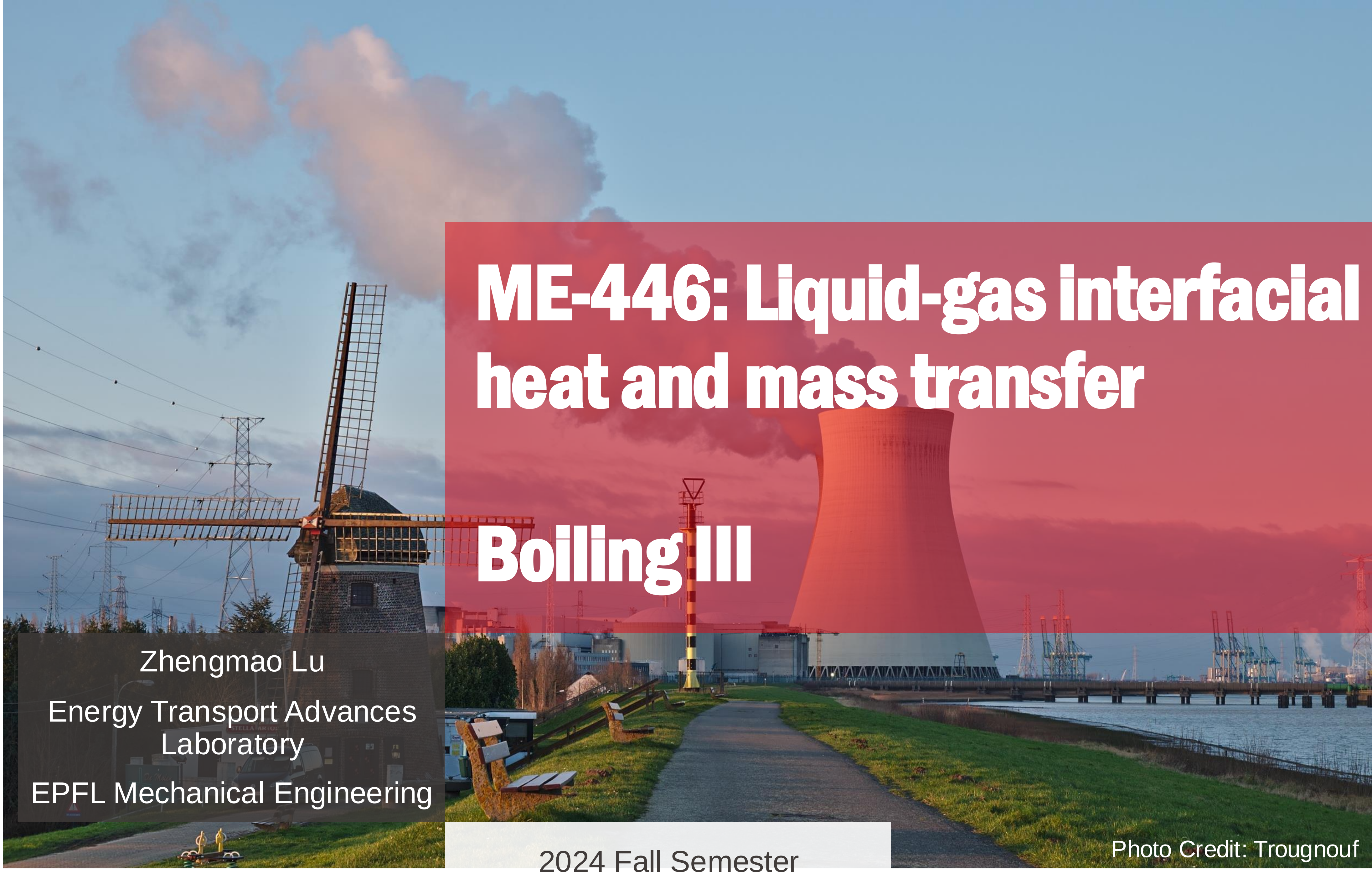
EPFL

ETA-Lab
Energy Transport Advances



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

Boiling III

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2024 Fall Semester

Photo Credit: Trougnouf

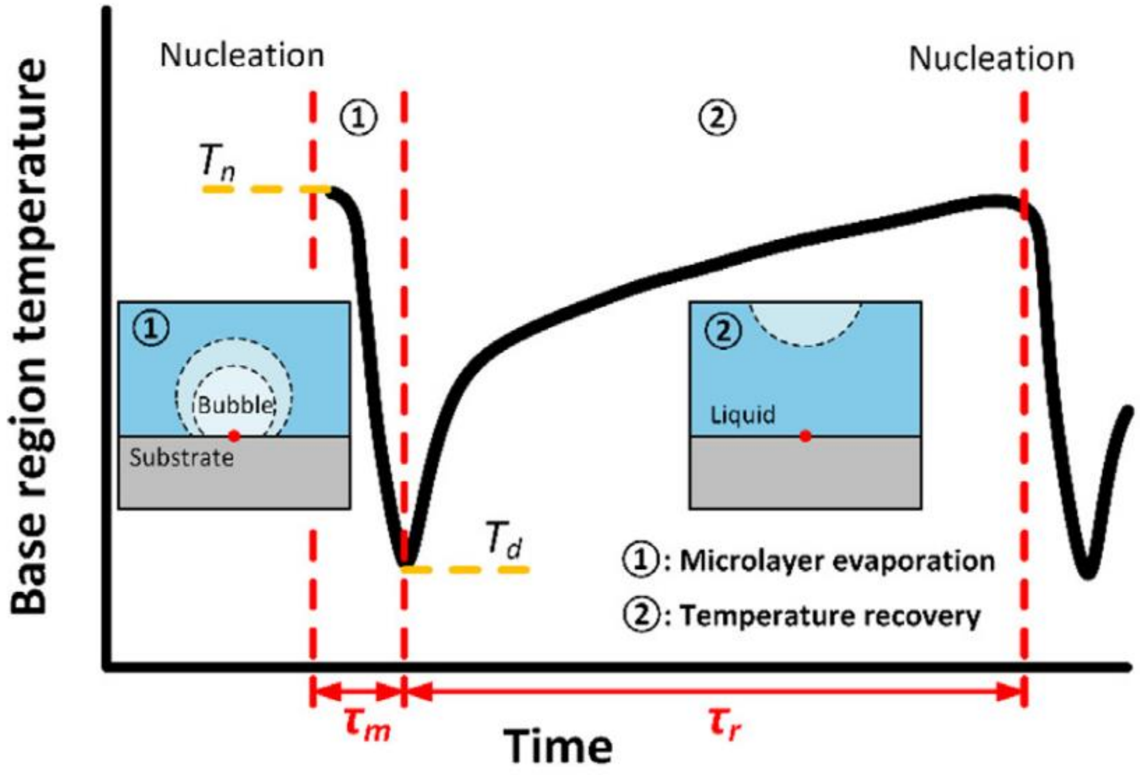
Last Time

- Entrapped gas/vapor theory
- Onset of nucleation coupled with thermal boundary layer (Hsu’s model)

Intended Learning Objectives Today

- Bubble departure frequency and diameter
- Different regimes in pool boiling
- Rohsenow’s microconvection model for nucleate boiling
- Zuber’s CHF model based on Helmholtz and Taylor instabilities

