EPFL

ETA-Lab
Energy Transport Advances

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

Boiling: Heterogeneous Nucleation

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Photo Credit: Trougnouf

Last Time

- Analyze the free energy of vapor embryo (Thermodynamics)
- Understand the derivation of bubble growth kinetics and the implication for homogeneous nucleation

Heterogeneous Nucleation

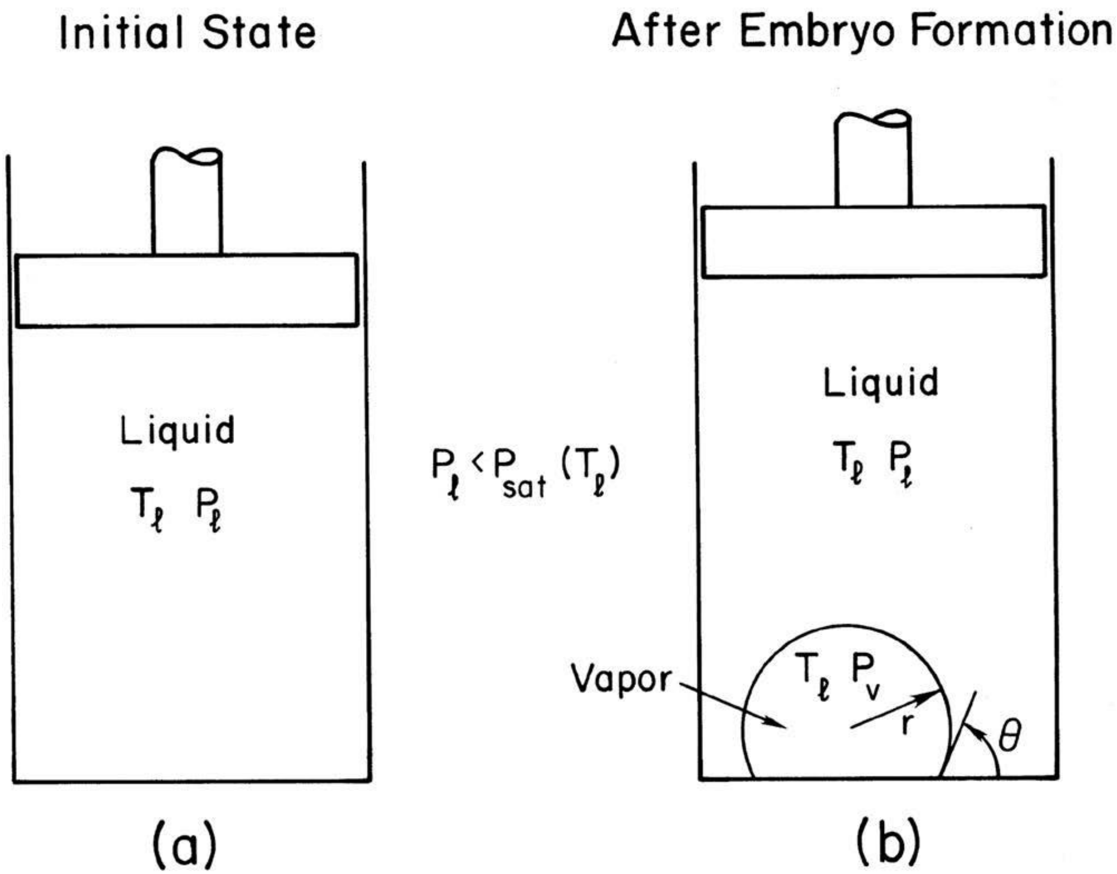
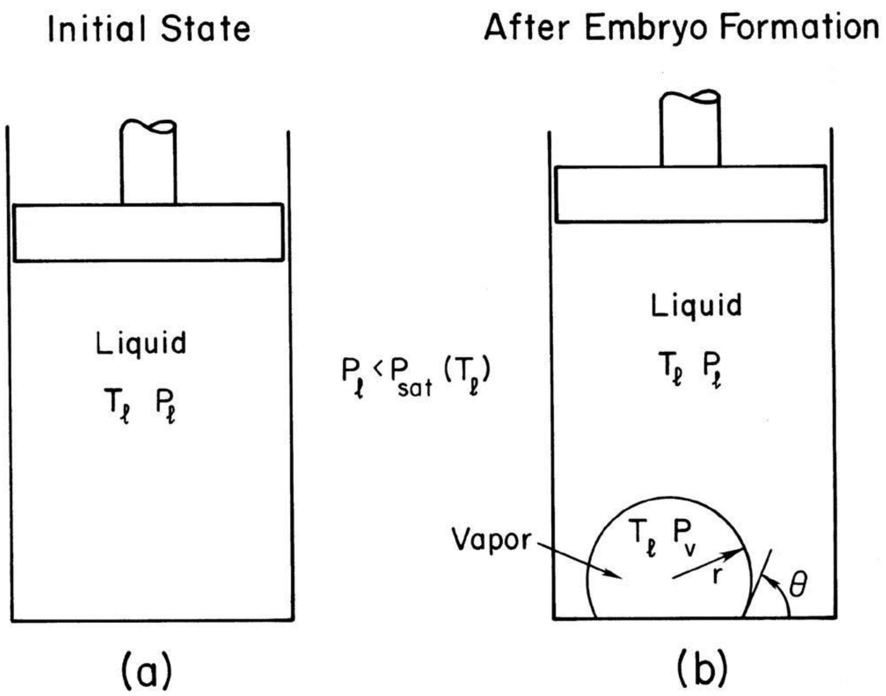
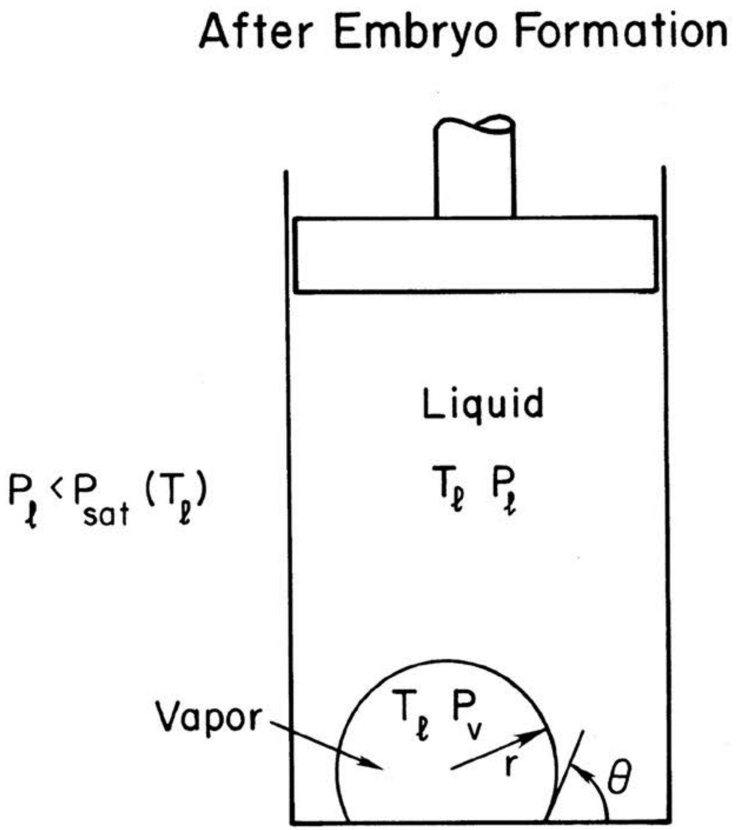


