



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

Boiling: Pool Boiling Curve

Zhengmao Lu

Energy Transport Advances
Laboratory

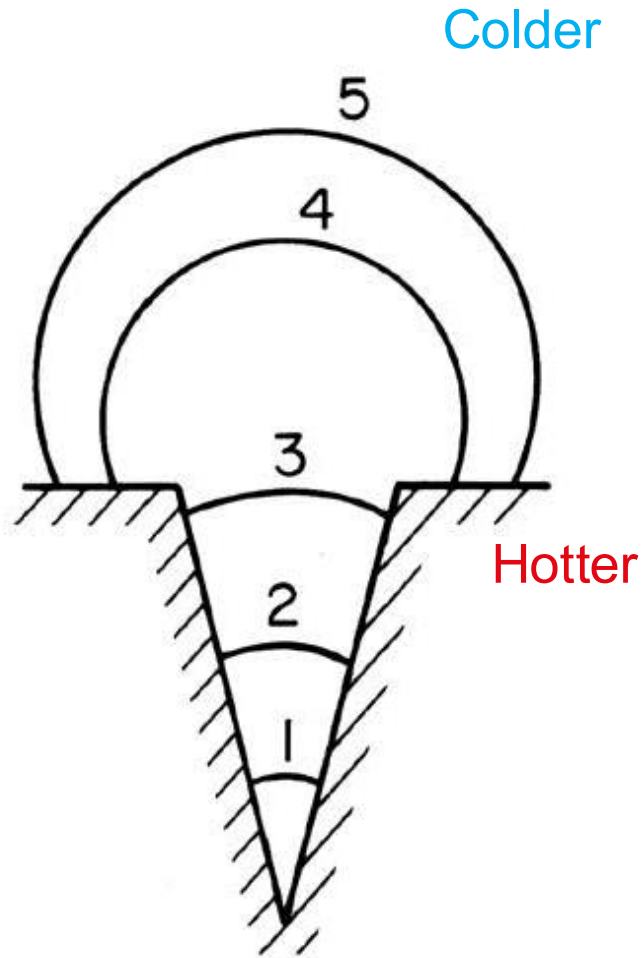
EPFL Mechanical Engineering

2025 Fall Semester

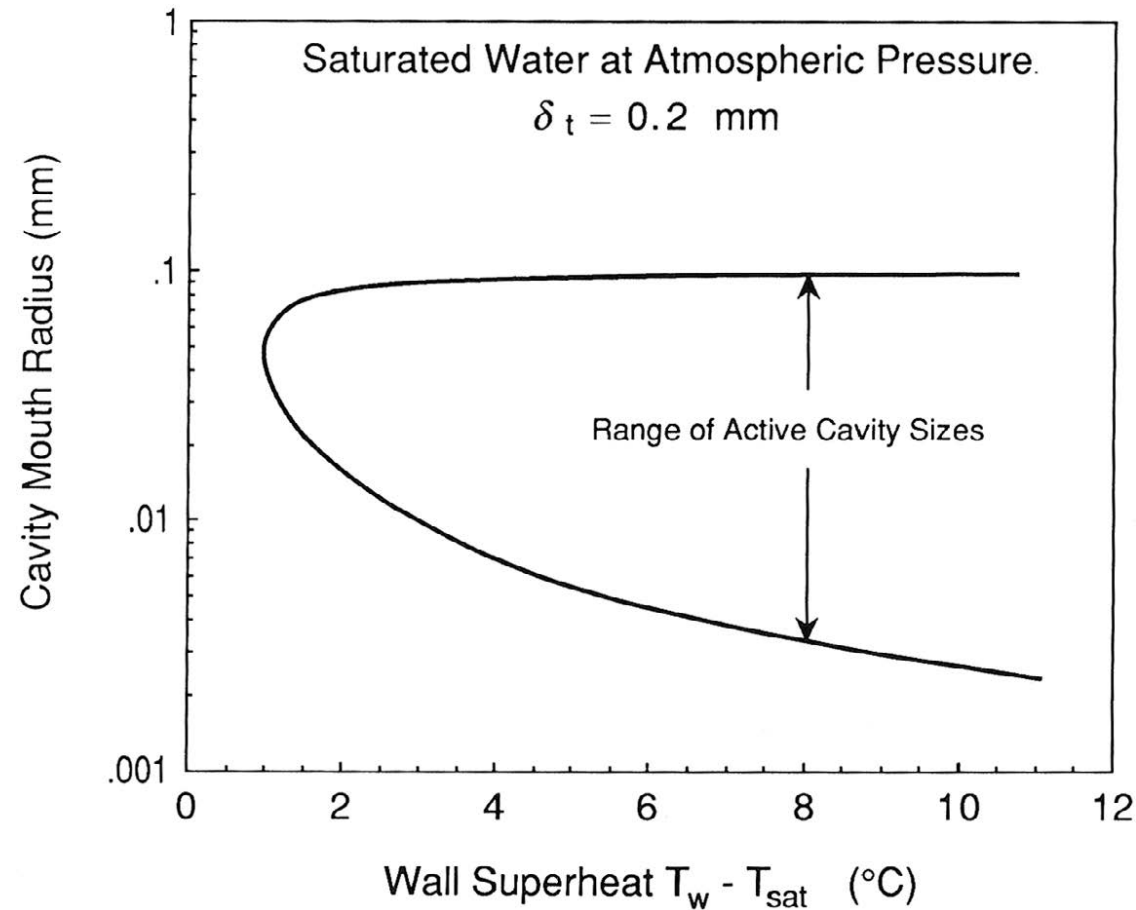
Photo Credit: Trougnouf



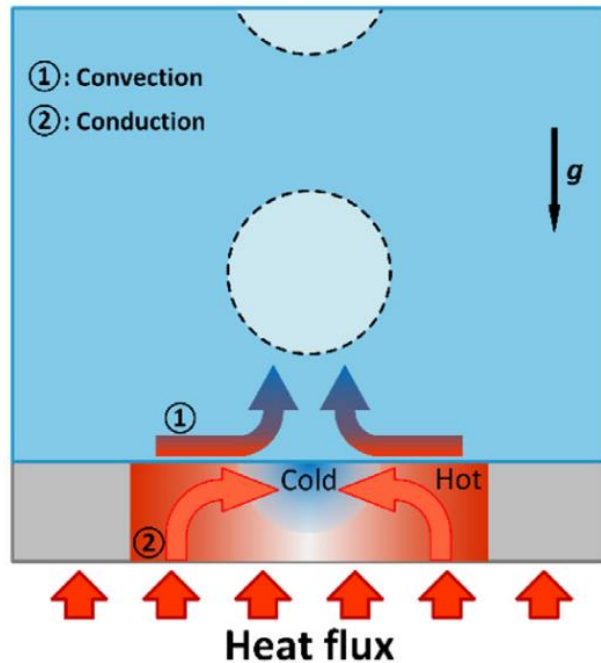
- Understand the mechanism for heterogeneous nucleation in practical systems (entrapped gas/vapor theory)
- Understand Hsu's criteria for nucleation site activation
- Analyze the timescales in the bubble cycle to evaluate bubble departure frequency



