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

Final Review

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EPFL Mechanical Engineering

2024 Fall Semester

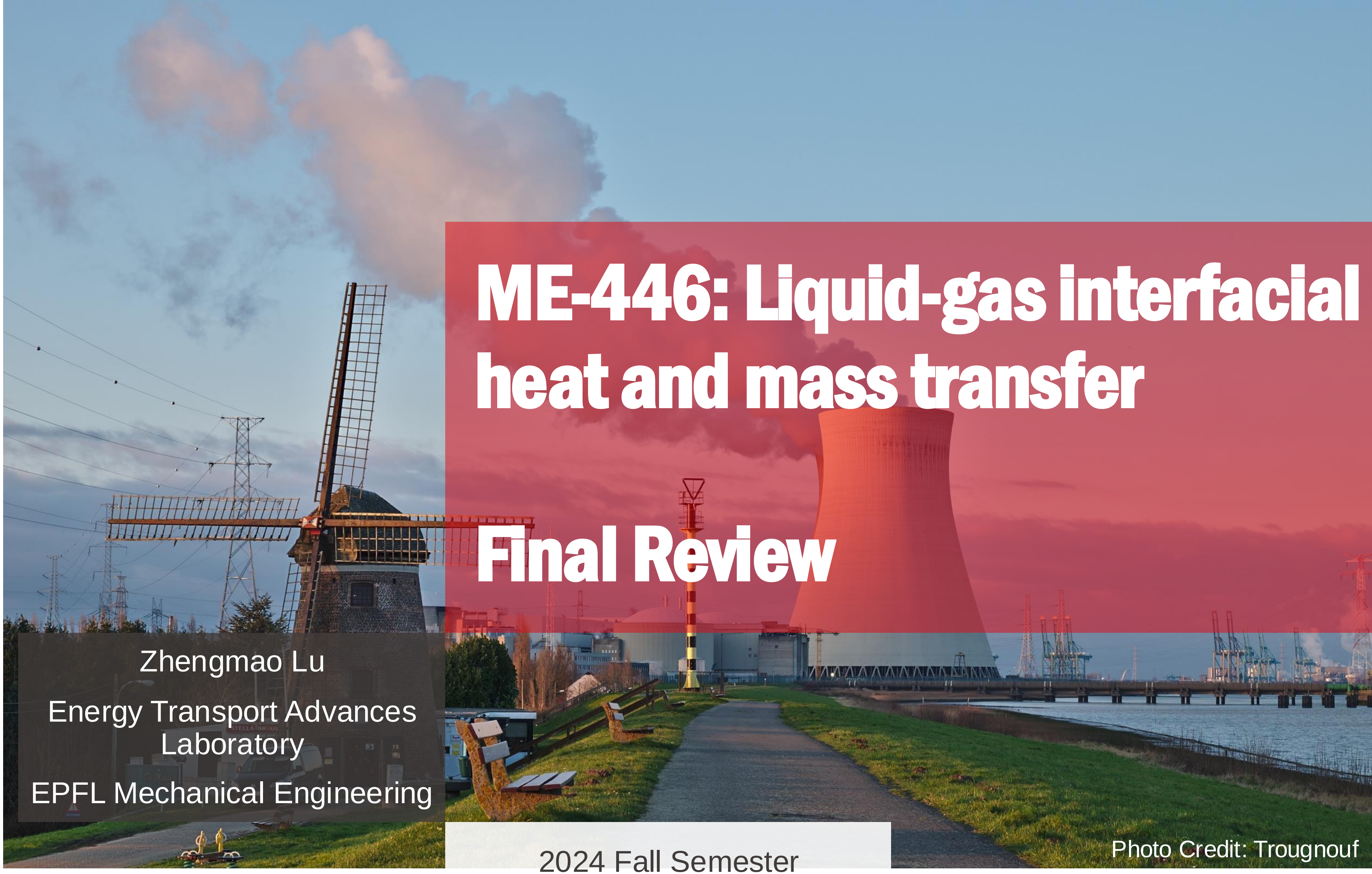


Photo Credit: Trougnouf

Assessment

- Homework presentation 25%
  - In each week's exercise session, 3-4 of you will form a HW group, work together on a problem set, and present your solution to the class.
  - We will post a Google Sheet of the HW group with preassigned names on Moodle, but feel free to trade slots.
  - The rest of the class is also expected to work on the same problem set prior to the exercise session. Solution will be posted the week after for self-correction. You do NOT need to submit anything.
  - For the HW presentation, you get the full score if you show reasonable amount of effort regardless whether you get the correct answer.

Assessment

- Journal presentation 25%

  - We will post several more recent papers in the area of liquid-gas interfacial phenomena. You can sign up for the one that you are most interested.

  - People who choose the same paper form a JP group. Each group has a size limit based on the specific paper. The sign-up sheet and the papers will be posted later, first come first service.

  - In the two weeks before the last lecture week, each JP group will give an oral presentation (presentation period = group size x 5 min + 5 min Q&A)