Beyond Nucleation

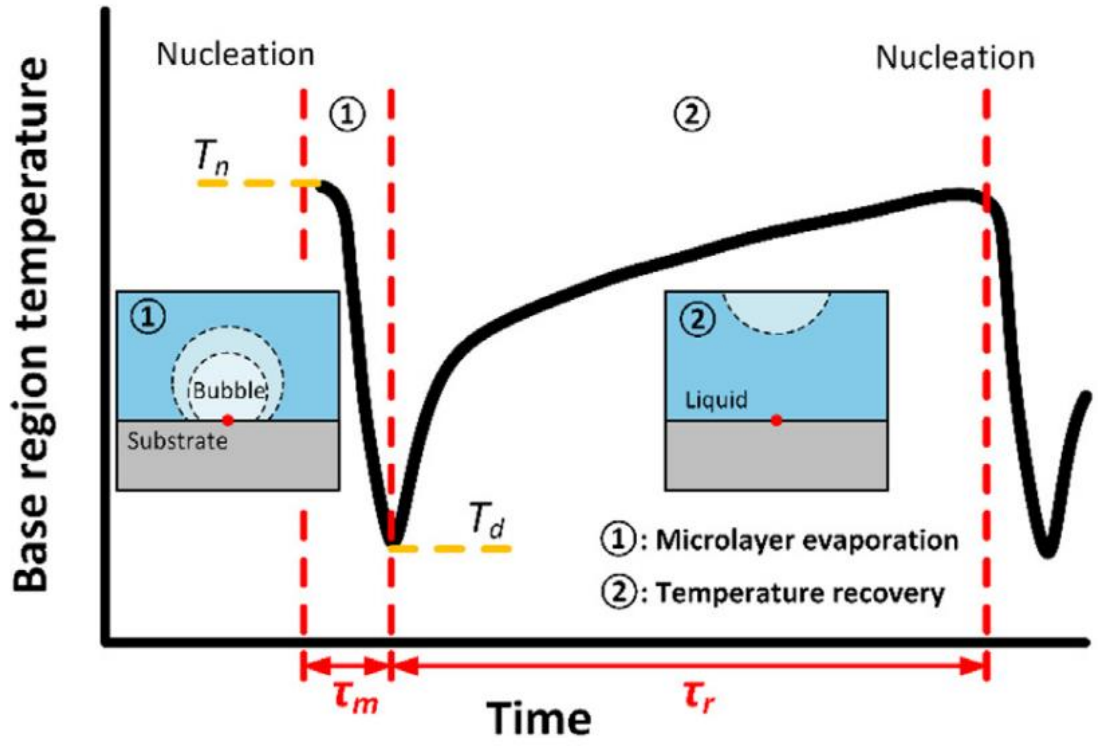


Zhang *et al.*, 2021

https://doi.org/10.1016/j.ijheatmasstransfer.2020.120640

- Right after nucleation, substrate temperature drops due to rapid evaporation
- After bubble departure, the substrate needs to be reheated through convection and conduction to reach nucleation temperature again

Timescale Analysis



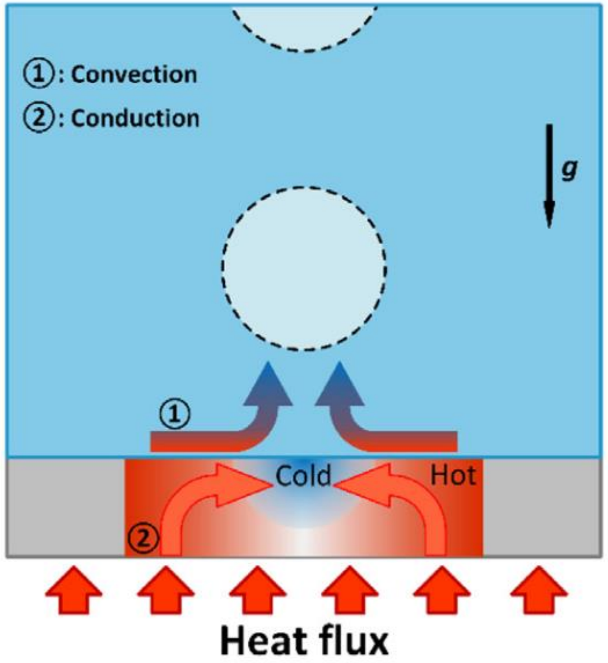
We are interested in departure frequency and the departure bubble size

In isolated bubble regime, evaporation (cooling) much faster than temperature recovery (heating)