- Whether bubble can grow out of the cavity overcoming capillary pressure?
- Whether bubble can keep growing as it gets closer to the bulk fluid which is colder than the heated wall



- 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



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

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

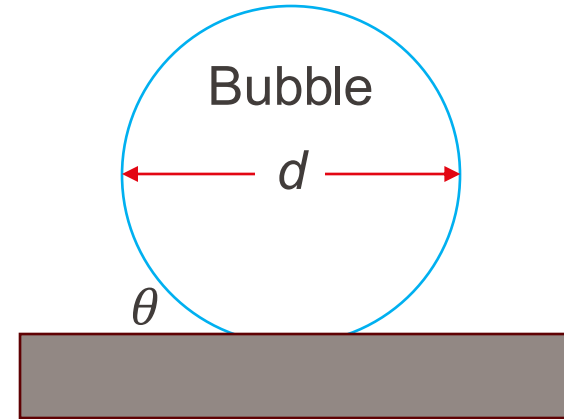
When D is relatively large, rewetting-induced convection dominates

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

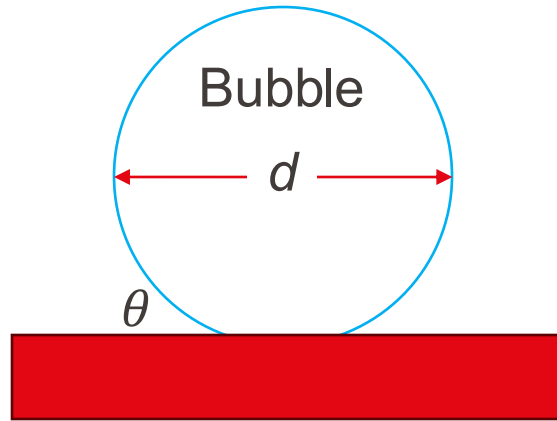
When D is relatively small, conduction dominates

