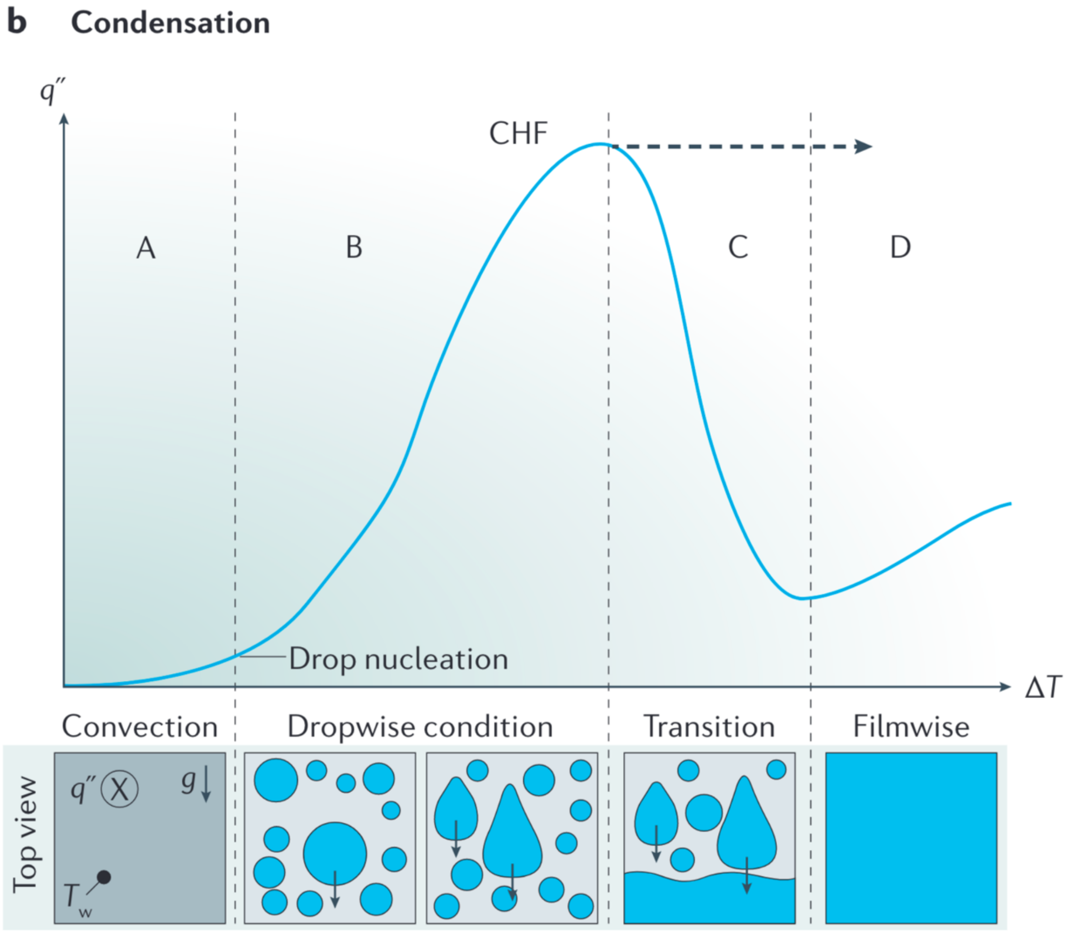
$$g_l - g_{sat} = \int_{P_{sat}}^{P_l} v_l dP = v_l(P_l - P_{sat})$$