Assessment

- Final Exam 50%
  - Will be closely related to exercise problems

What We Have Covered This Semester

- Capillarity and wetting
- Evaporation
- Boiling
- Condensation

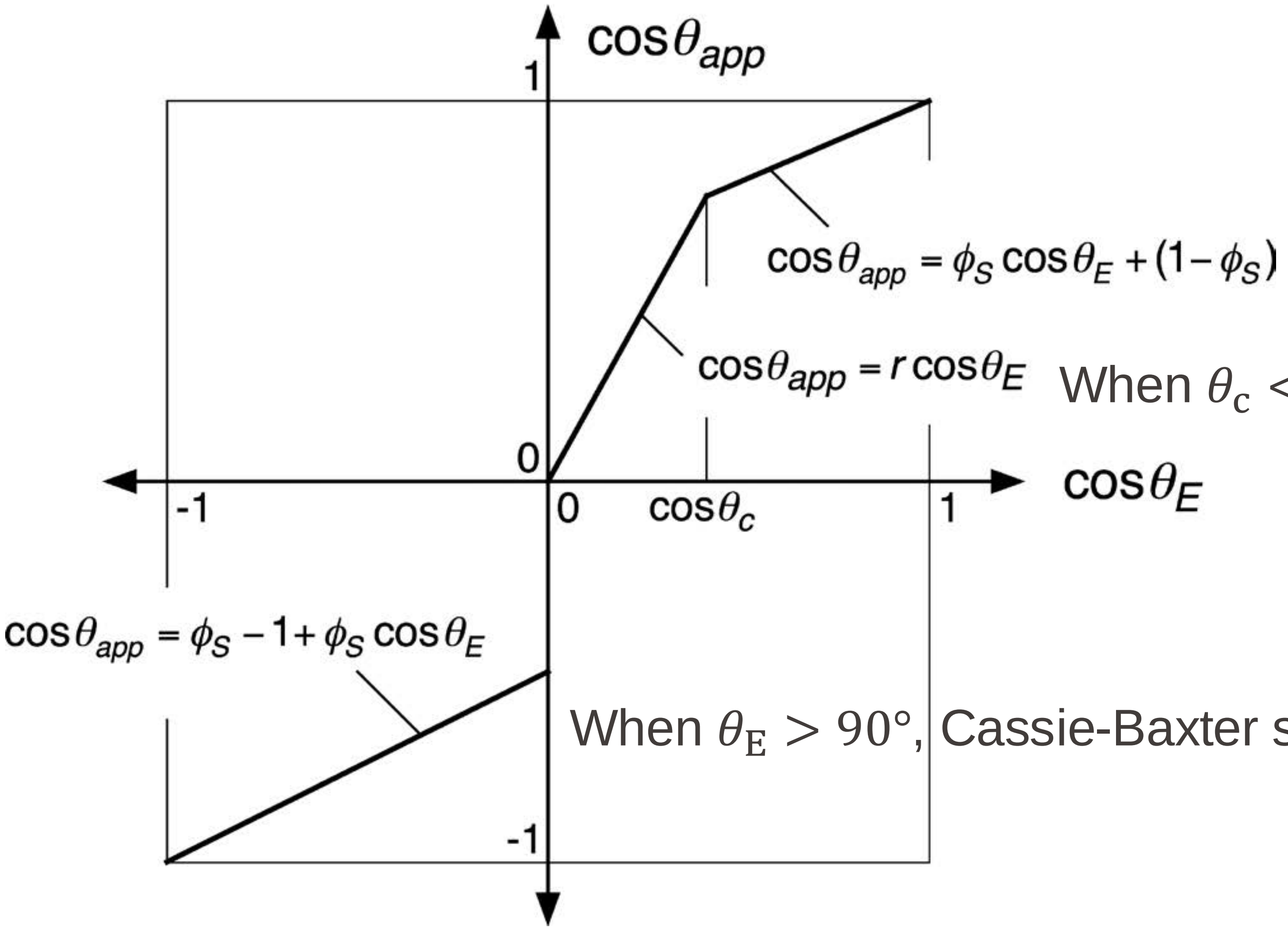
Capillary and Wetting

- Surface energy and surface tension
- Laplace pressure and Young-Laplace equation
- Contact angle: Young’s equation, hysteresis, effect of surface structures

Effect of Surface Structures

θ_E: equilibrium contact angle

$$\cos\theta_c = \frac{1-\phi}{r-\phi}$$



When $\theta_E < \theta_c$, hemi-spreading state

When $\theta_c < \theta_E < 90°$, Wenzel state

When $\theta_E > 90°$, Cassie-Baxter state

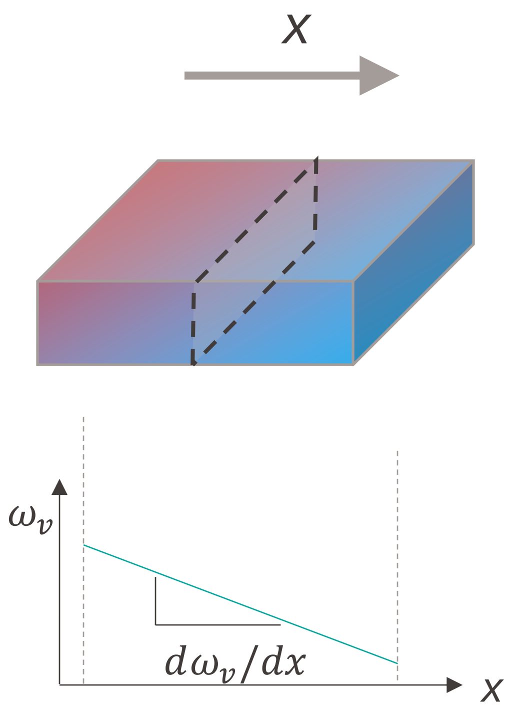
Figure 3.24 in Carey

Evaporation Physics

- Fick’s law of diffusion
- Heat and mass transfer analogy
- Coffee ring effects
- Kinetic theory of gases
- Schrage equation: expression and limits

Fick's Law of Diffusion for Moist Air

Empirical law $$j_{\mathrm{vd}} = -\rho D_{\mathrm{va}} \frac{d\omega_{\mathrm{v}}}{dx}$$

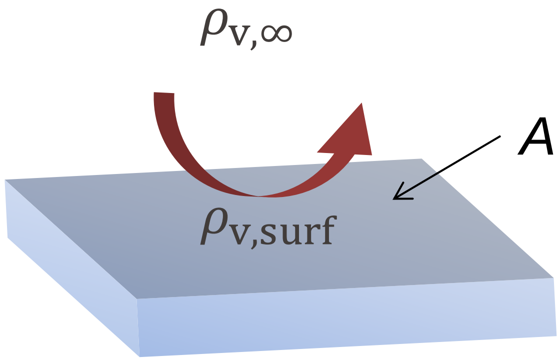


j_{vd}: mass flux in the mixture reference frame

ρ: mixture mass density

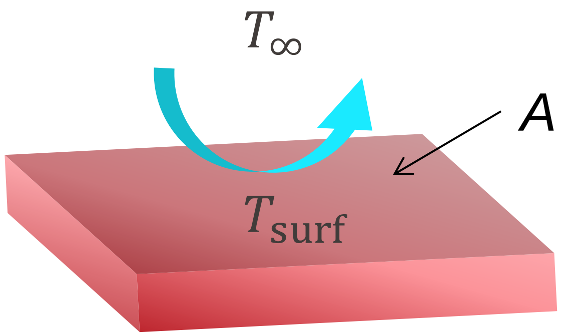
ω_v: vapor mass fraction

Heat and Mass Transfer Analogy



Mass transferred due to **bulk movement** of fluids

Rate Equation: $\dot{m} = \eta A(\rho_{\mathrm{v,surf}} - \rho_{\mathrm{v},\infty})$