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

Bubble Departure Diameter

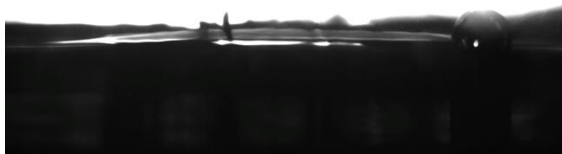


Comments on Fritz's Expression



Fritz expression $Bo_d = 0.0208\theta$

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



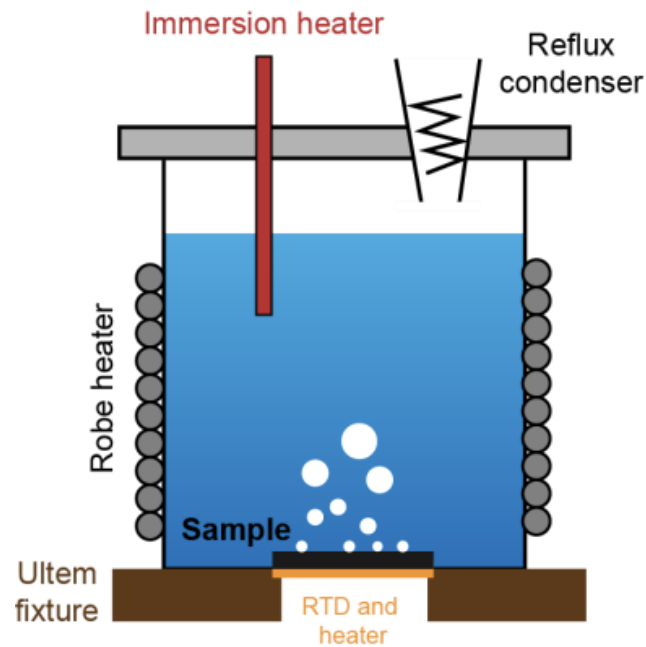
Credit: Sk Rameez Iqbal

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

Intended Learning Objectives Today

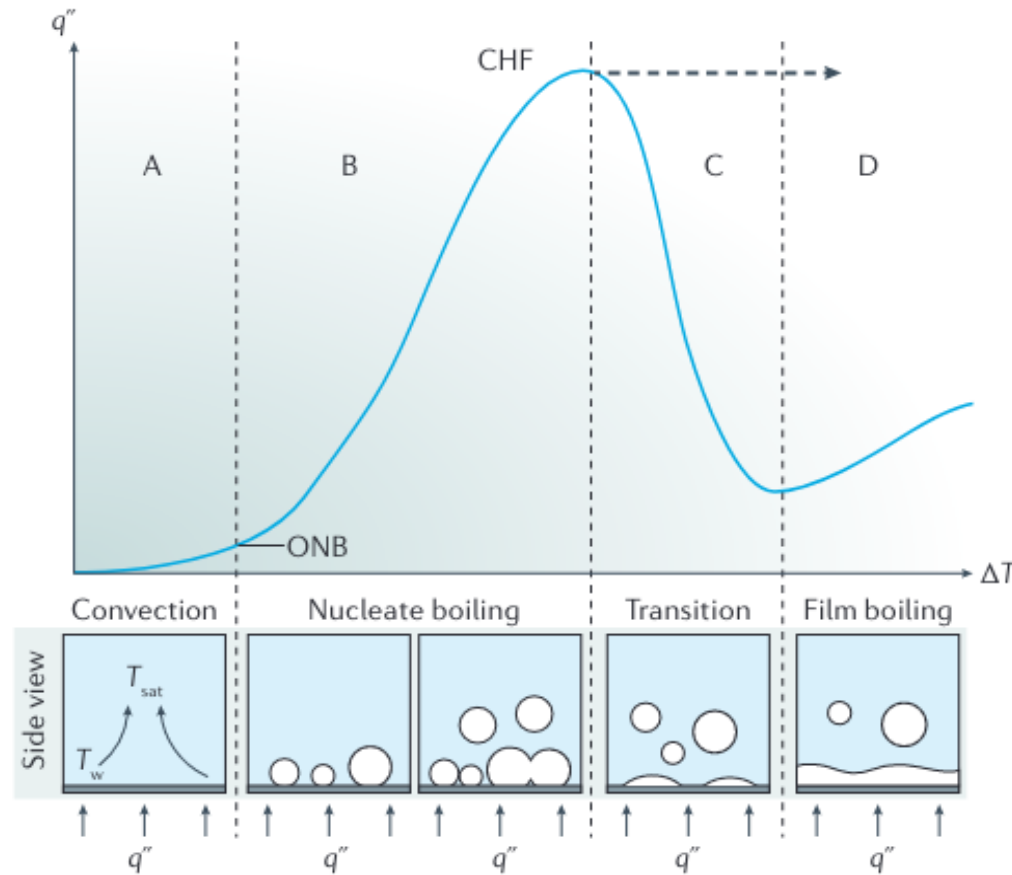
- Pool boiling (concept, heat transfer regimes,...)
- Rohsenow's microconvection model for nucleate boiling
- Zuber's CHF model based on Helmholtz and Taylor instabilities

: boiling a liquid on a heated surface that is submerged in the liquid, without any forced flow; the liquid motion is driven only by natural convection and bubble activity



We are interested in the relationship between the average heat flux at the boiling surface q'' and the surface super heat $\Delta T = T_w - T_{sat}(P_l)$

We focus on saturated pool boiling ($T_\infty = T_{sat}(P_l)$) unless stated otherwise



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

Rohsenow's Microconvection Model

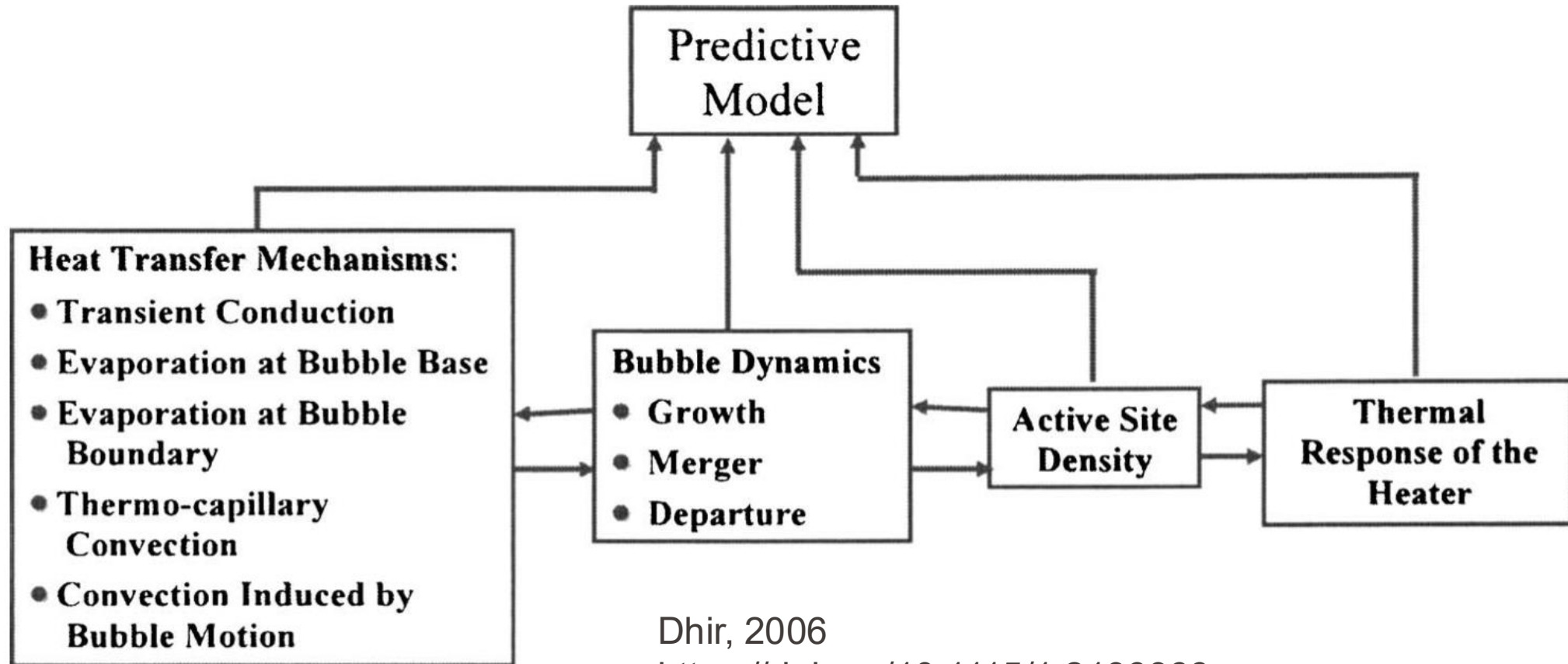
$$\frac{q''}{\mu_l h_{lv}} \left[\frac{\sigma}{g(\rho_l - \rho_v)} \right]^{1/2} = \left(\frac{1}{C_{sf}} \right)^{1/r} \text{Pr}_l^{-s/r} \left[\frac{c_{pl} \Delta T}{h_{lv}} \right]^{1/r}$$

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 \Rightarrow More active bubble nucleation sites