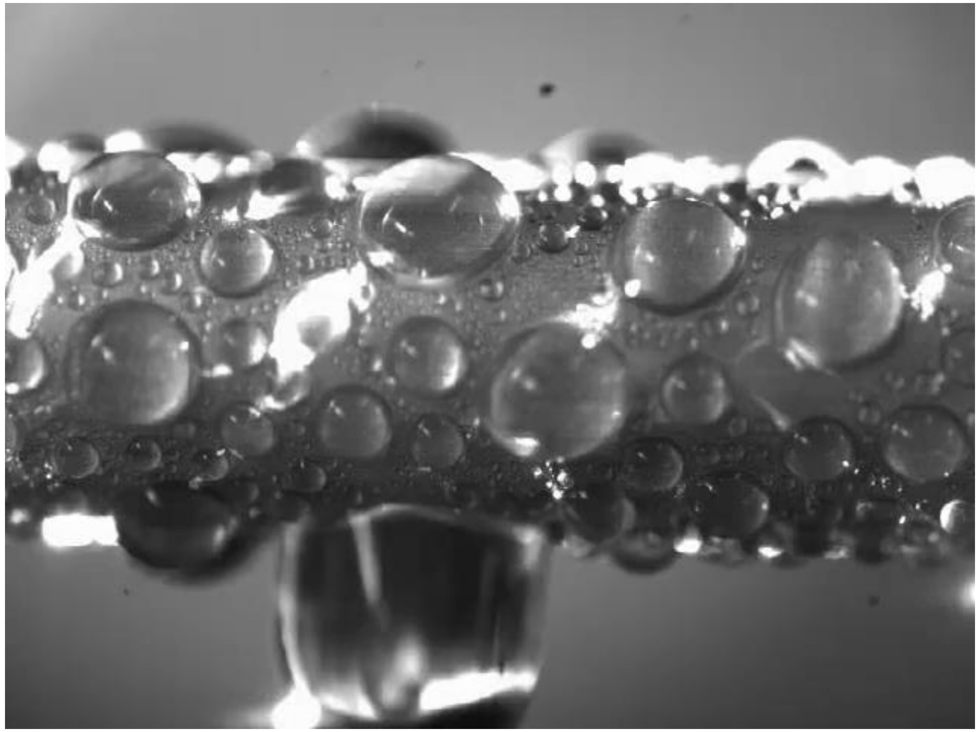
$$P_l - P_v = 2\sigma / r_e$$

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

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

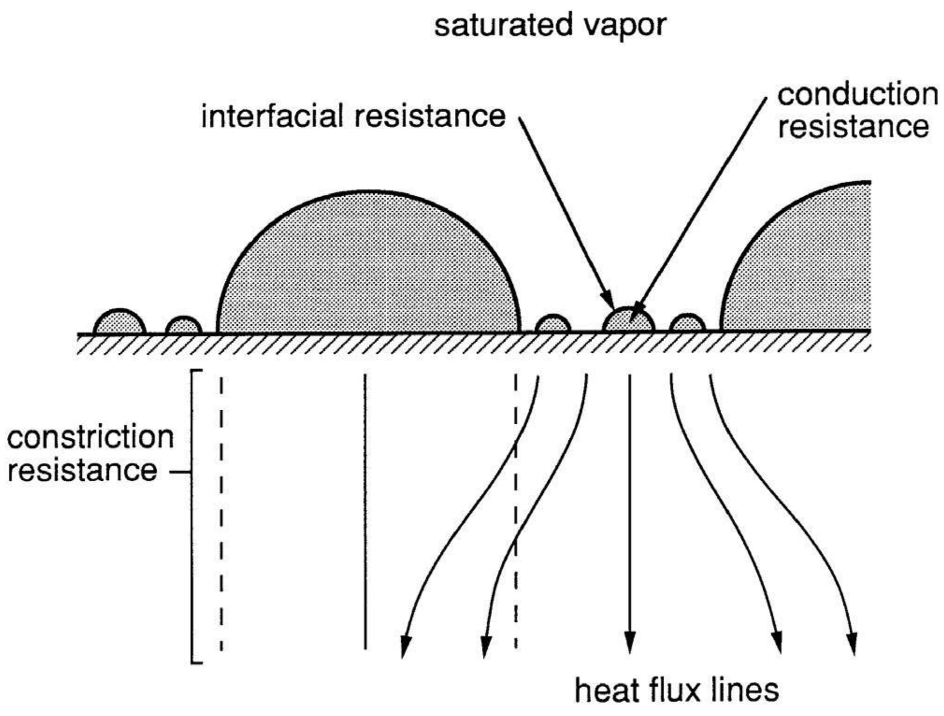
Dropwise Condensation





https://doi.org/10.1021/nl303835d

Thermal Resistance Associated with a Droplet



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

Interfacial Resistance

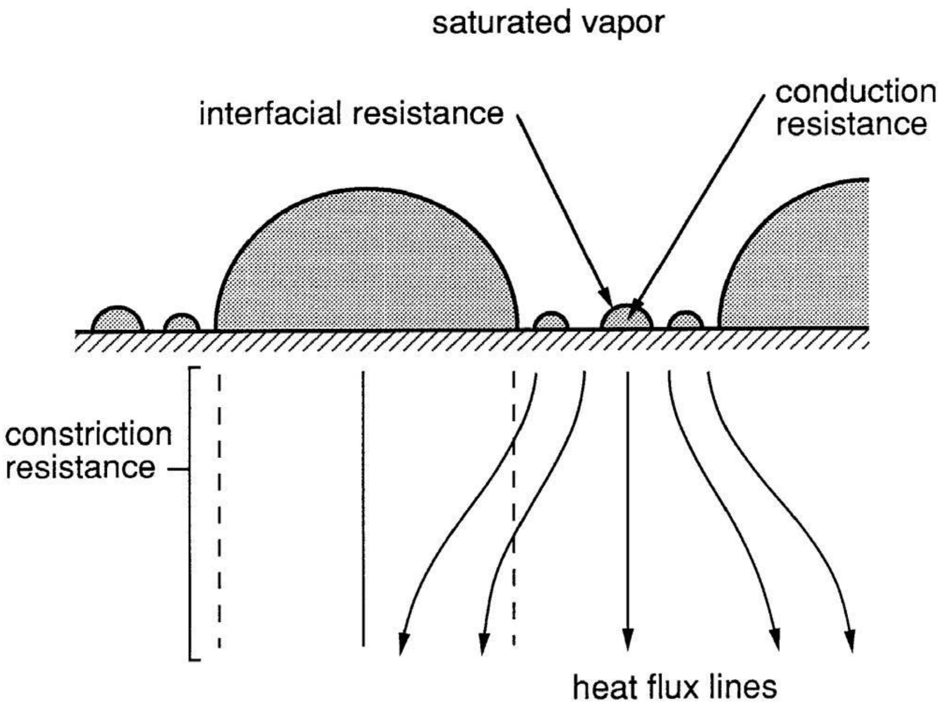
- Schrage equation (condensation)