Energy transferred due to **bulk movement** of fluids

Rate Equation: $Q = hA(T_{\mathrm{surf}} - T_\infty)$

Heat and Mass Transfer Analogy

Mass Transfer Correlations

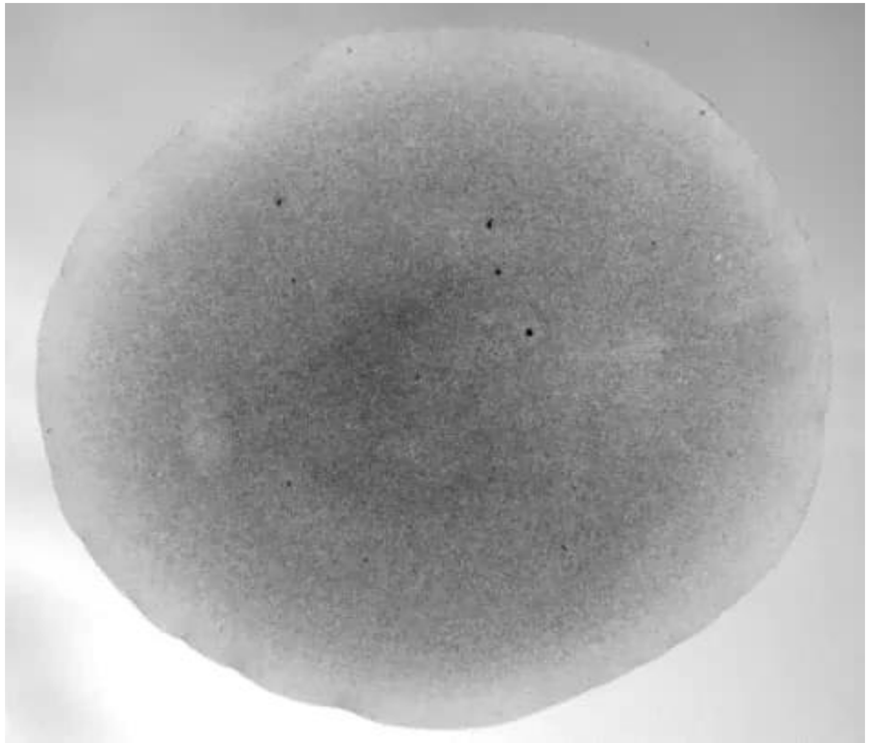
Heat Transfer Correlations

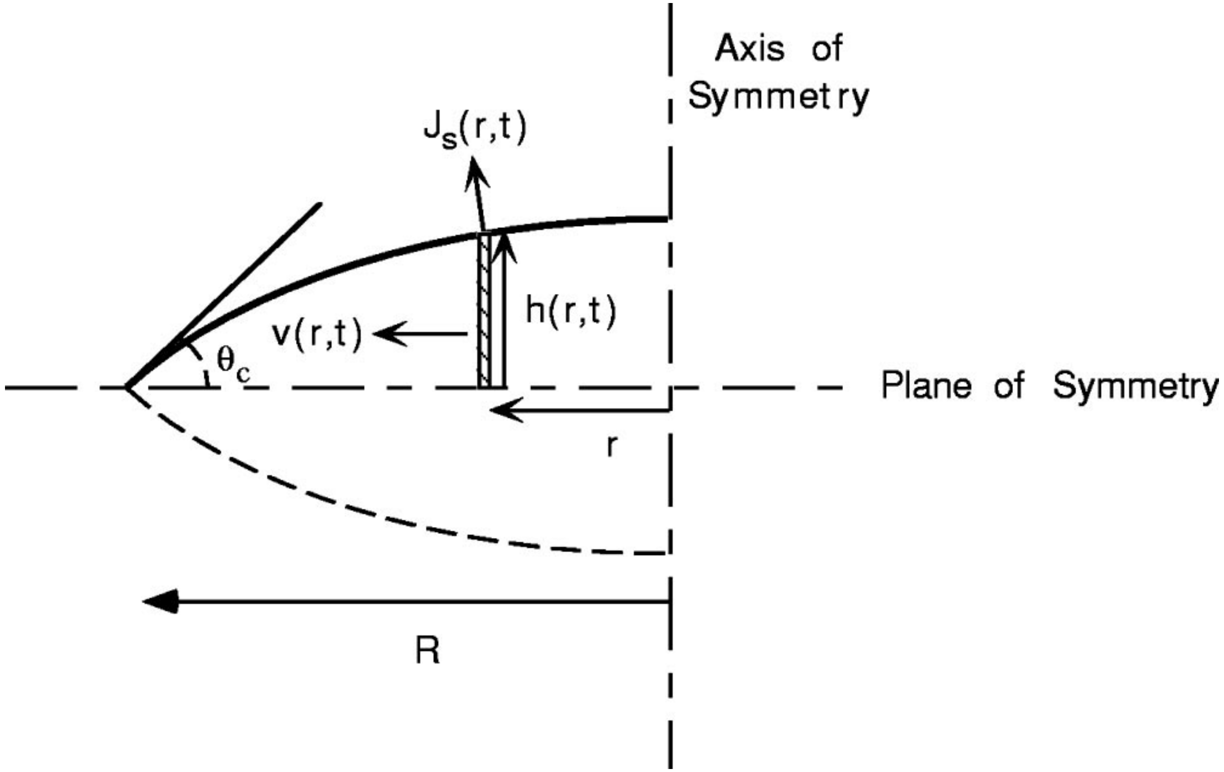
$$\mathrm{Re} = \rho U L / \mu$$

Same functional form

$$\mathrm{Sh} = \mathrm{fn}(\mathrm{Re}, \mathrm{Sc}) \qquad\qquad \mathrm{Nu} = \mathrm{fn}(\mathrm{Re}, \mathrm{Pr})$$

Coffee Ring Effects





Velocity Distribution Function

$$\frac{dn_{\vec{v}}}{dn} = f(v_x, v_y, v_z)dv_x dv_y dv_z$$

How is temperature defined from the velocity distribution?

What is the equilibrium Maxwell-Boltzmann distribution?

How to calculate mass flux from velocity distribution?

Schrage Equation

- How to construct the mass conservation equation from velocity distribution functions

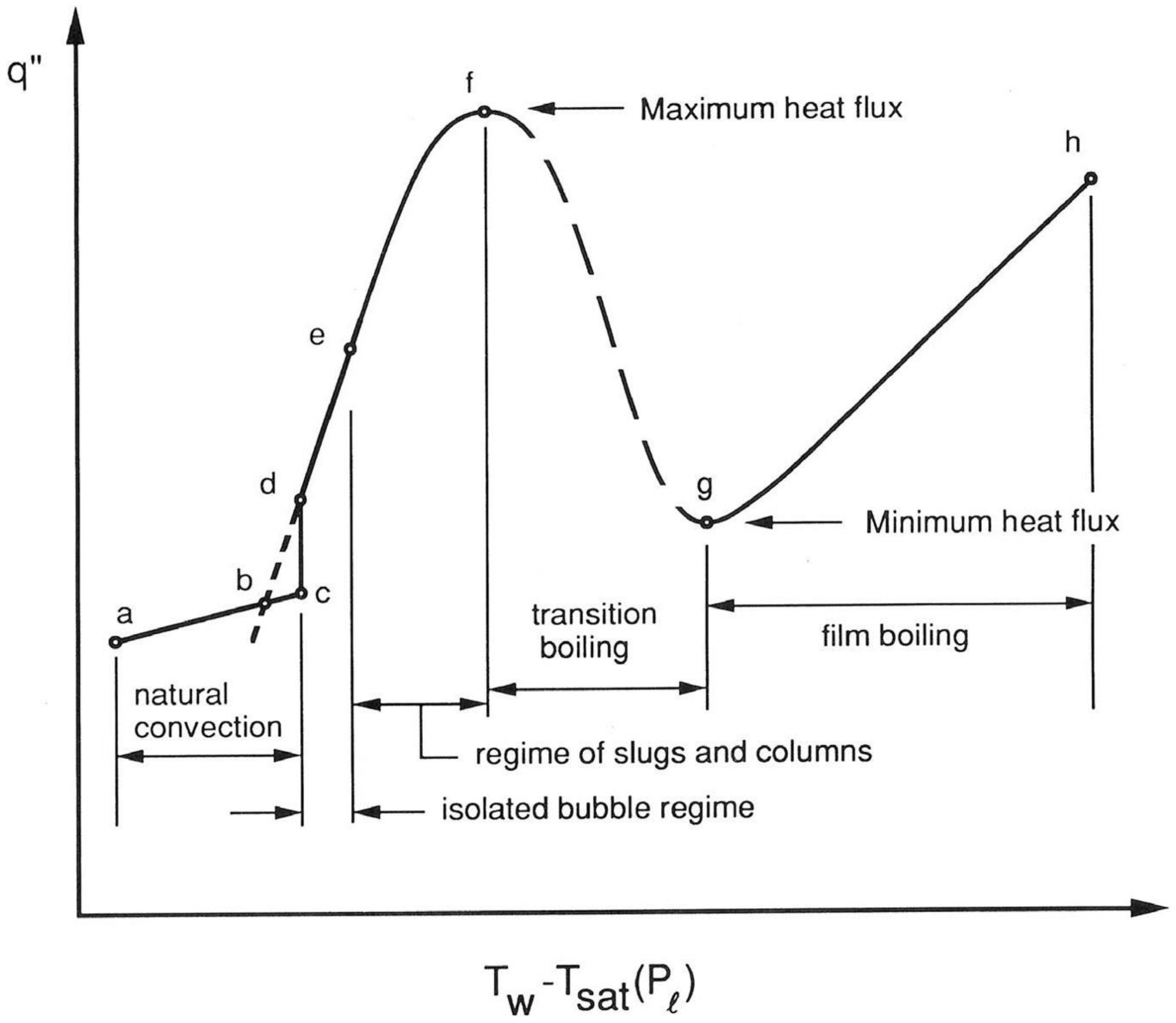
- How to construct the momentum balance equation from velocity distribution functions