What's Needed for Mechanistic Understanding



Dhir, 2006

<https://doi.org/10.1115/1.2136366>

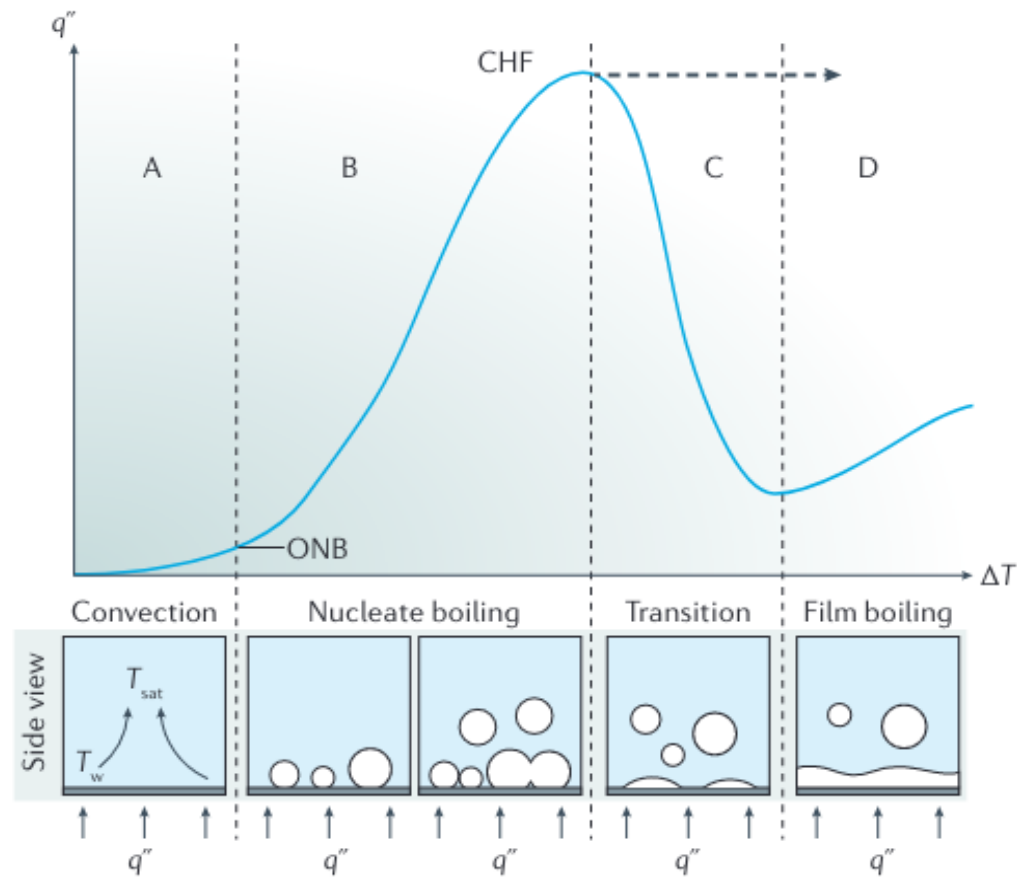


Working fluid: R134a

Heat flux:
from 1.5 W/cm² to 38 W/cm²

Yazdani, 2016

<https://doi.org/10.1063/1.4940042>



U.S. Department of Energy
Test of Nuclear Rods

Helmholtz Instability of Vapor Columns

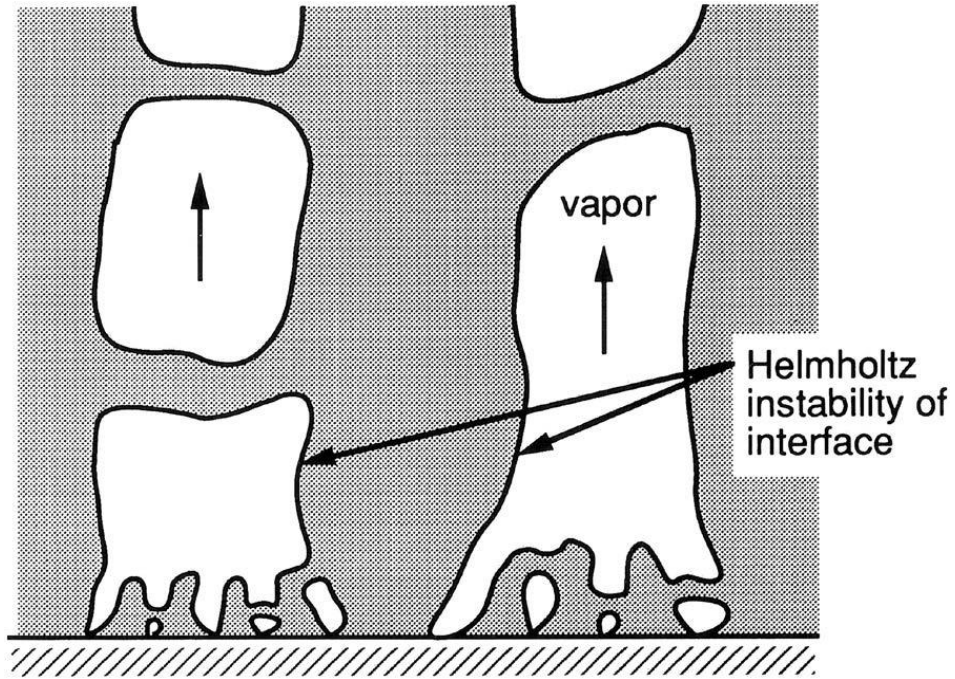
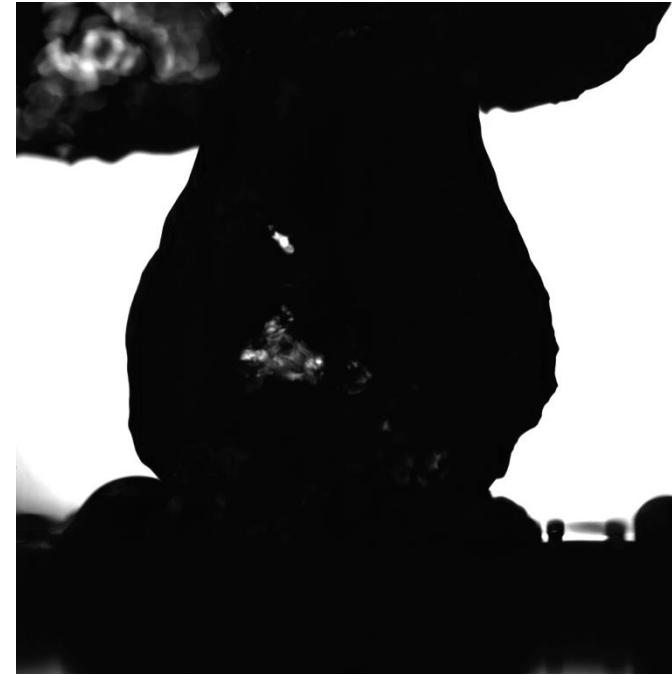