$\tau_m \ll \tau_r$

Bubble departure frequency $f = \dfrac{1}{\tau_m + \tau_r} \approx \dfrac{1}{\tau_r}$

Temperature Recovery Mechanism



① Rewetting of surrounding superheated liquid

② Heat conduction from surrounding solid region

Timescale Analysis

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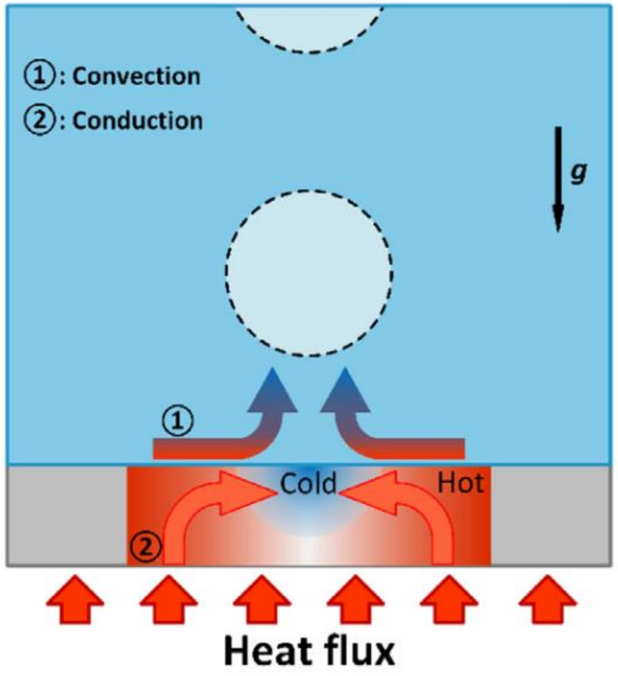


① Rewetting of surrounding superheated liquid

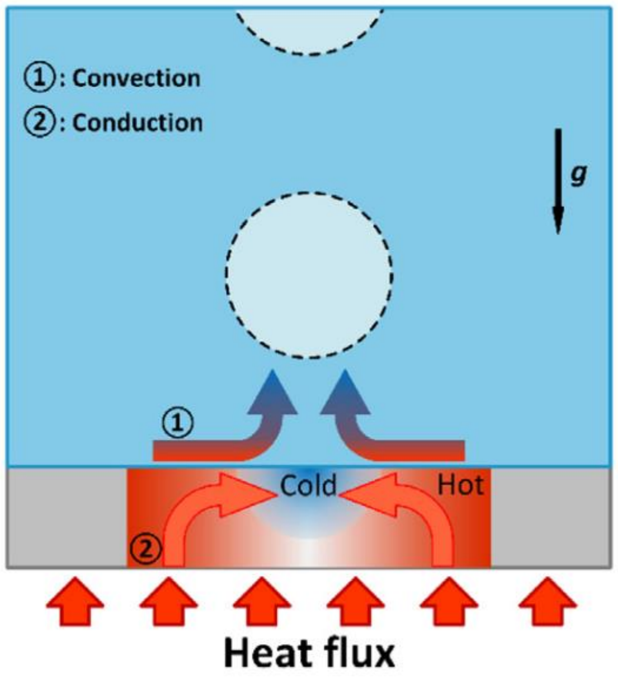
Transient heat conduction of a semi-infinite wall with a convective boundary condition

$$\frac{T_b(t) - T_d}{T_n - T_d} = 1 - e^{\frac{t}{\tau_w}}\left[1 - \mathrm{erf}\left(\sqrt{\frac{t}{\tau_w}}\right)\right]$$

$$\tau_w = \frac{k_s^2}{h^2 \alpha_s}$$

Characteristic time for rewetting induced convection

Timescale Analysis



① Rewetting of surrounding superheated liquid

$$\tau_w = \frac{k_s^2}{h^2 \alpha_s}$$

How to determine *h*

Rewetting flow is caused by density difference

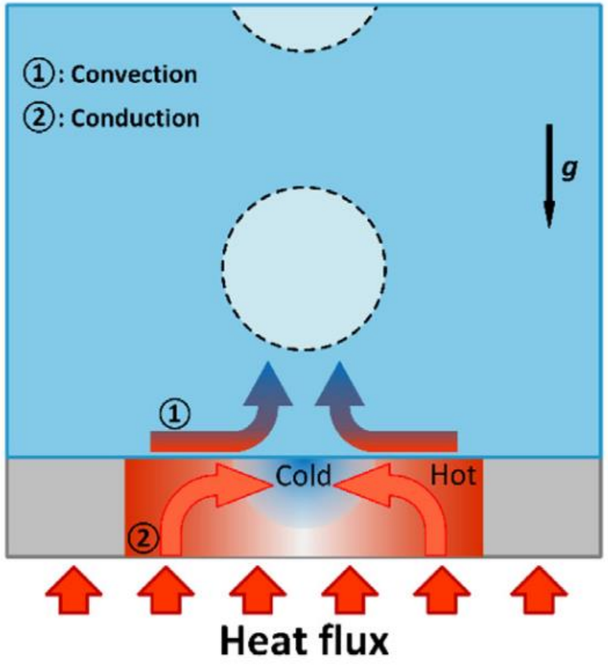
$$\mathrm{Ra} = \frac{g \Delta\rho D^3}{\mu_l \alpha_l} \approx \frac{g D^3}{\nu_l \alpha_l}$$

$$\frac{hD}{k_l} = \mathrm{Nu} \propto \mathrm{Ra}^{1/4}$$

$$\mathrm{Ra} = \frac{\text{time scale for thermal transport via diffusion}}{\text{time scale for thermal transport via convection at speed } u}.$$

$$\tau_w \propto \frac{k_s^2}{k_l^2} \left(\frac{\nu_l \alpha_l}{g} \right)^{\frac{1}{2}} \alpha_s^{-1} D^{\frac{1}{2}}$$