$$
\begin{aligned}
q_i'' &= \left(\frac{2\hat{\sigma}}{2-\hat{\sigma}}\right) h_{lv} \sqrt{\frac{1}{2\pi R}} \left(\frac{P_v}{\sqrt{T_v}} - \frac{P_l}{\sqrt{T_l}}\right) \\
&= \left(\frac{2\hat{\sigma}}{2-\hat{\sigma}}\right) h_{lv} \sqrt{\frac{1}{2\pi R}} \left(\frac{P_v}{\sqrt{T_v}} - \frac{P_l}{\sqrt{T_v}} + \frac{P_l}{\sqrt{T_v}} - \frac{P_l}{\sqrt{T_l}}\right) \\
&\approx \left(\frac{2\hat{\sigma}}{2-\hat{\sigma}}\right) h_{lv} \sqrt{\frac{1}{2\pi R}} \left(\frac{\Delta P}{\sqrt{T_v}} - \frac{1}{2}(P_v - \Delta P) T_v^{-\frac{3}{2}} \Delta T\right) \\
&\approx \left(\frac{2\hat{\sigma}}{2-\hat{\sigma}}\right) h_{lv} \sqrt{\frac{1}{2\pi R T_v}} \left(\frac{\Delta P}{\Delta T} - \frac{1}{2} P_v T_v^{-1}\right) \Delta T \\
&\approx \left(\frac{2\hat{\sigma}}{2-\hat{\sigma}}\right) \frac{\rho_v h_{lv}^2}{T_v} \sqrt{\frac{1}{2\pi R T_v}} \left(1 - \frac{P_v}{2\rho_v h_{lv}}\right) \Delta T
\end{aligned}
$$

Clausius-Clapeyron

$$\frac{dP}{dT} \approx \frac{\rho_v h_{lv}}{T}$$ on the saturation curve

Interfacial Resistance



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

$$\Delta T_i = \frac{q_d}{2\pi r^2 h_i} \qquad q_d \text{ [W]}$$

Hemispherical shape assumed

Curvature-Induced Resistance

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

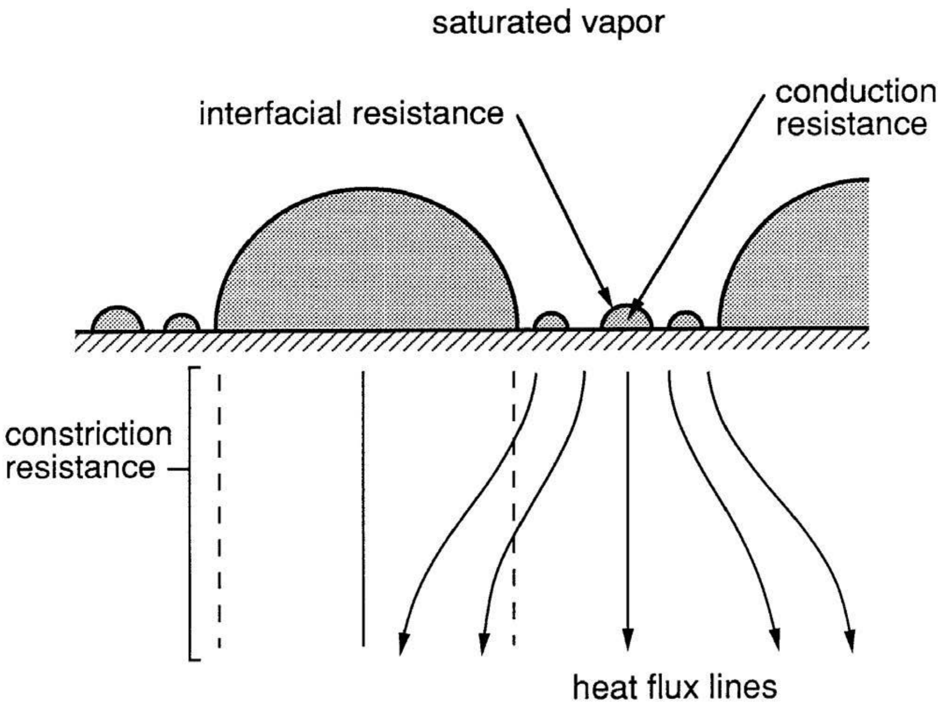
$$r \approx \frac{2\sigma}{\frac{RT_{eq}}{v_l}\ln\left(\frac{P_v}{P_{sat}(T_{eq})}\right)}$$