Figure 7.16 Carey



Video credit: Dr. Rameez Iqbal

Vapor columns form at high heat fluxes

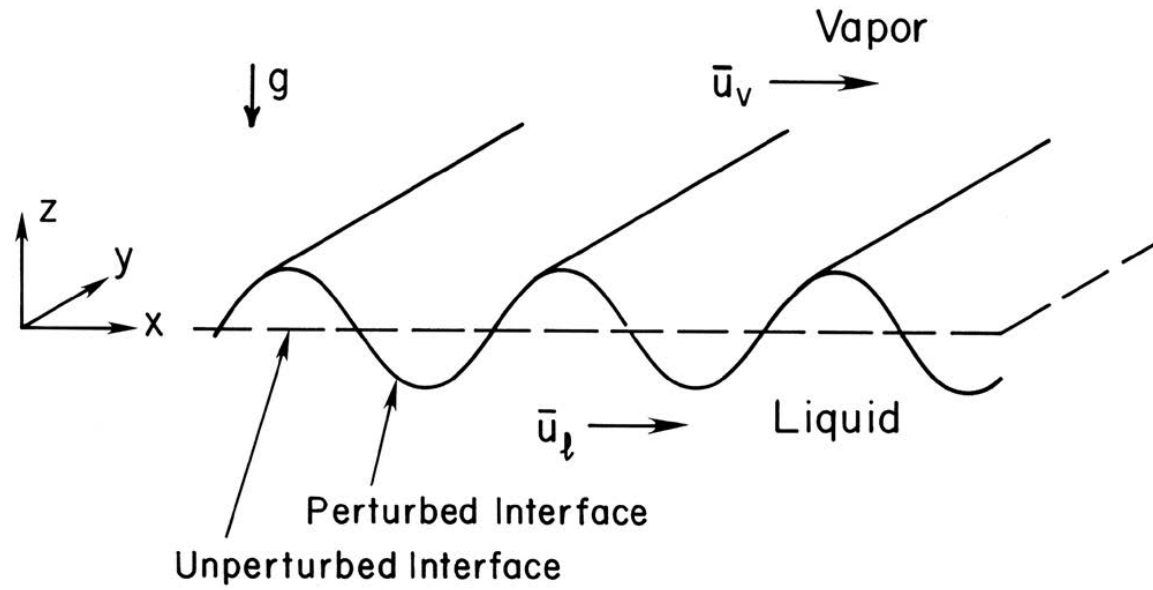
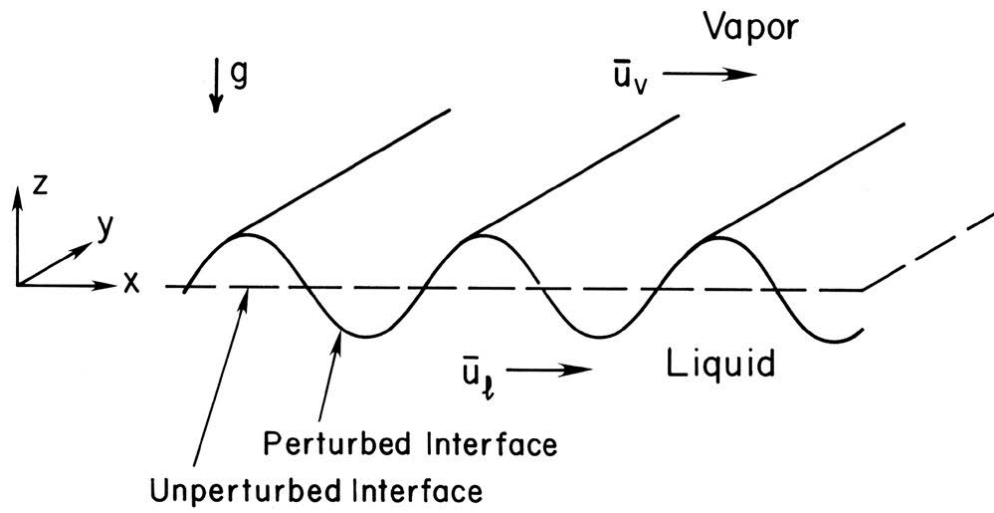