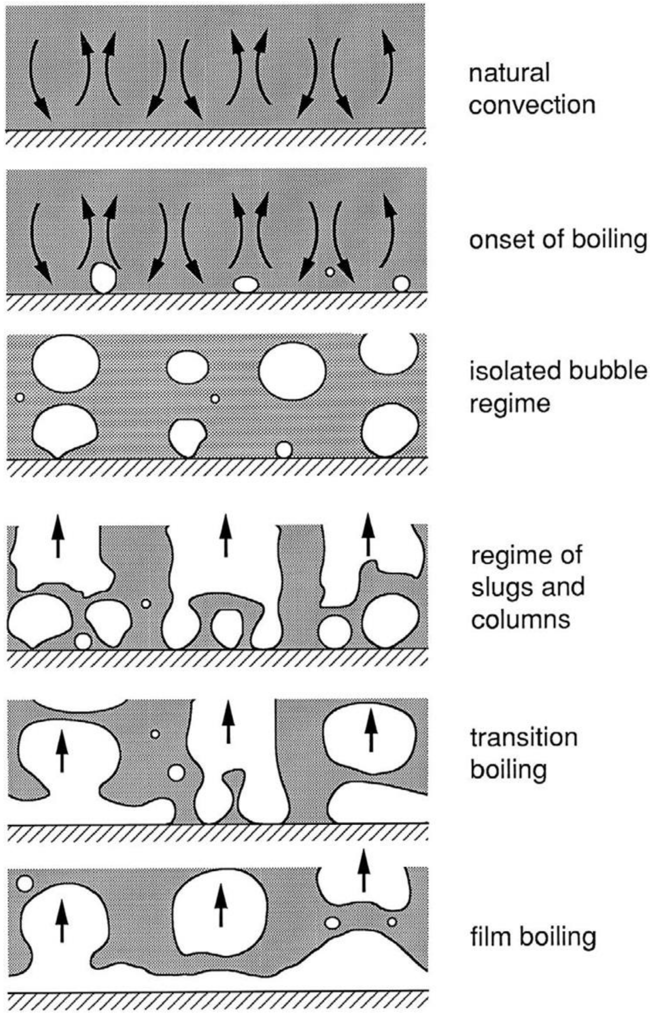
- How to construct the energy balance equation from velocity distribution functions

Pool Boiling

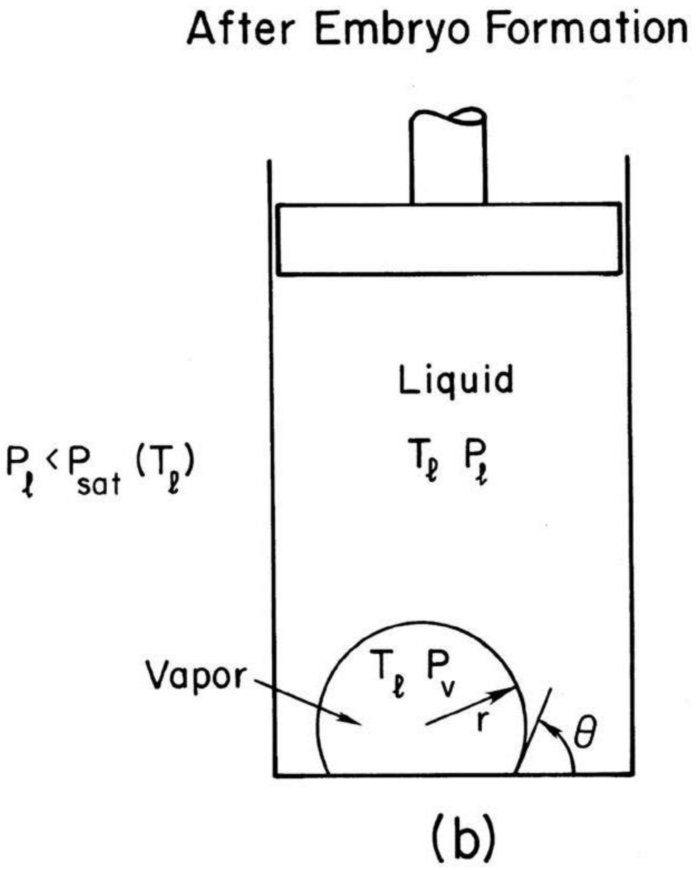
- Pool Boiling Curve
- Initial stage of boiling: nucleation and bubble departure
- Nucleate boiling heat transfer
- Critical heat flux

Boiling Curve





Equilibrium Bubble Radius



$$\hat{g}_{sat,l}(T_l, P_{sat}) = \hat{g}_{sat,v}(T_l, P_{sat}) = \hat{g}_{sat}$$

$$d\hat{g} = vdP - SdT$$

$$\hat{g}_v - \hat{g}_{sat} = \int_{P_{sat}}^{P_v} v_v dP = \int_{P_{sat}}^{P_v} \frac{RT_l}{P} dP = RT_l \ln\left(\frac{P_v}{P_{sat}}\right)$$

$$\hat{g}_l - \hat{g}_{sat} = \int_{P_{sat}}^{P_l} v_l dP = v_l(P_l - P_{sat})$$

In equilibrium

$$\hat{g}_v = \hat{g}_l$$

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

$$r_e = 2\sigma/\{P_{sat}\exp[v_l(P_l - P_{sat})/RT_l] - P_l\} \approx 2\sigma/(P_{sat} - P_l)$$