Timescale Analysis

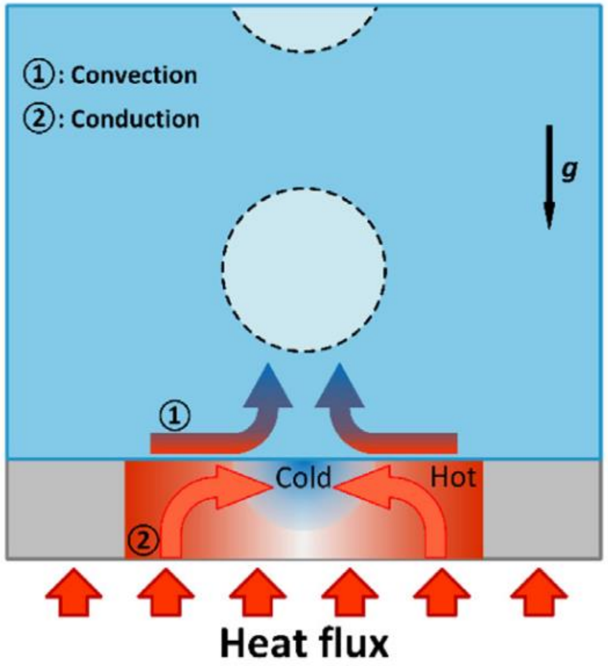


② Heat conduction from surrounding solid region

Characteristic timescale $\tau_d \propto \frac{D^2}{\alpha_s}$

$$\Rightarrow \frac{\tau_d}{\tau_w} \sim D^{1.5}$$

Timescale Analysis



- Rewetting and heat conduction are two competing mechanisms for temperature recovery

$$\frac{\tau_d}{\tau_w} \sim D^{1.5}$$

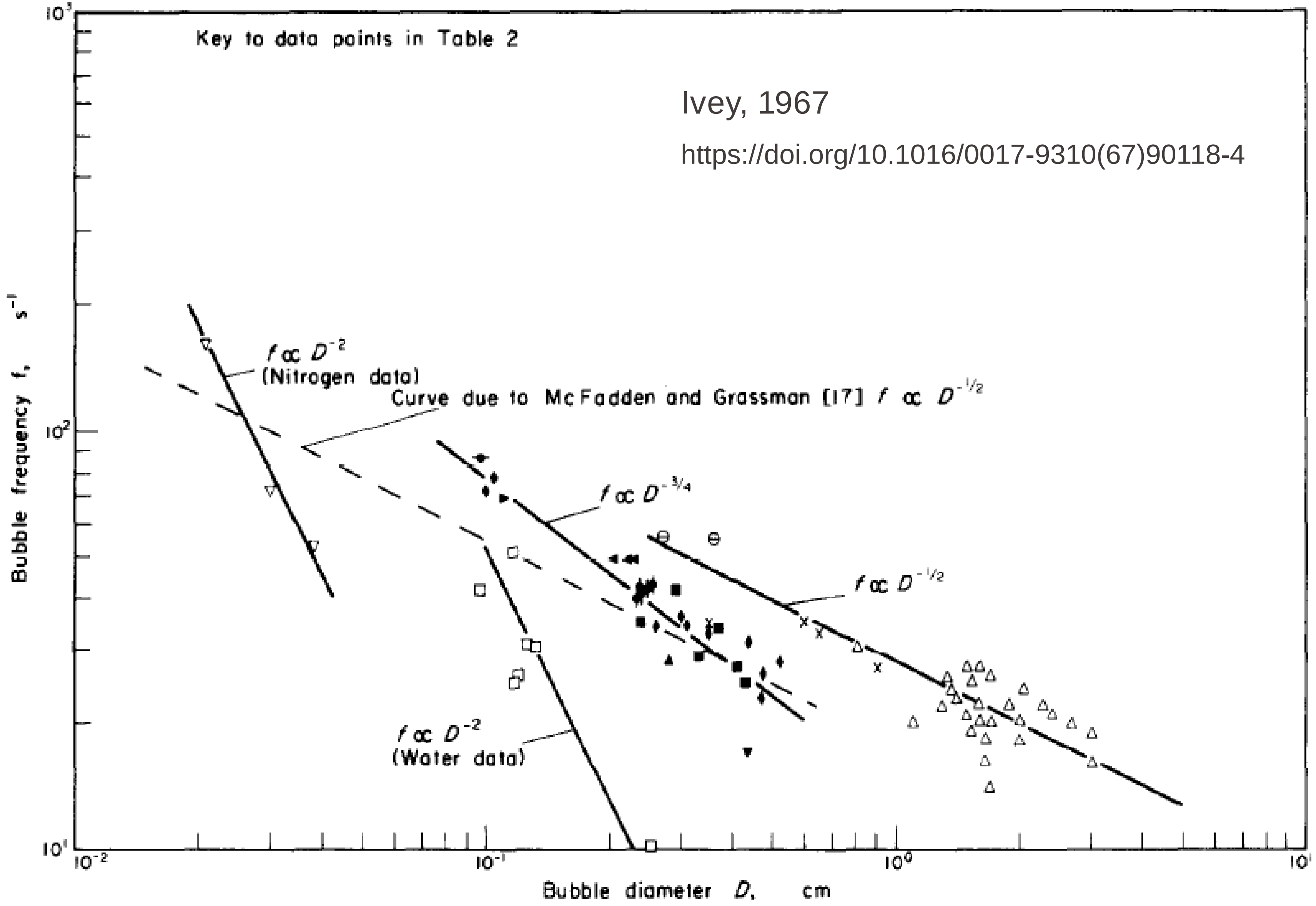
When *D* is relatively large, rewetting-induced convection dominates