Clausius-Clapeyron $\quad \frac{dP}{dT} = \frac{\rho_v h_{lv}}{T} = \frac{P h_{lv}}{RT^2} \Rightarrow \frac{dP}{P} = \frac{h_{lv}}{RT^2}dT \Rightarrow d\ln P = -\frac{h_{lv}}{R}d\frac{1}{T}$

$$r \approx \frac{2\sigma}{-\frac{RT_{\mathrm{eq}}}{v_l}\cdot\frac{h_{lv}}{R}\left(\frac{1}{T_{sat}(P_v)} - \frac{1}{T_{eq}}\right)} = \frac{2\sigma v_l T_{sat}(P_v)}{h_{lv}\left(T_{sat}(P_v) - T_{eq}\right)}$$

$$\Delta T_{cap} = \frac{2\sigma v_l T_{sat}(P_v)}{h_{lv} r}$$

Conduction Resistance

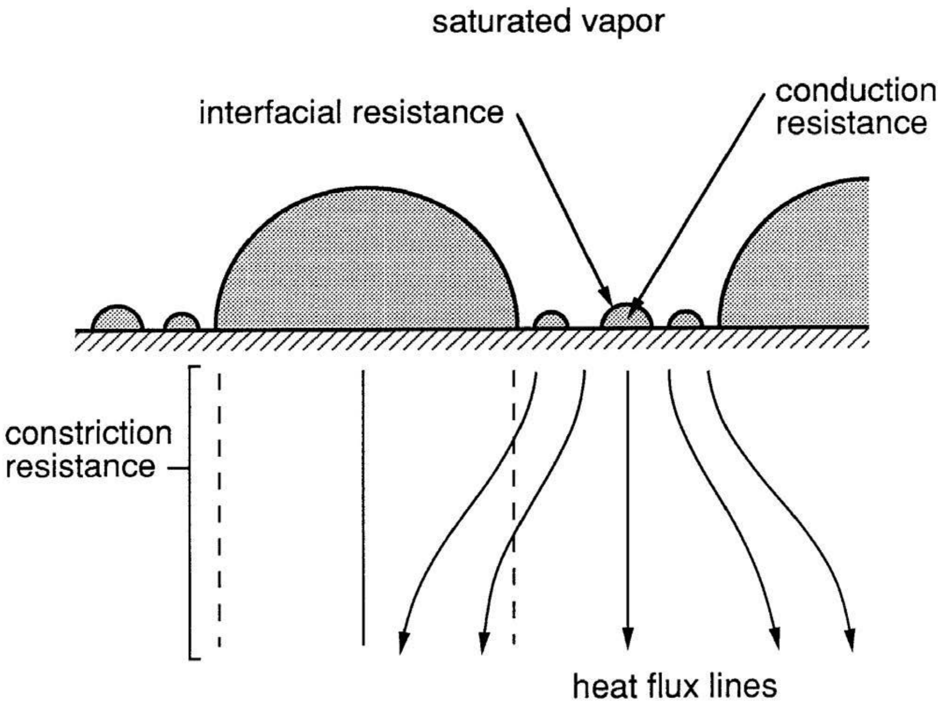


$$q_d \approx \frac{k_l \Delta T_{con}}{r/2} \cdot 2\pi r^2$$

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

q_d [W]

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

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

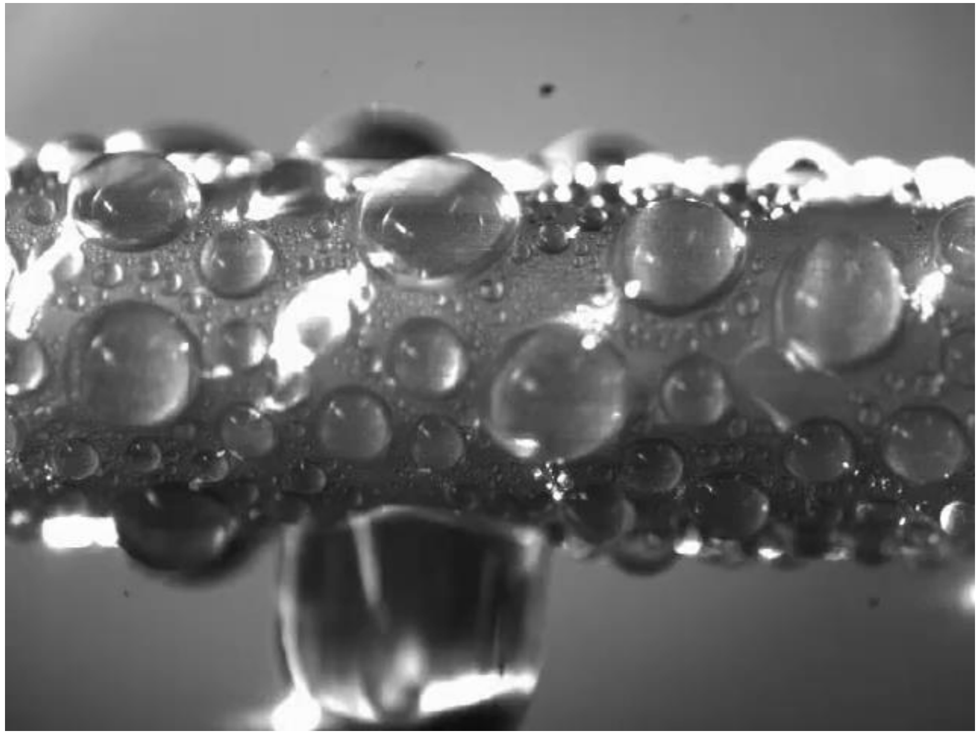
$$h_{dc} = \frac{1}{\Delta T_t} \int_{r_e}^{r_{max}} \frac{q_d}{2\pi r^2} A(r)dr$$