Bubble Nucleation Criteria

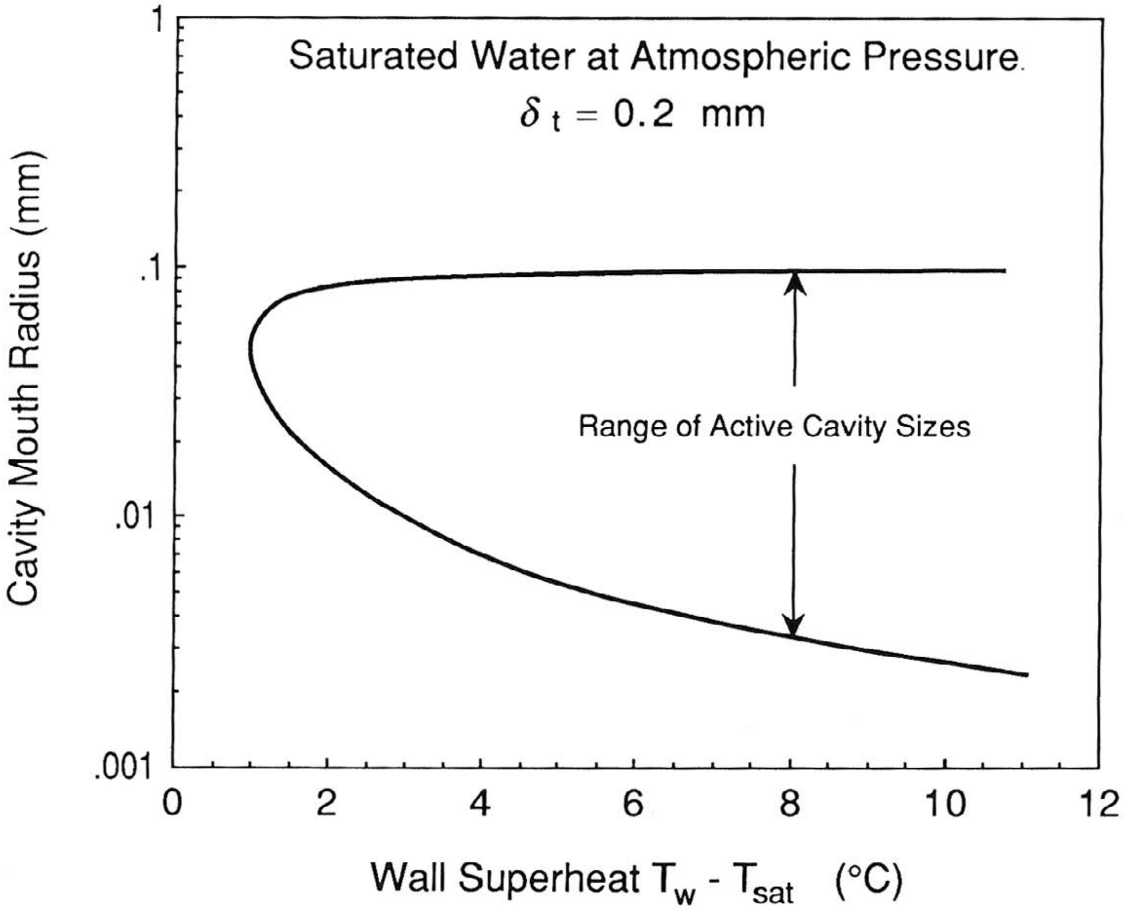
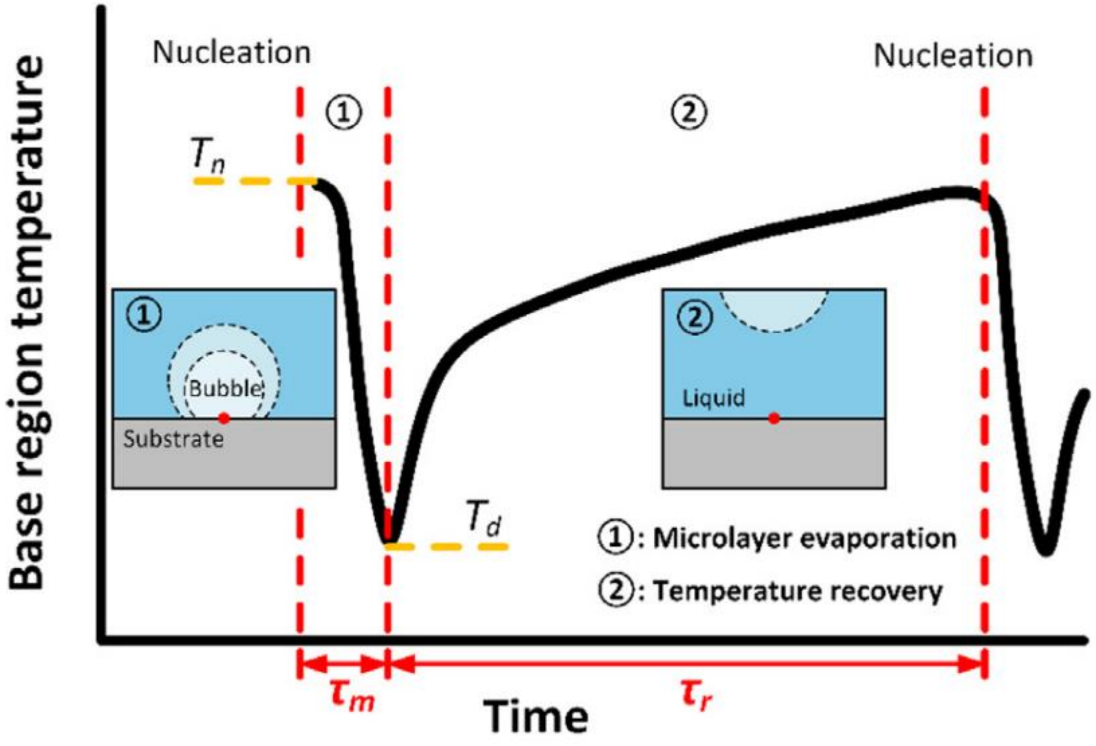


Figure 6.13 in Carey

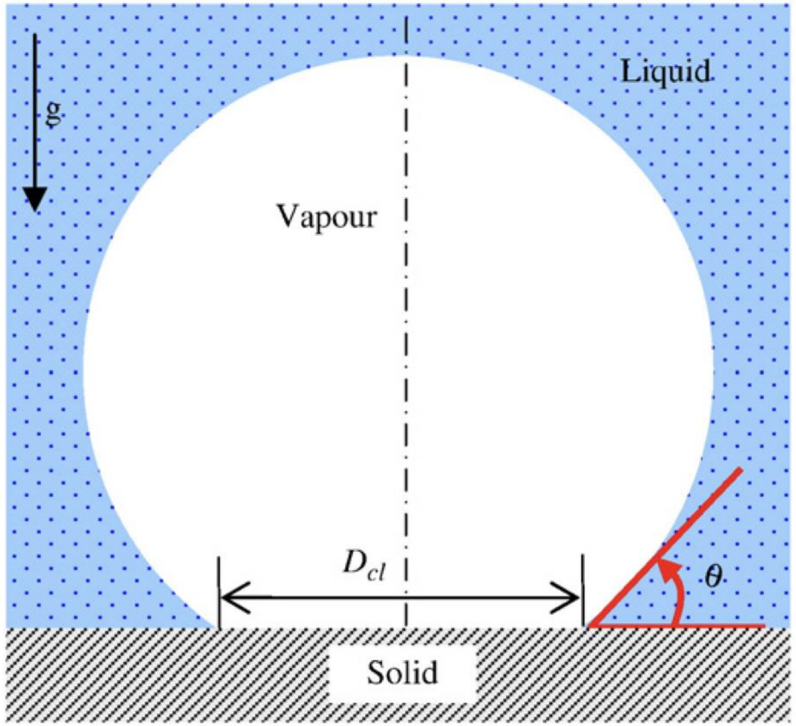
- If the bubble is too small, the Laplace pressure will be too large for nucleation to occur
- If the bubble is too large, the top of the bubble may be surrounded by liquid of not-high-enough temperature

Bubble Timescale Analysis



Microlayer evaporation (cooling) much faster than temperature recovery (heating)