$$f = \frac{1}{\tau_w} \sim g^{0.5} D^{-0.5}$$

When *D* is relatively small, conduction dominates

$$f = \frac{1}{\tau_d} \sim D^{-2}$$

Comparison to Experiments



Ivey, 1967

https://doi.org/10.1016/0017-9310(67)90118-4

Bubble Departure Diameter

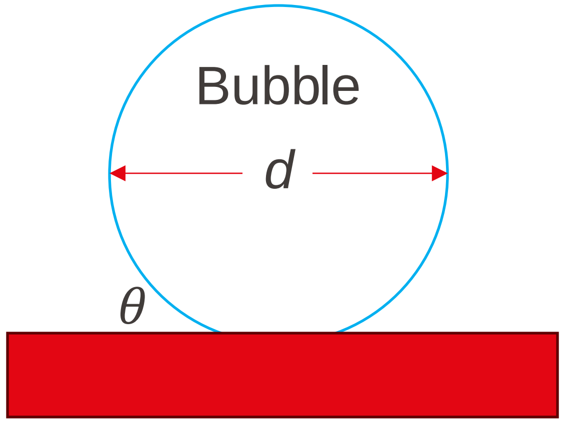
Buoyancy force $\sim(\rho_l - \rho_v)d^3 g$

Surface tension force $\sim\sigma_{lv} d$

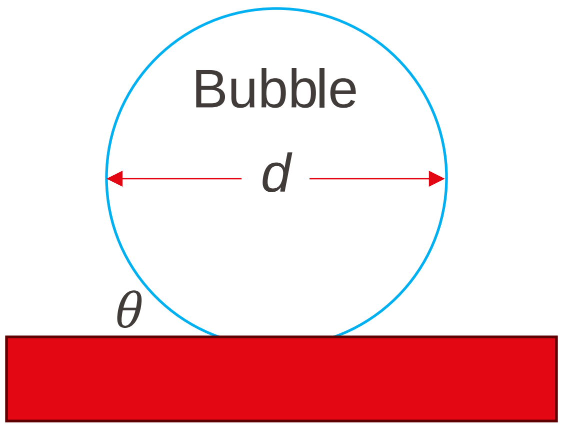
Bond number $$\mathrm{Bo}_d = \frac{(\rho_l - \rho_v)gd^2}{\sigma_{lv}}$$

Most correlations are written in terms of $\mathrm{Bo_d}$

Fritz expression $$\mathrm{Bo_d^{1/2}} = 0.0208\theta$$



Comments on Fritz's Expression

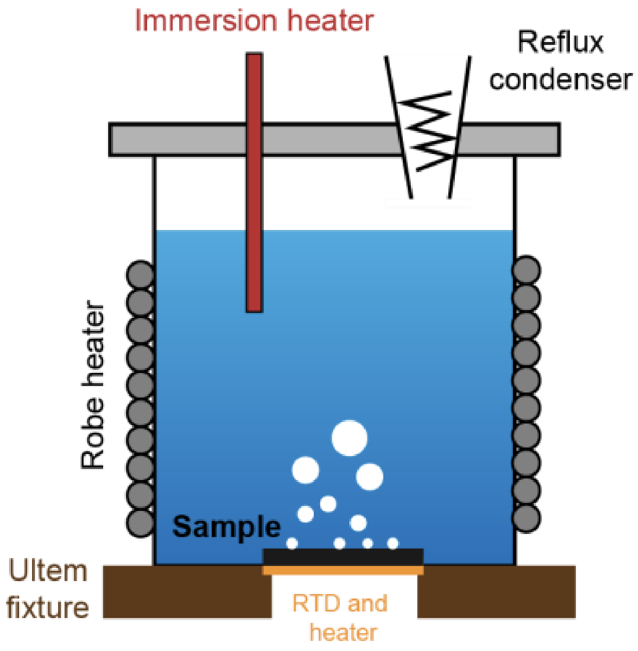


Simple balance between surface tension force and buoyance force. The effect of the contact angle is taken into account in an empirical manner

At different heat fluxes, the bubble may have different growth rate, corresponding to a different momentum force

Archimedes' principles not exactly suitable given that there is no liquid underneath the bubble base