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

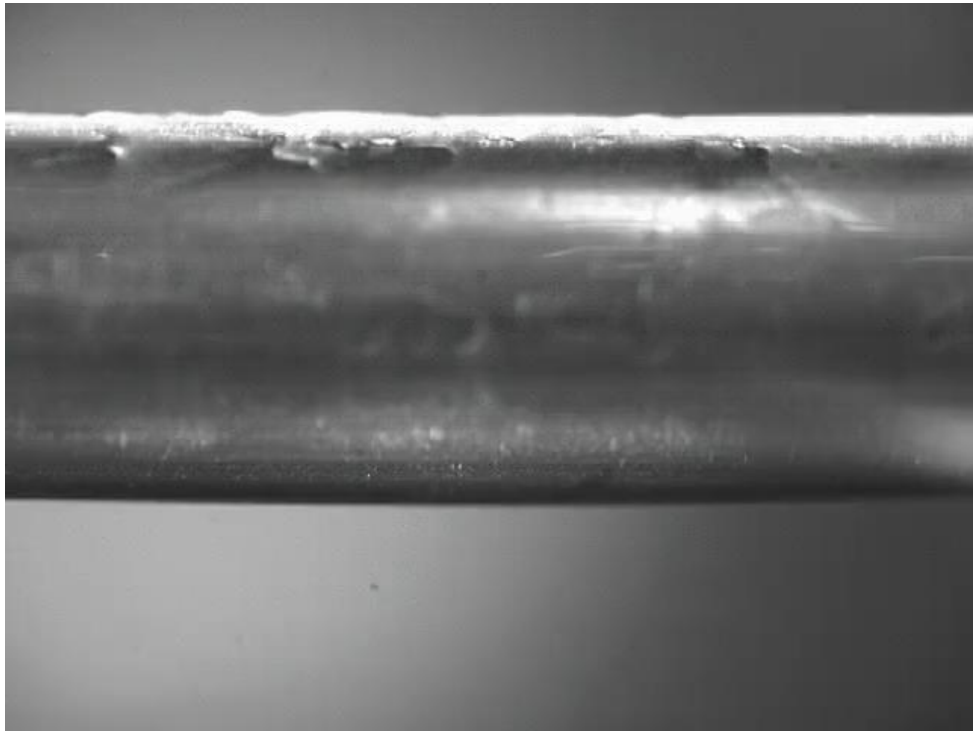
$$h_{dc} = T_v^{0.8}[5 + 0.3(T_{sat} - T_w)]$$ Eq. 9.42 in Carey