Bubble Departure Diameter



- Buoyancy

$$\sim(\rho_l - \rho_v)D^3 g$$

- Surface tension force

$$\sim\sigma D$$

$$D\sim\sqrt{\frac{\sigma}{(\rho_l - \rho_v)g}}$$

Kelvin-Helmholtz Instability

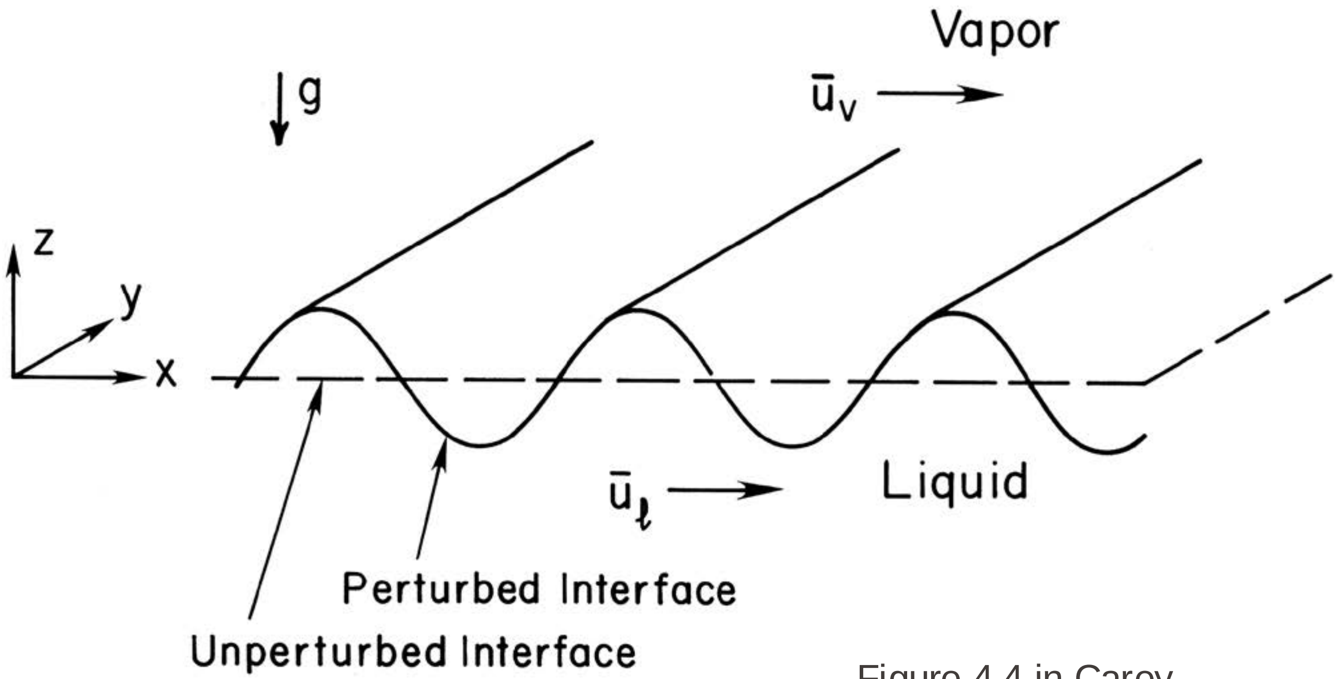
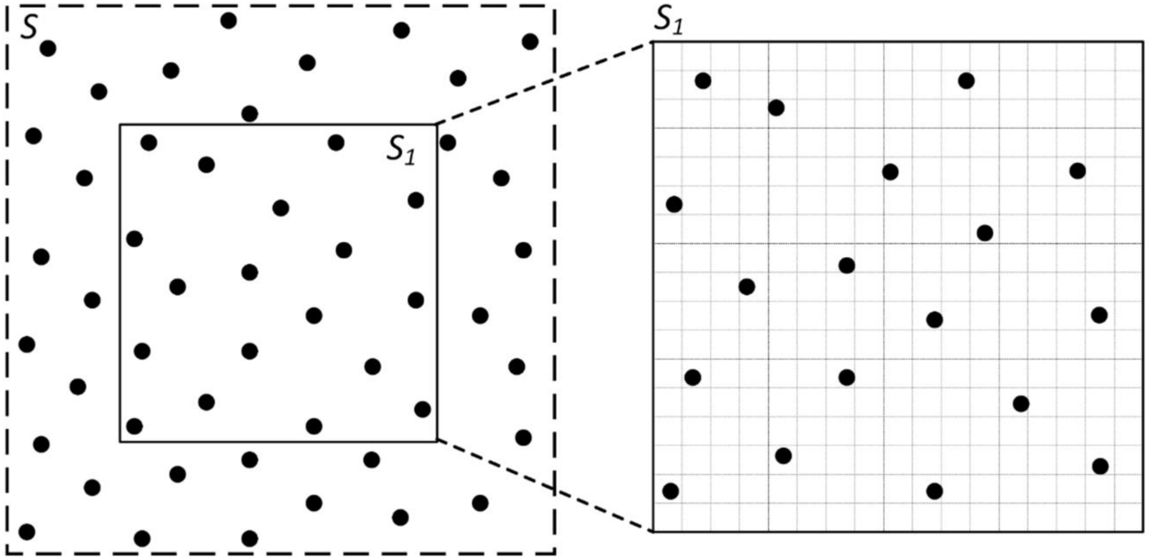


Figure 4.4 in Carey

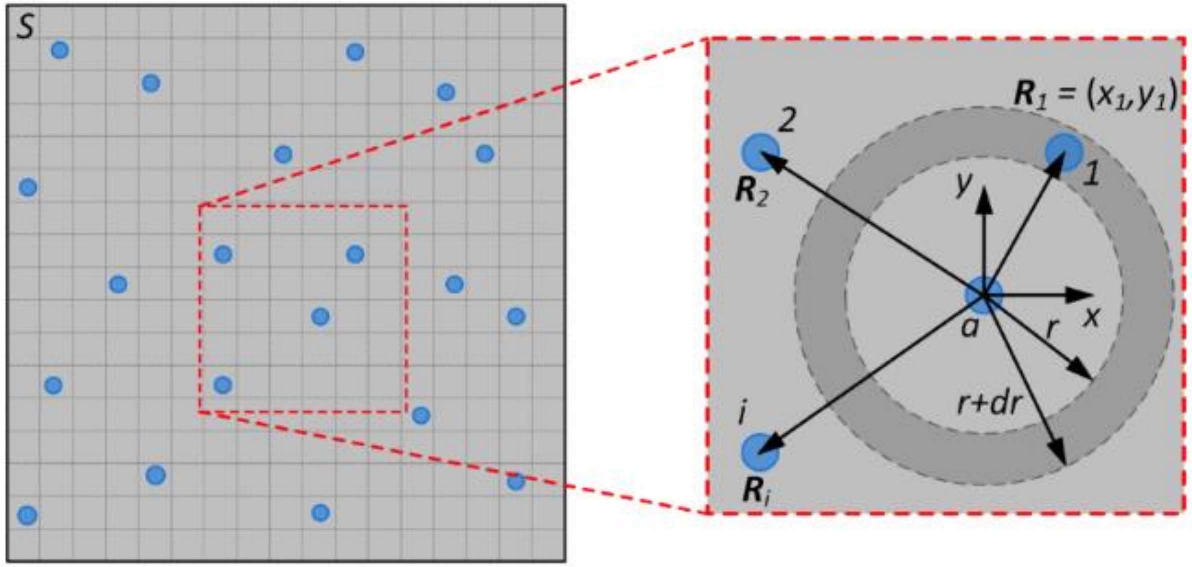
$$|\bar{u}_l - \bar{u}_v| > \sqrt{\left(\frac{2\pi\sigma}{\lambda} + \frac{\Delta\rho g\lambda}{2\pi}\right)\frac{\rho_l + \rho_v}{\rho_l\rho_v}}$$