Pool Boiling

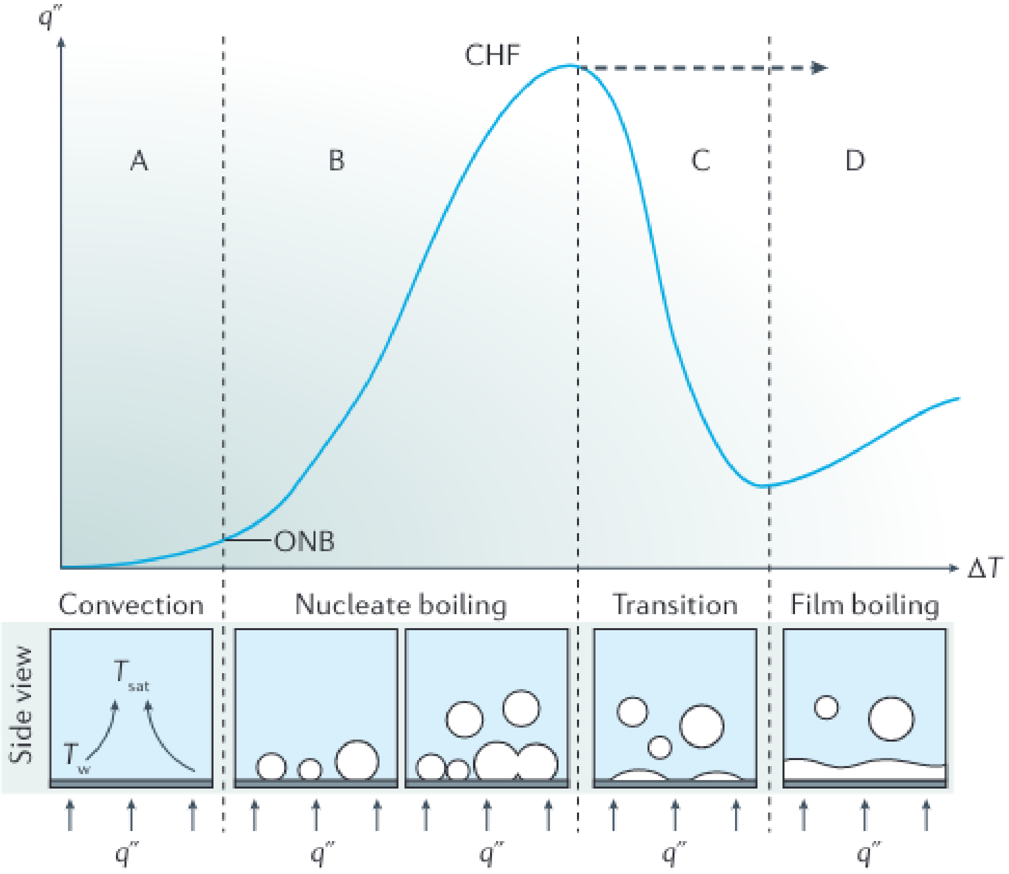


Capillary length $L_b = \sqrt{\dfrac{\sigma}{g(\rho_l - \rho_v)}}$ by setting Bo = 1

Pool boiling surface characteristic length $L >> L_b$

We are interested in the relationship between the average heat flux at the boiling surface q" and the surface super heat $\Delta T = T_w - T_{sat}(P_l)$

Boiling Curve



A. At very low superheats, heat transfer is mostly due to natural convection

B. After superheat is large enough to form vapor bubbles, nucleate boiling dominates, promoting bubble-motion-induced convection

C-D. After vapor generation becomes too much, passing the critical heat flux (CHF), insulating vapor film will start to form, decreasing the HTC

Rohsenow's Microconvection Model

Convective transport facilitated by bubbles

$$\mathrm{Nu}_b = \frac{hL_b}{k_l} \propto \mathrm{Re}_b^{1-r}\mathrm{Pr}_l^{1-s}$$

$$\mathrm{R}e_b = \frac{\rho_v U L_b}{\mu_L} \qquad U = \frac{q''}{\rho_v h_{lv}} = \frac{h\Delta T}{\rho_v h_{lv}}$$

$$\frac{q''}{\mu_l h_{lv}}\left[\frac{\sigma}{g(\rho_l - \rho_v)}\right]^{1/2} = \left(\frac{1}{C_{sf}}\right)^{1/r} \mathrm{Pr}_l^{-s/r}\left[\frac{c_{pl}\Delta T}{h_{lv}}\right]^{1/r}$$

Rohsenow's Microconvection Model

$$\frac{q''}{\mu_l h_{lv}}\left[\frac{\sigma}{g(\rho_l-\rho_v)}\right]^{1/2}=\left(\frac{1}{C_{sf}}\right)^{1/r}\mathrm{Pr}_l^{-s/r}\left[\frac{c_{pl}\Delta T}{h_{lv}}\right]^{1/r}$$

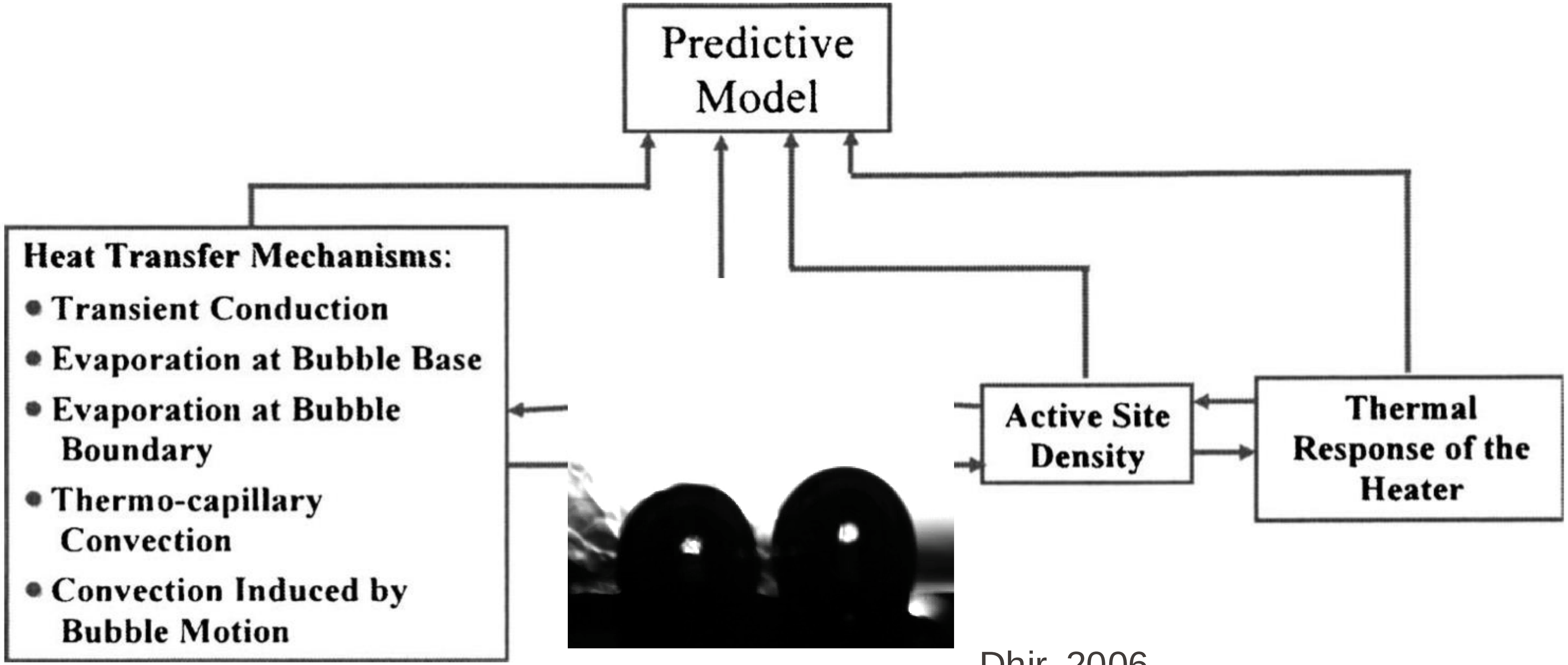
See Chapter 7.7 in Carey for recommended values of r, s, C_{sf}

Most commonly used correlation for nucleate boiling heat transfer

For hydrophobic surfaces, C_{sf} is smaller.