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

Dropwise vs Filmwise Condensation

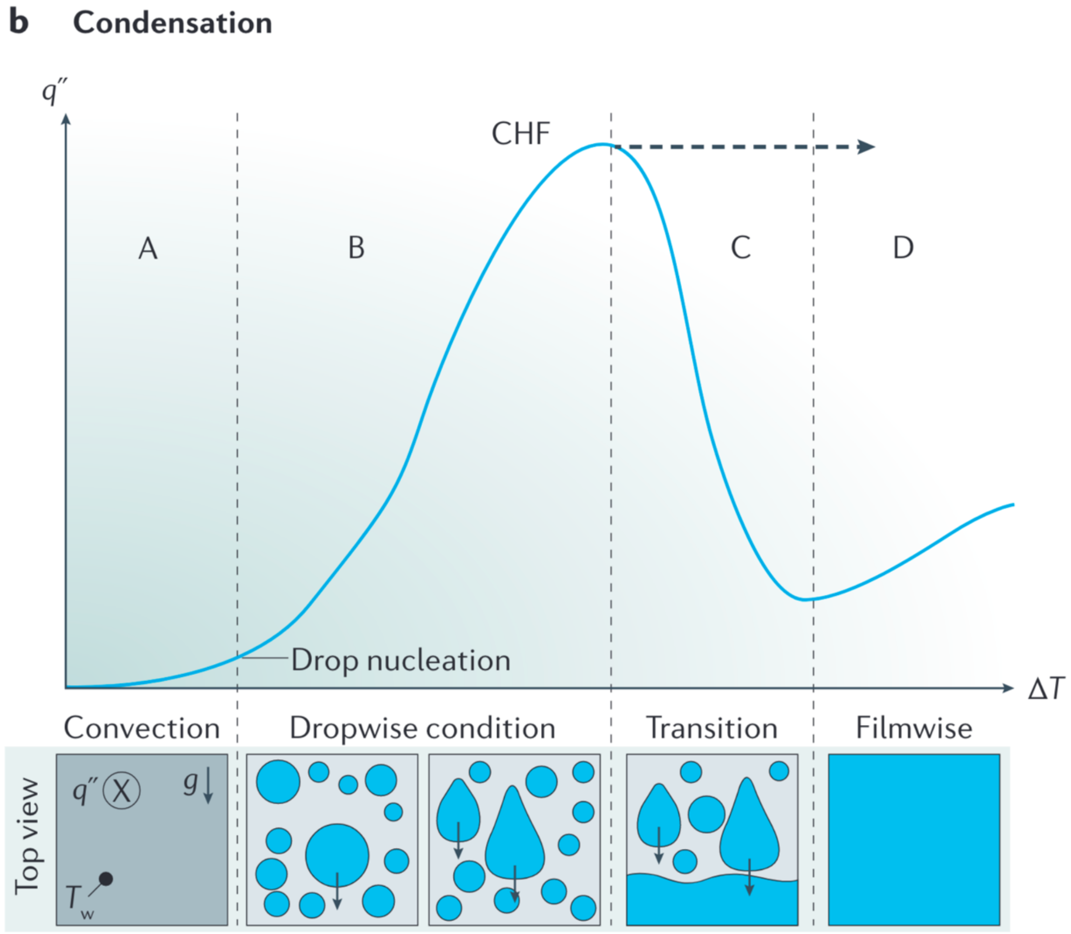


Dropwise condensation