Population Distribution of Intrinsic Nucleation Sites



$$\mathrm{Po}(N, N_0) = \frac{N_0^N}{N!} e^{-N_0}$$

Nearest Neighbor Distance Between Nucleation Sites

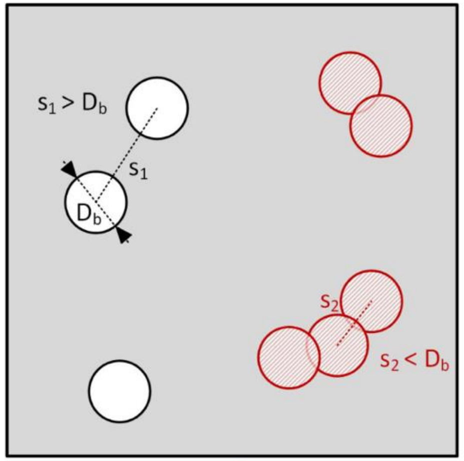


The probability distribution function for distance between nearest neighbors if there are N points randomly distributed on a surface of area A

$$f(s) = \frac{2\pi N s}{A} e^{-\frac{\pi N s^2}{A}}$$

Rayleigh distribution

Number of Isolated Bubbles



CHF Criteria: $\frac{\partial N_{iso}}{\partial T} = 0$

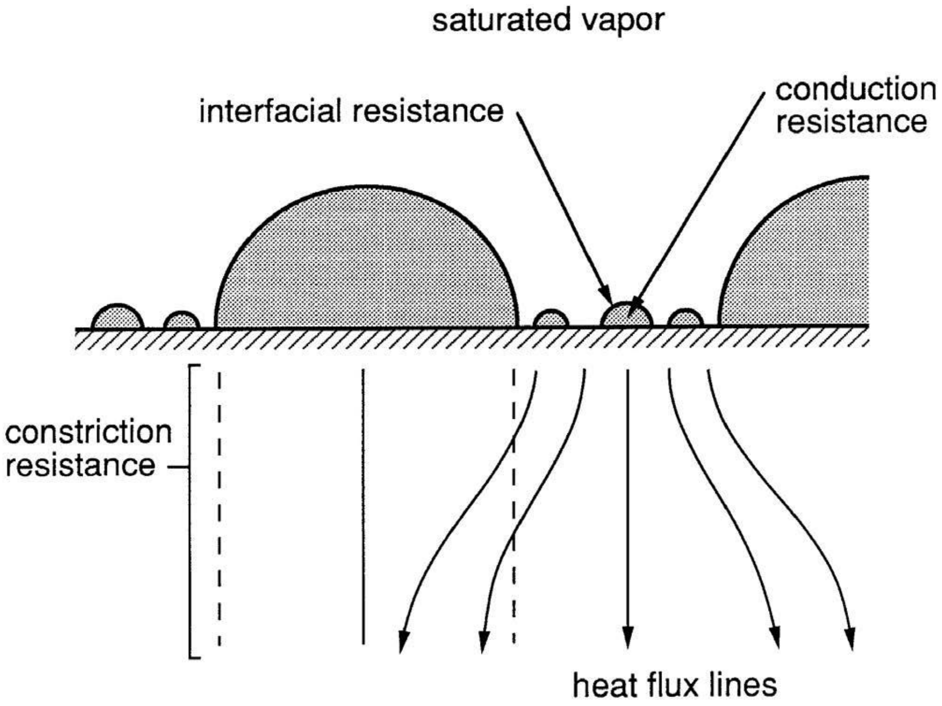
$$P_{iso} = P(s > D_b) = \int_{D_b}^{\infty} f(s)ds = \int_{D_b}^{\infty} \frac{2\pi N s}{A} e^{-\frac{\pi N s^2}{A}} ds = e^{-\frac{\pi N D_b^2}{A}}$$

$$N_{iso} = \sum_{N=1}^{\infty} N P_{iso} \mathrm{Po}(N, N_0) = \sum_{N=1}^{\infty} \frac{N_0^N}{(N-1)!} \exp\left(-N_0 - \frac{\pi N D_b^2}{A}\right)$$

Condensation

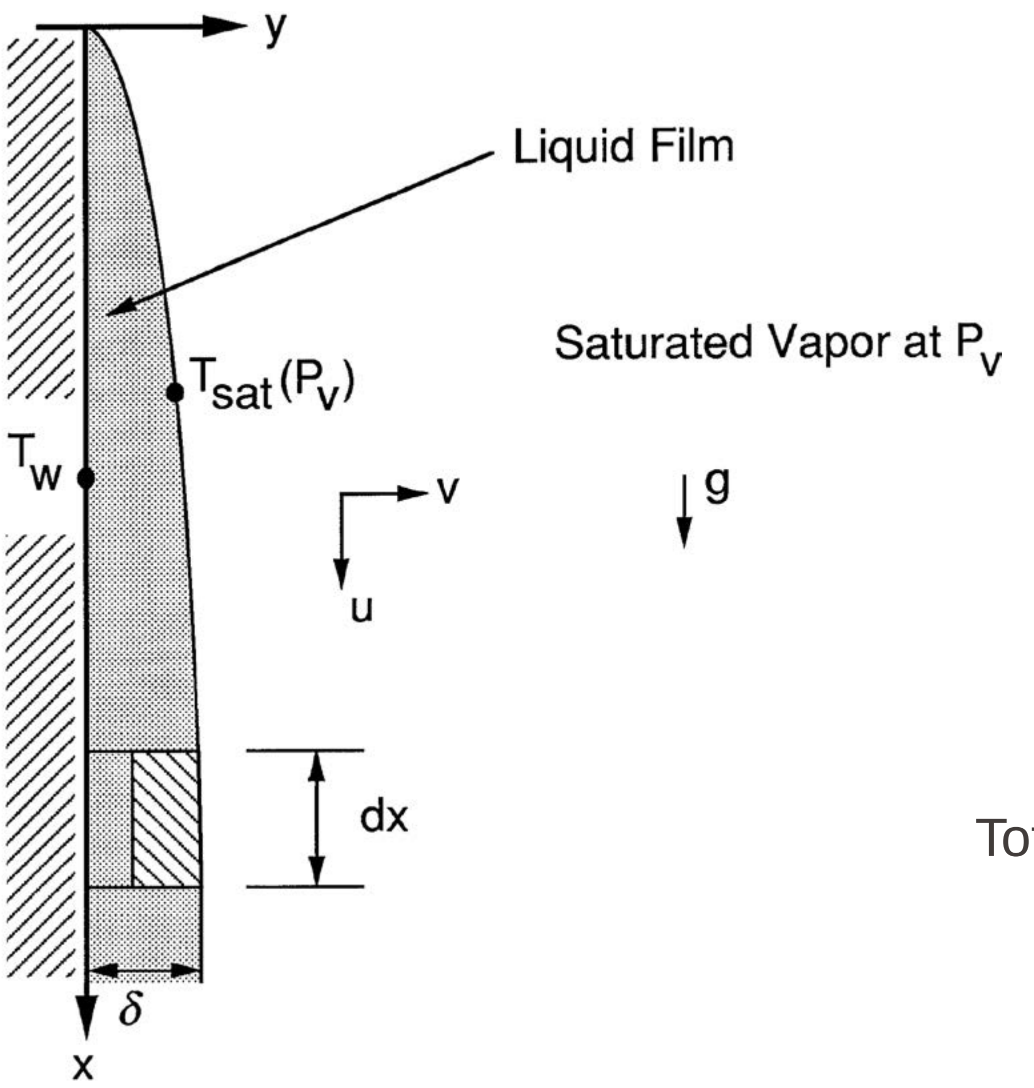
- Dropwise condensation
- Filmwise condensation
- Jumping droplet condensation
- Lubricant infused surfaces
- Wicking condensation