Trapping gas/vapor is easier ⇒ More active bubble nucleation sites

What's Needed for Mechanistic Understanding



Dhir, 2006
https://doi.org/10.1115/1.2136366

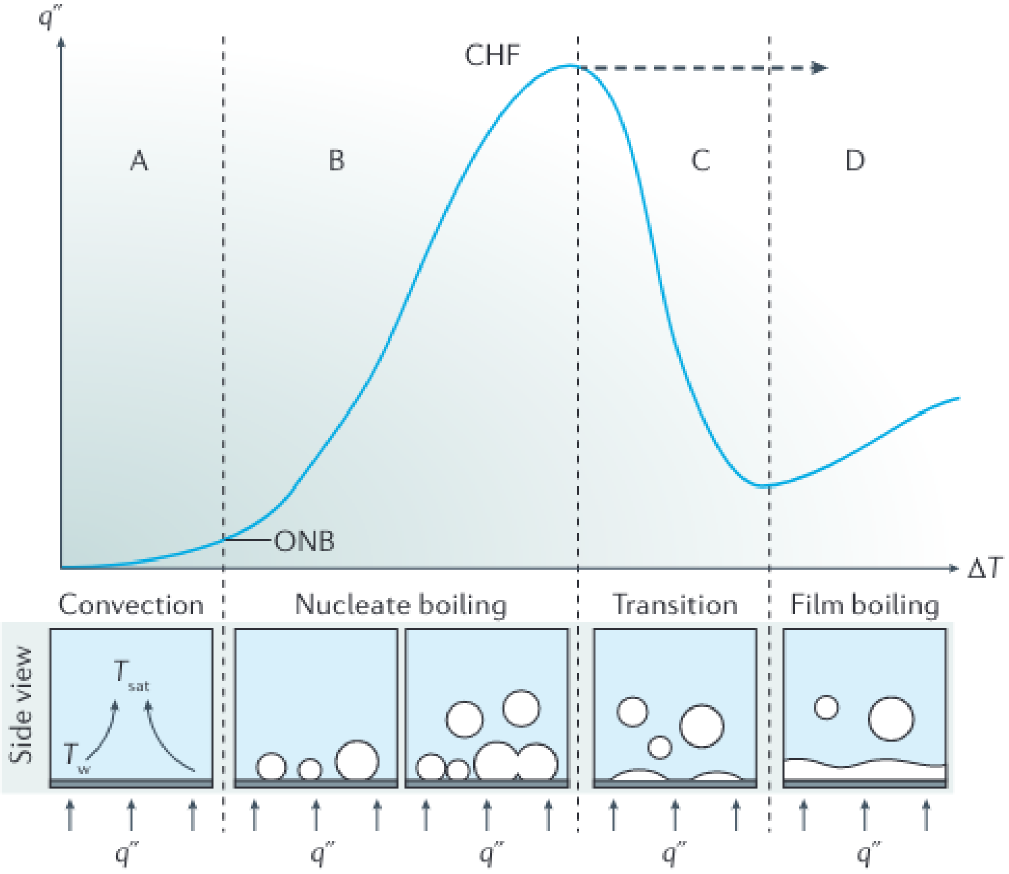
Numerical Simulation

Working fluid: R134a

Heat flux:
from 1.5 W/cm^2 to 38 W/cm^2

Yazdani, 2016
https://doi.org/10.1063/1.4940042

Critical Heat flux



U.S. Department of Energy
Test of Nuclear Rods

Helmholtz Instability of Vapor Columns

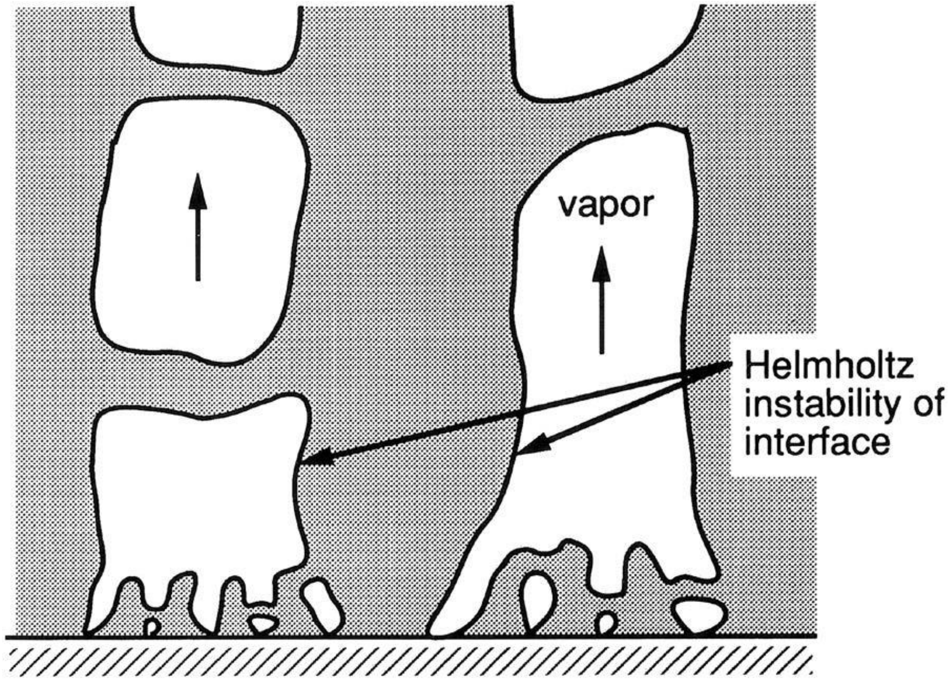


Figure 7.16 Carey

Video credit: Dr. Rameez Iqbal

Vapor columns form at high heat fluxes

Helmholtz Instability

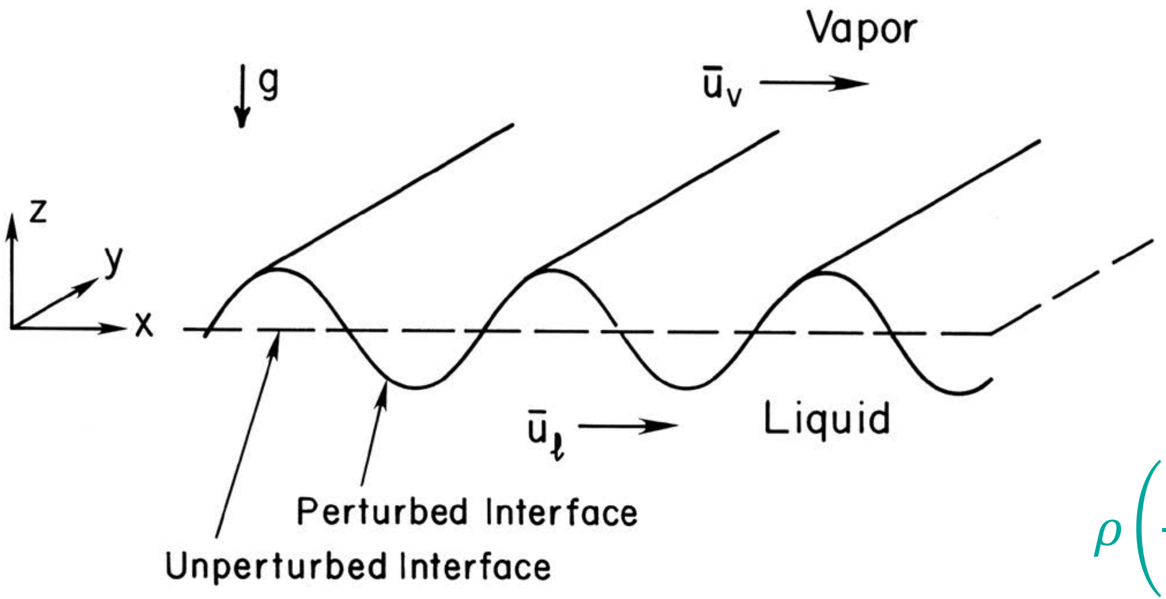


Figure 4.4 in Carey

Continuity

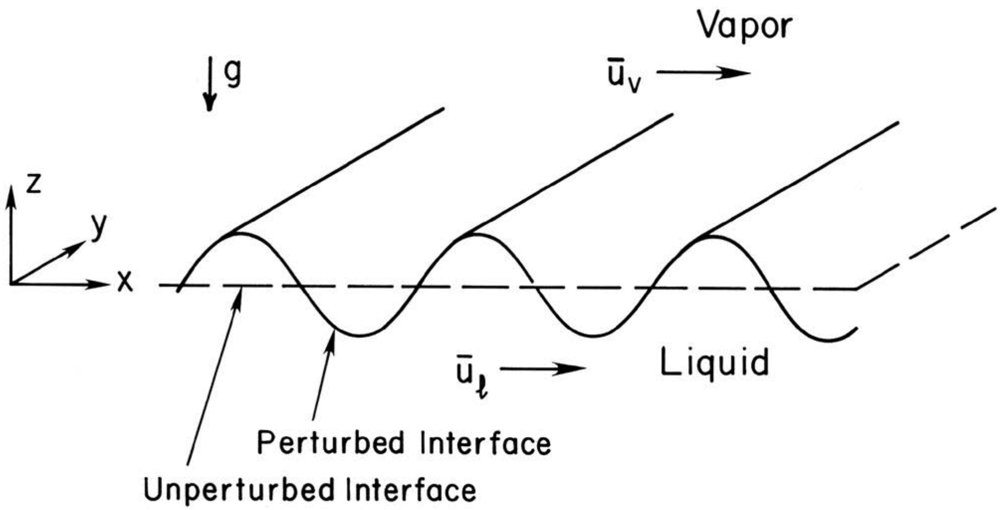
$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0$$

Momentum balance
(neglecting viscosity)

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial P}{\partial x}$$

$$\rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial P}{\partial z} - \rho g$$

Helmholtz Instability



Consider after a perturbation $\delta(x, t=0) = Ae^{i\alpha x}$

$$u: \bar{u} \to \bar{u} + u', \qquad w: 0 \to w', \qquad P: \bar{P} \to \bar{P} + P'$$

$$\frac{\partial u'}{\partial x} + \frac{\partial w'}{\partial z} = 0$$

$$\rho\left(\frac{\partial u'}{\partial t} + \bar{u}\frac{\partial u'}{\partial x}\right) = -\frac{\partial P'}{\partial x}$$

$$\rho\left(\frac{\partial w'}{\partial t} + \bar{u}\frac{\partial w'}{\partial x}\right) = -\frac{\partial P'}{\partial z}$$

$$\Rightarrow \frac{\partial^2 P'}{\partial x^2} + \frac{\partial^2 P'}{\partial z^2} = 0$$

Postulate the form of the response function:

$$\delta = Ae^{i\alpha x + \beta t} \qquad w' = \hat{w}(z)e^{i\alpha x + \beta t} \qquad P' = \hat{P}(z)e^{i\alpha x + \beta t}$$

We are interested in β

Helmholtz Instability

Helmholtz Instability