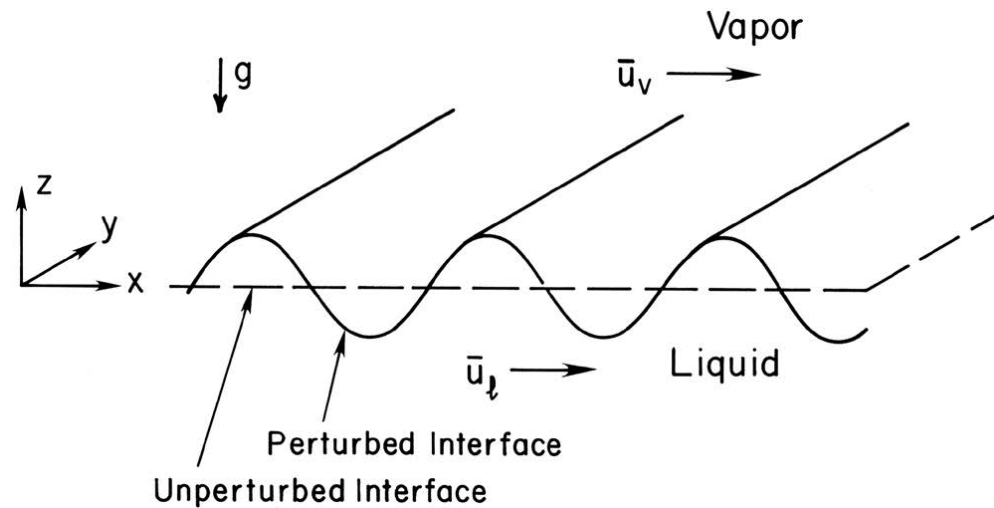
Figure 4.4 in Carey

Helmholtz Instability



Helmholtz Instability

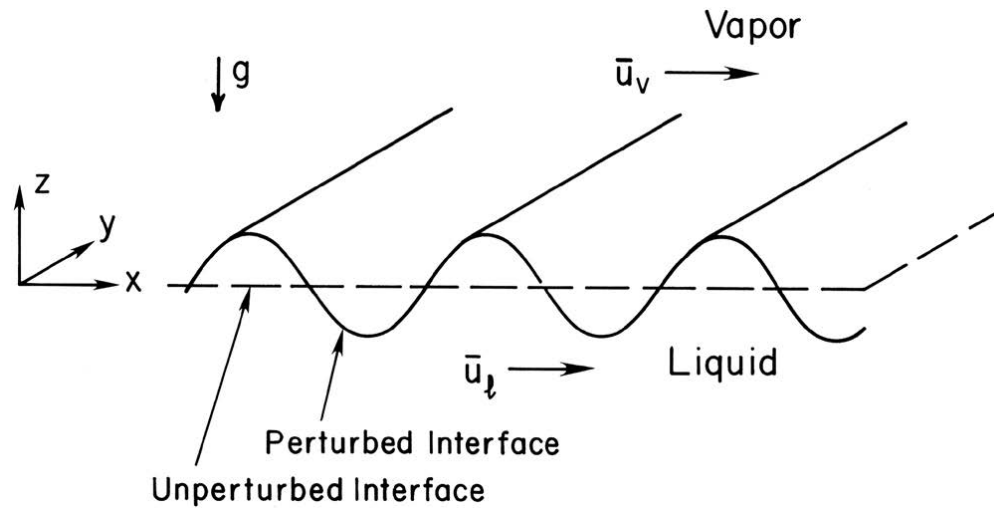
$$\frac{\partial^2 P'}{\partial x^2} + \frac{\partial^2 P'}{\partial z^2} = 0 \quad P' = \hat{P}(z)e^{i\alpha x + \beta t}$$



$$w' = \hat{w}(z)e^{i\alpha x + \beta t} \quad \rho \left(\frac{\partial w'}{\partial t} + \bar{u} \frac{\partial w'}{\partial x} \right) = - \frac{\partial P'}{\partial z}$$

Helmholtz Instability

$$\frac{\partial u'}{\partial x} + \frac{\partial w'}{\partial z} = 0 \quad w' = \hat{w}(z)e^{i\alpha x + \beta t}$$



$$\delta = Ae^{i\alpha x + \beta t} \quad \hat{w}_v(z) = \frac{a_v \alpha}{\rho_v (\beta + i\alpha \bar{u})} e^{-\alpha z}$$

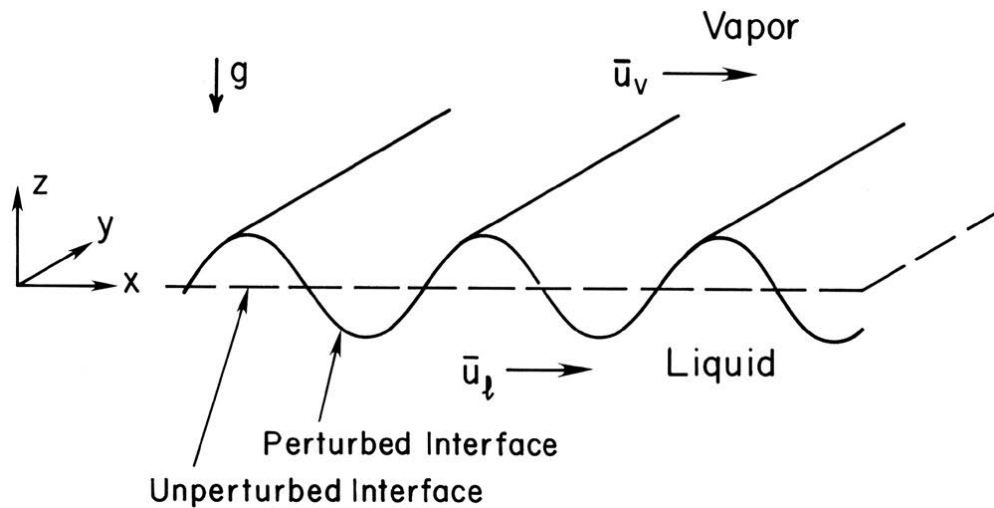
$$\hat{w}_l(z) = -\frac{a_l \alpha}{\rho_l (\beta + i\alpha \bar{u})} e^{\alpha z}$$

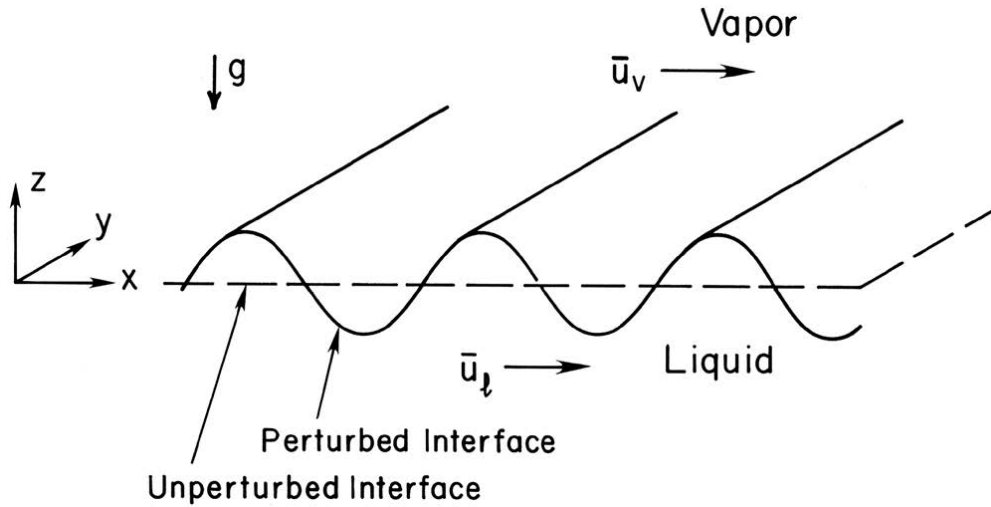
Helmholtz Instability

$$a_v = \frac{\rho_v}{\alpha} (\beta A + i\alpha \bar{u}_v)^2 A$$

$$a_l = -\frac{\rho_l}{\alpha} (\beta A + i\alpha \bar{u}_l)^2 A$$

$$\hat{P}_v = a_v e^{-\alpha z} \quad \hat{P}_l = a_l e^{\alpha z}$$





$$\text{Perturbation } \delta(x, t = 0) = Ae^{i\alpha x}$$

$$\delta = Ae^{i\alpha x + \beta t}$$

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

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

The perturbation will cause a growing response if and only if β has a positive real part

- When $|\bar{u}_v - \bar{u}_l| > \left[\frac{2(\rho_l + \rho_v)}{\rho_l} \right]^{\frac{1}{2}} \left(\frac{\sigma \Delta \rho g}{\rho_v^2} \right)^{\frac{1}{4}}$, there will be some range of disturbances that are unstable (grow exponentially)
- $\bar{u}_v - \bar{u}_l$ promotes instability while gravity and surface tension suppressing instability, we can adjust the value of g based on the orientation of the system.