Filmwise condensation

Dropwise vs Filmwise Condensation



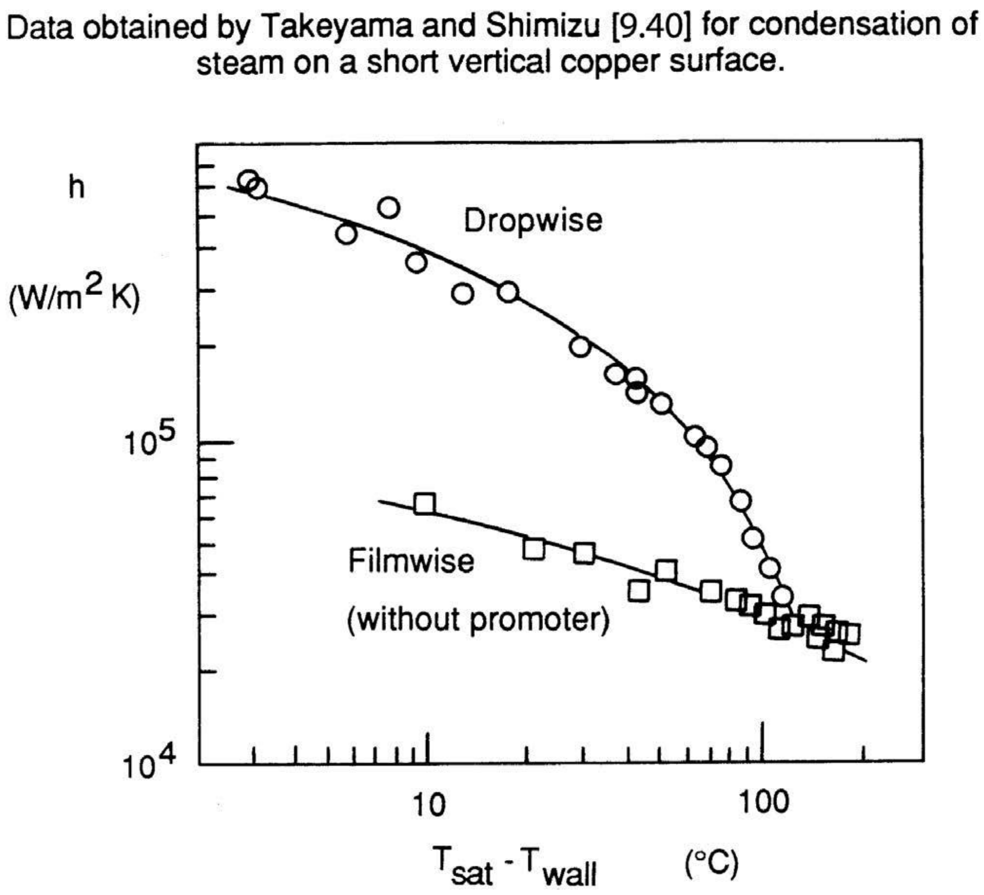
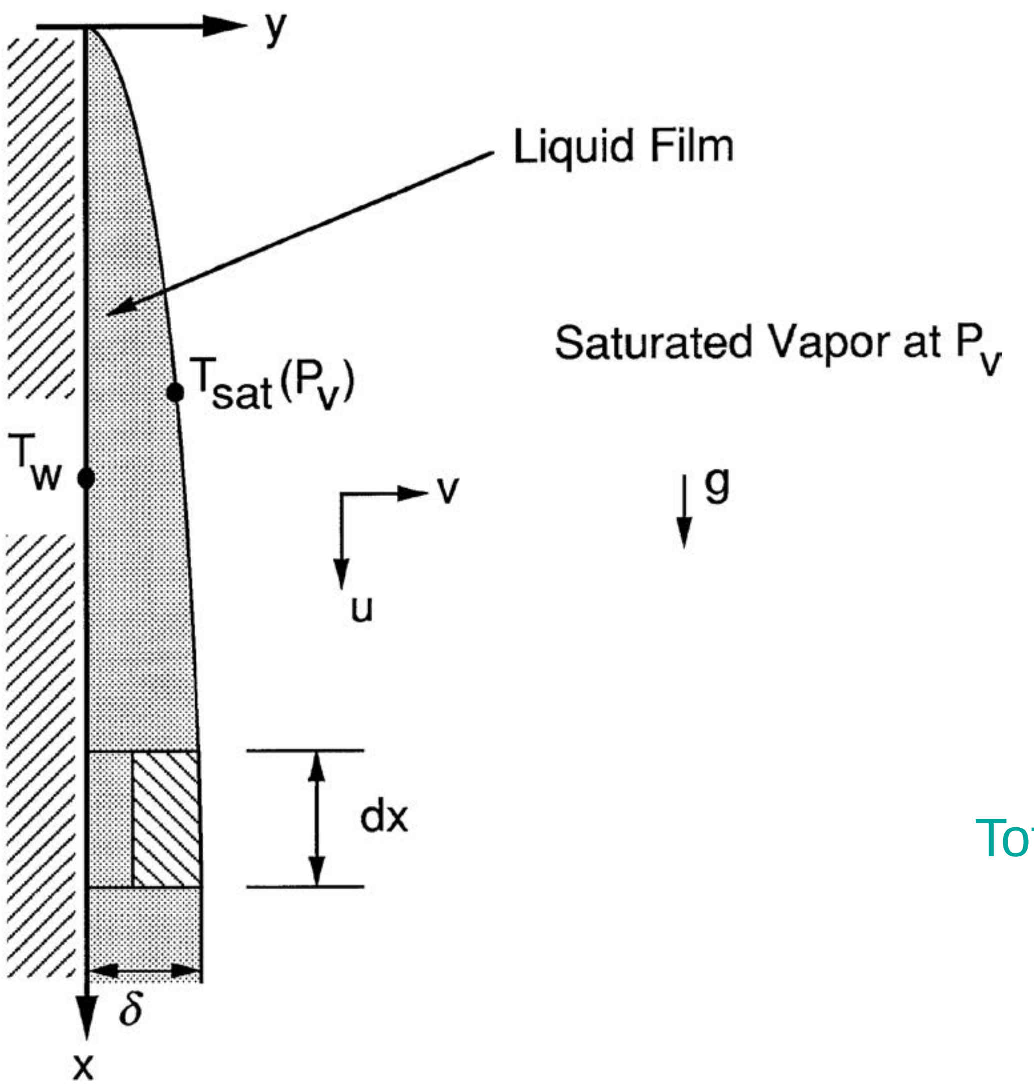