Dropwise Condensation Thermal Resistances



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

Filmwise Condensation on a Flat Vertical Surface



Force balance on the shaded film element

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

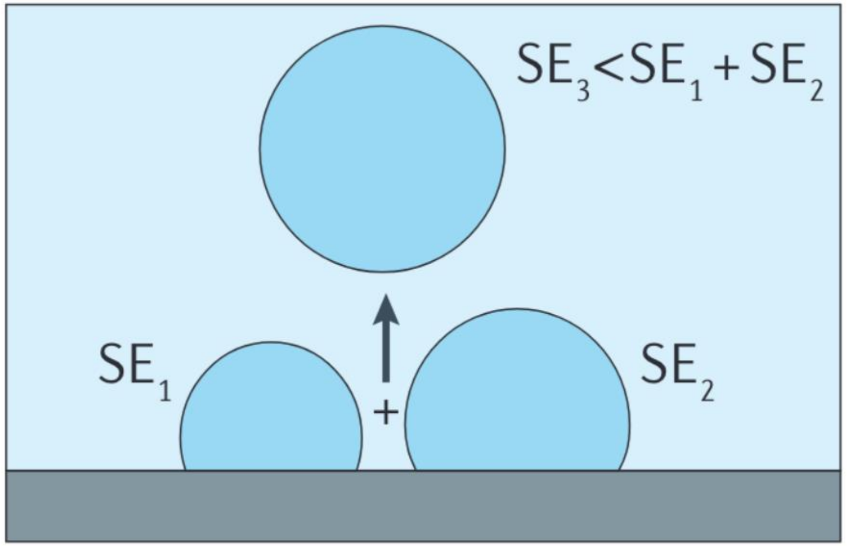
Integrating this equation w.r.t. *y*

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

Total mass flow rate per unit depth in y-direction

$$\dot{m}' = \rho_l\int_0^{\delta} u dy = \frac{\rho_l(\rho_l - \rho_v)g\delta^2}{3\mu_l}$$

Jumping Droplet Condensation



Coalescence departure

$$\Delta E_s \sim \sigma \Delta A \sim \sigma R^2$$

$$KE \sim \frac{1}{2} \rho R^3 U^2$$

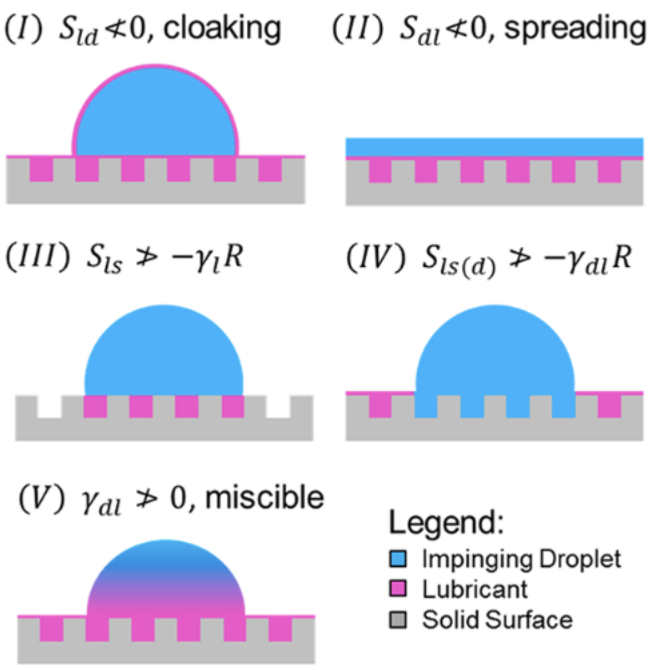
$$U \sim \sqrt{\frac{\sigma}{\rho R}}$$

Viscous dissipation ignored

How to Design LIS

Spreading Coefficient $S_{xy} = \gamma_y - (\gamma_{xy} + \gamma_x)$

$S_{xy} \geq 0$ implies *x* can spread on *y*



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Possible ways to fail

(I) Lubricant cloaking $S_{ld} \geq 0$

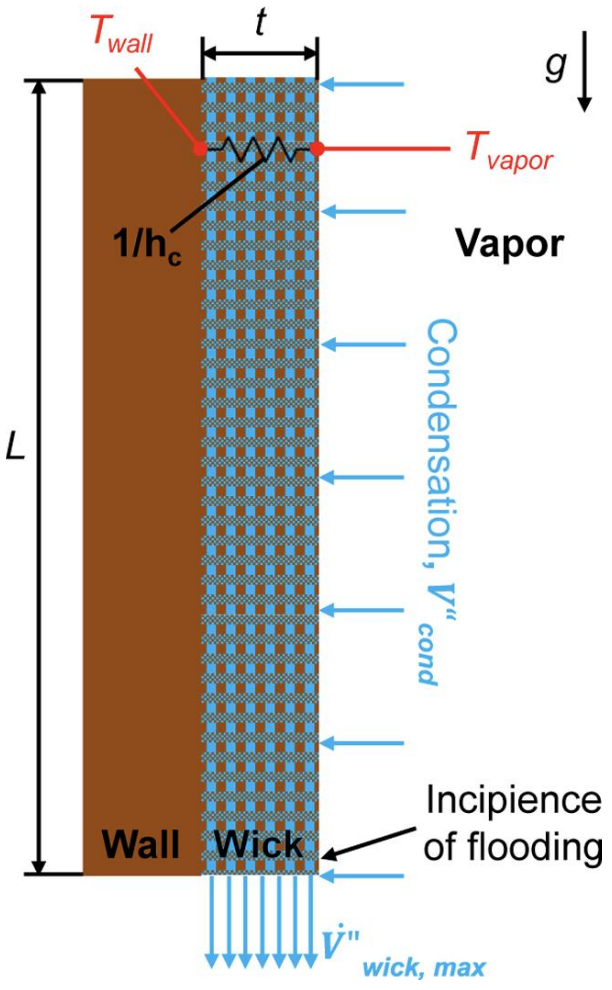
(II) Droplet spreading $S_{dl} \geq 0$

(III) No infusing $S_{ls} \leq \frac{r-1}{r-\phi} \gamma_l$

(IV) No infusing $S_{ls(d)} \leq \frac{r-1}{r-\phi} \gamma_{dl}$

(V) Miscible

Wicking Condensation



Langmuir 2018, 34, 4658−4664

$$h_c = \frac{k_{wick}}{t}$$

$$V''_{cond} \cdot h_{fg} = h_c \Delta T$$

$$\dot{V}''_{wick,max} = \frac{V''_{cond} L}{t} = \frac{K}{\mu}\left|\frac{dP}{dx}\right|_{max}$$

$$\left|\frac{dP}{dx}\right|_{max} = \rho g$$

$$\Delta T < \frac{K \rho^2 g h_{fg} t^2}{L k_{wick} \mu}$$

Final Exam Format

- 3 hour written exam: Friday 24.01.2025 from 09h15 to 12h15 (CM1106)
- 3-4 calculation/analysis questions
- You are allowed to bring a cheat sheet (one A4 paper; you can write things on both sides) and a calculator with you to the exam
- **A favor to ask**: fill in the course evaluation form after finishing your test