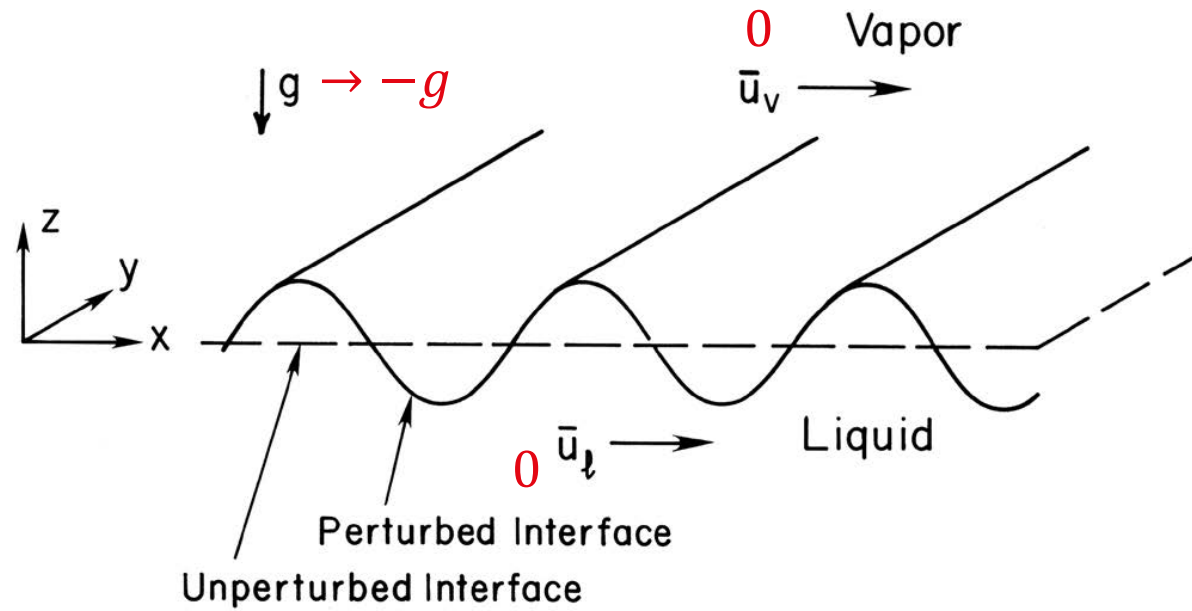


Helmholtz Instability

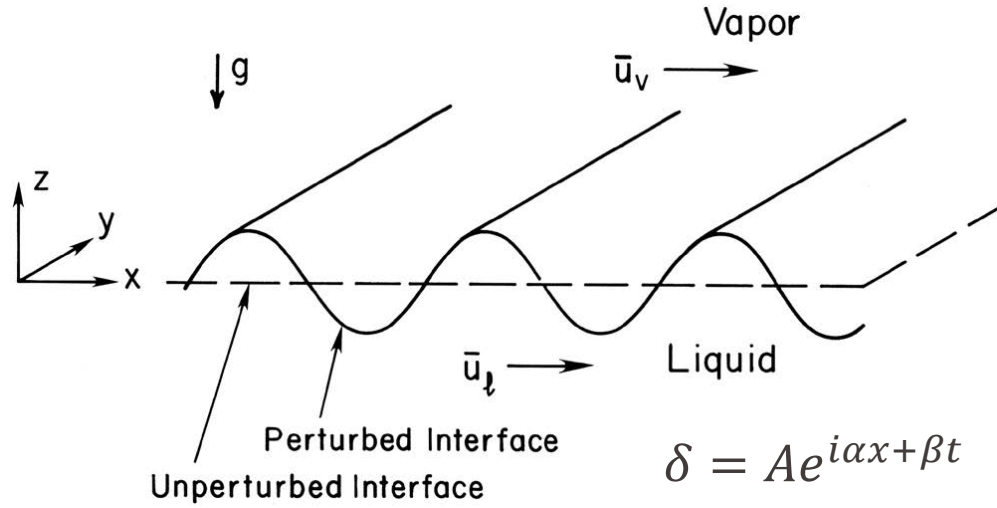


Facebook/ Rachel Gordon

$$\delta = Ae^{i\alpha x + \beta t}$$

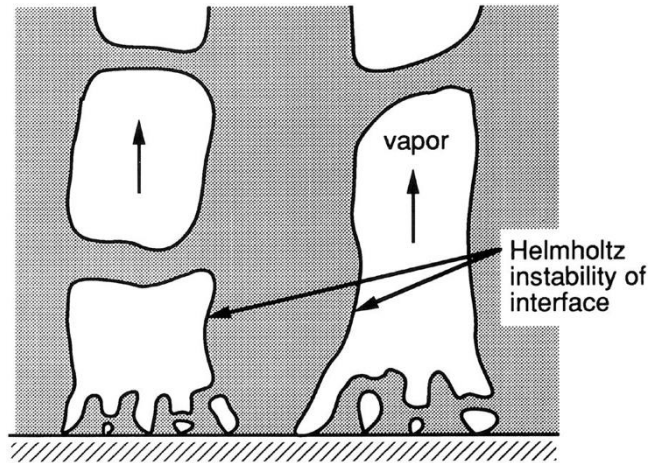


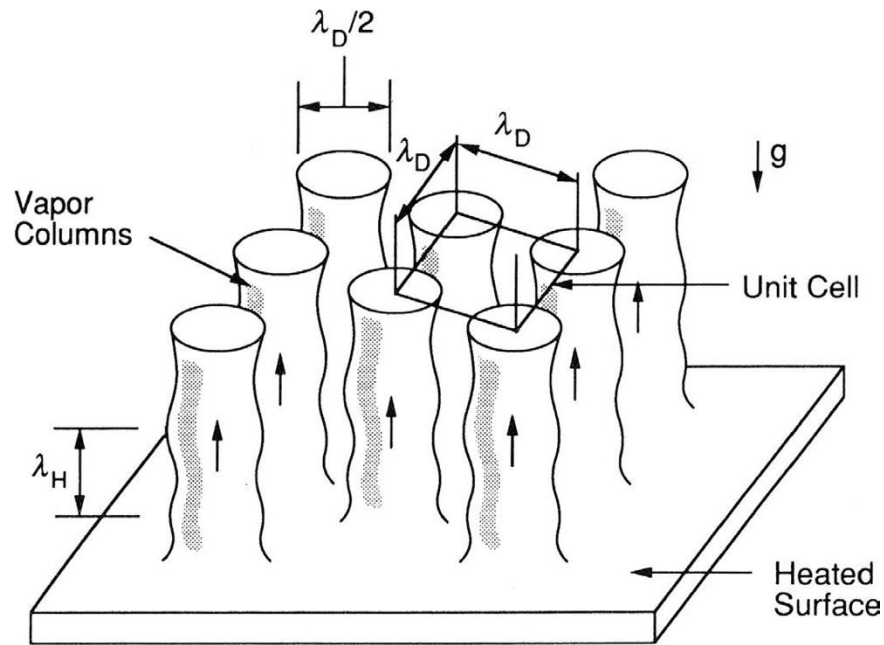
How It's Related to Boiling



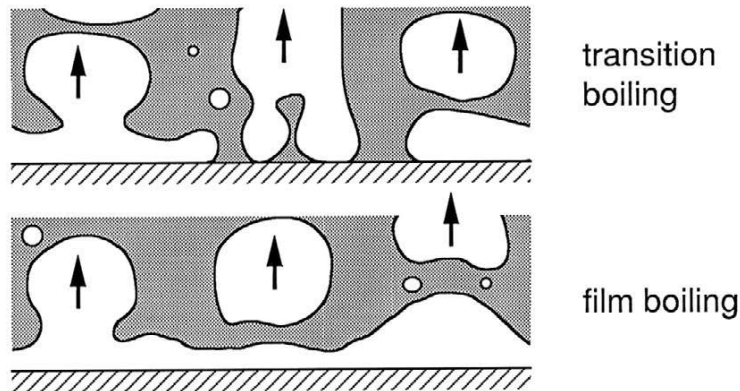
Helmholtz Instability

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

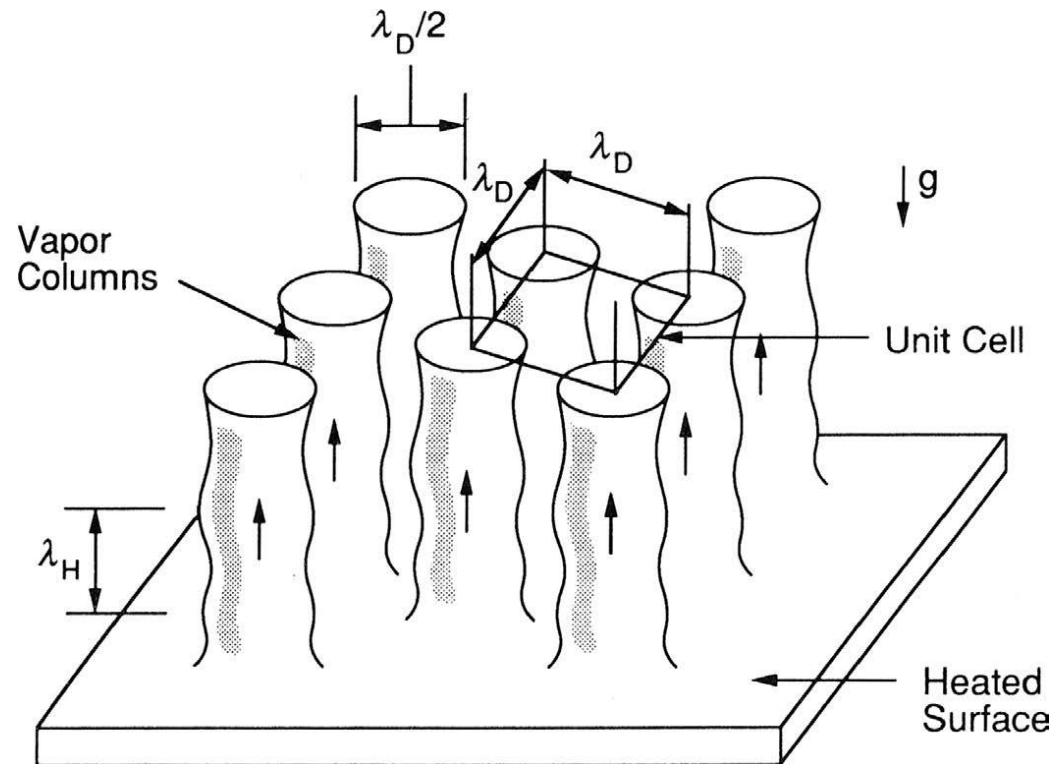




- CHF is reached when interface of vapor columns becomes Helmholtz unstable (with wavelength λ_H)
- The columns leave the surface in a rectangular array, with the pitch coinciding with the most dangerous wavelength in Taylor instability $\lambda_D = 2\pi\sqrt{3\sigma/\Delta\rho g}$
- The diameter of vapor column is $\lambda_D/2$
- $\lambda_H = \lambda_D$



$$u_c = \sqrt{\frac{2\pi\sigma}{\rho_v\lambda_D}} \quad \lambda_H = \lambda_D = 2\pi \sqrt{\frac{3\sigma}{\Delta\rho g}}$$



Comments on Zuber's Model

- No way to accommodate effects from geometry and surface wettability
- No clear justification for the choice of vapor column diameter as $\lambda_D/2$
- No visual observation of Helmholtz instability during boiling to date
- Still widely used as a reference model for all subsequence CHF models