Figure 9.6 in Carey

Filmwise Condensation on a Flat Vertical Surface



Force balance on the shaded film element

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

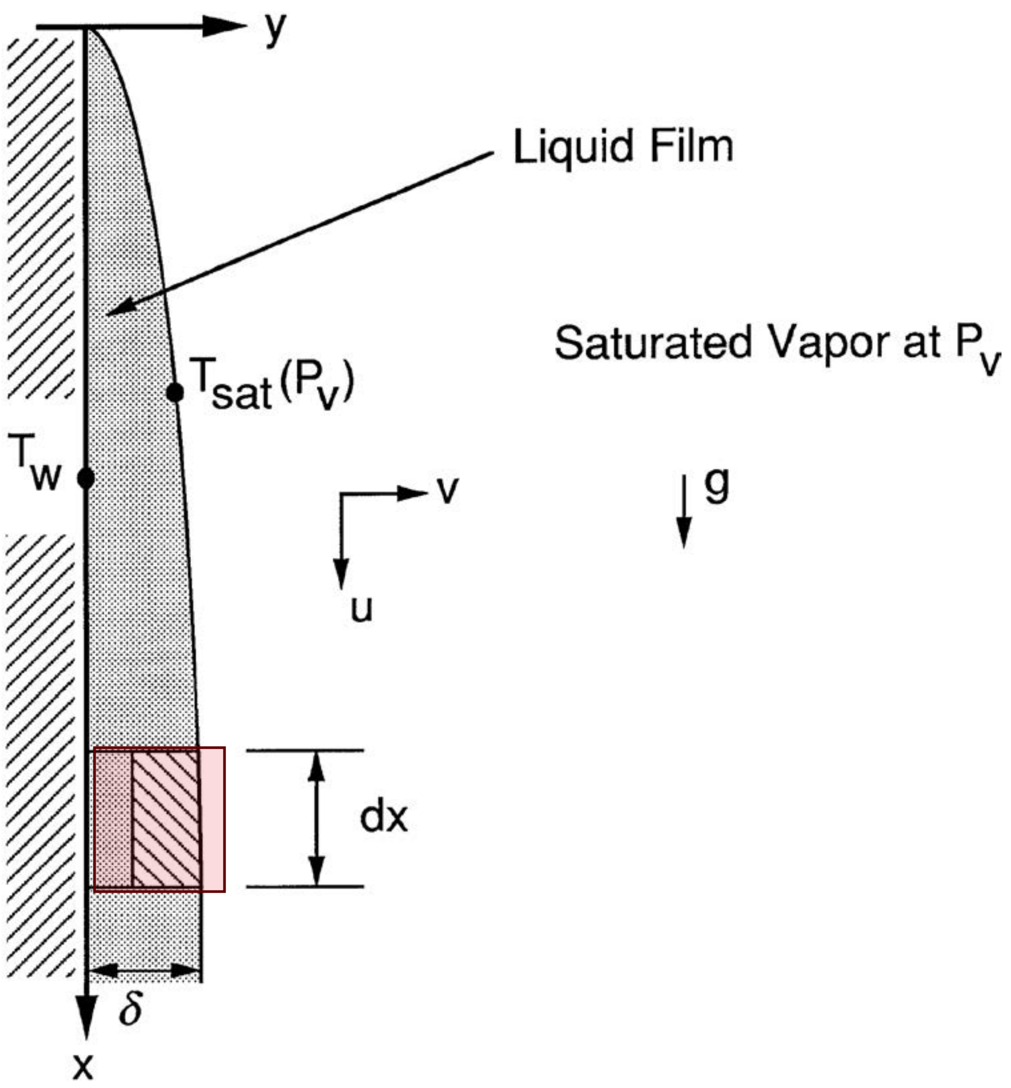
Integrating this equation w.r.t. *y*

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

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



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

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

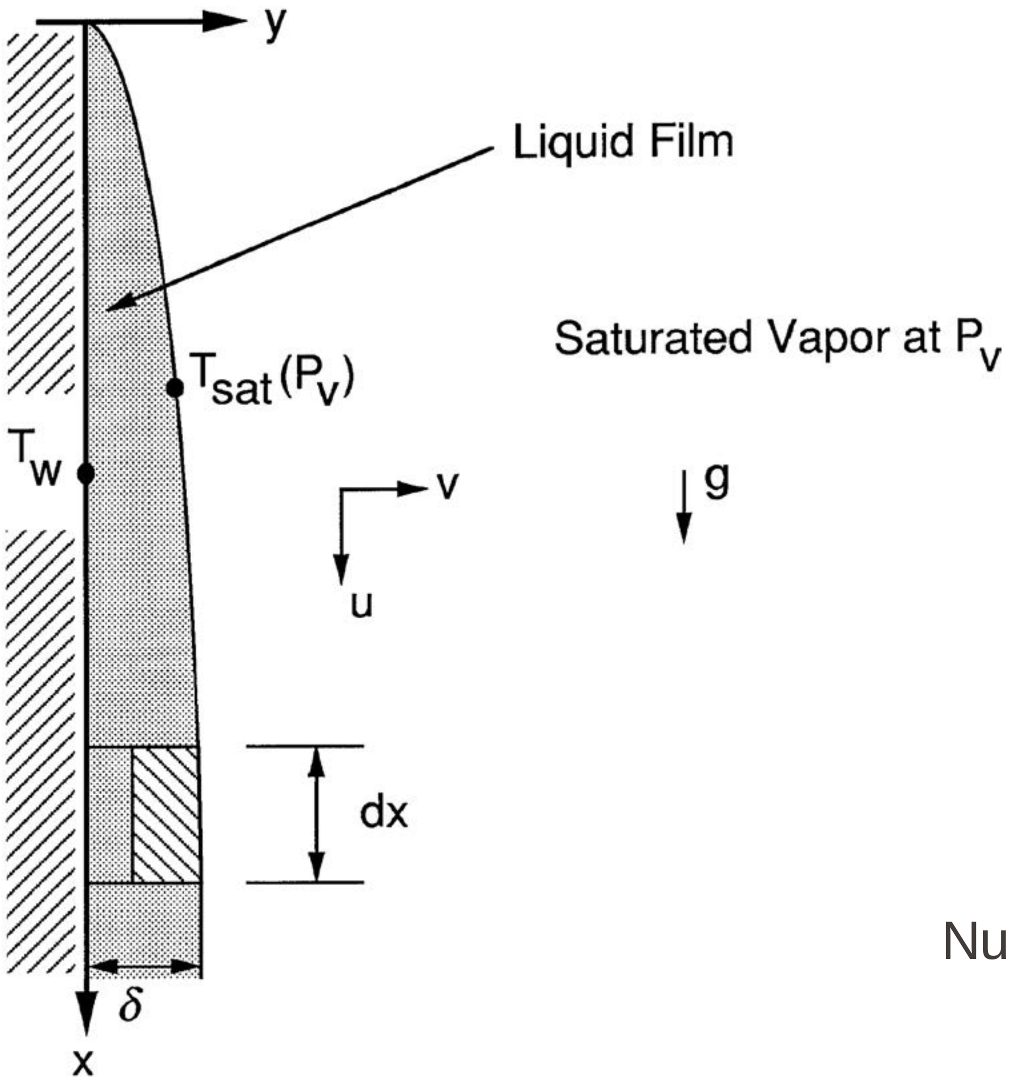
$$\frac{k_l \Delta T}{\delta} = \frac{h_{lv} d\dot{m}'}{dx}$$

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

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.