Figure 6.2 in Carey

Gibbs Free Energy Change



Equilibrium Bubble Radius



Physical Meaning of *J*

$$J_n = N_n^* A_n j_{ne} - N_{n+1}^* A_{n+1} j_{(n+1)c}$$

J_n : the rate at which embryo bubbles grow from n to n + 1 molecules per unit volume [$m^{-3}s^{-1}$], which is a constant at a steady state

This includes the rate at which bubbles of the critical size are generated

Higher J implies higher probability of nucleation

Heterogenous Critical Embryo Generation Rate

$$J = \frac{\rho_{N,l}^{\frac{2}{3}}(1+\cos\theta)}{2F}\left(\frac{3F\sigma_{lv}}{\pi m}\right)^{\frac{1}{2}}\exp\left(-\frac{\Delta G_e}{k_B T_l}\right)$$ [m^{-2}s^{-1}]

$\rho_{N,l}^{\frac{2}{3}}$ replaces $\rho_{N,L}$ because we consider nucleation from the surface

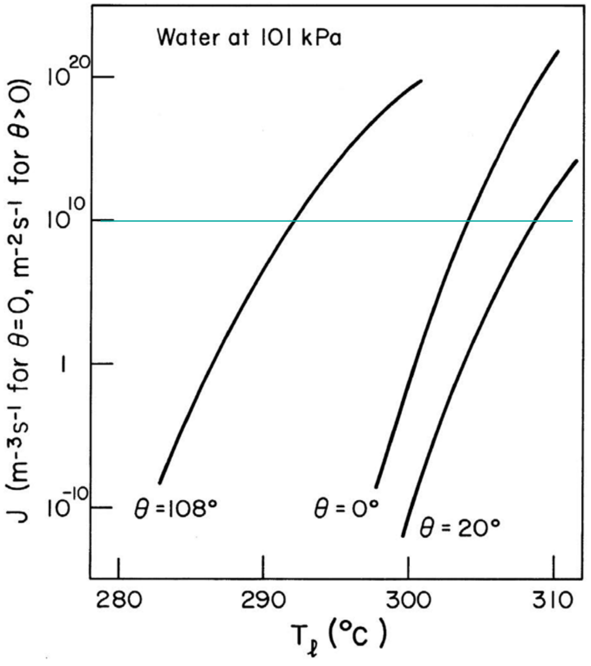


FIGURE 6.3

Given a threshold J (e.g., 10^{10} m^{-2}s^{-1}), one can determine the limiting liquid temperature beyond which rapid spontaneous nucleation occurs

This limiting superheat temperature is clearly a function of the contact angle

However, according to this model, heterogeneous nucleation occurs at ~300 ℃ on most common surfaces (**which is not what we observe**)

Intended Learning Objectives Today

- 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

  - Reading materials: Carey 6.2, 6.3;
    Zhang et al, 2021 (https://doi.org/10.1016/j.ijheatmasstransfer.2020.120640)

Entrapped Gas/Vapor Theory

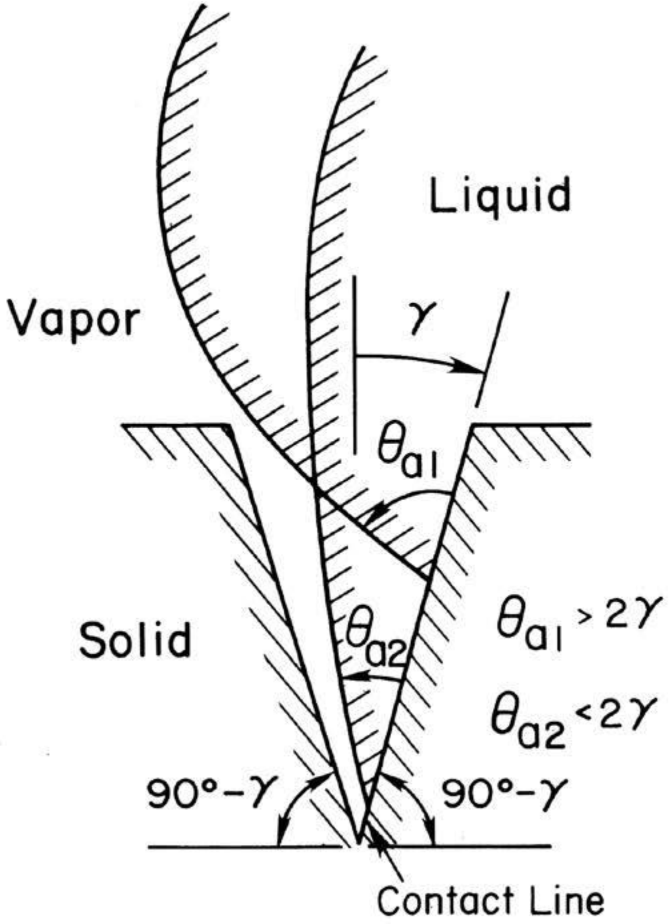


Figure 6.4 in Carey

- Most real solid surfaces contain pits, scratches, or other irregularities
- When liquid passes over a gas-filled groove, advancing CA θ_a is maintained during filling process
- Gas entrapped if $\theta_a > 2\gamma$ ("nose" of liquid striking the opposite wall)
- This initial gas core, entrapped or from outgassing of heated liquid, can facilitate nucleation

Entrapped Gas/Vapor Theory

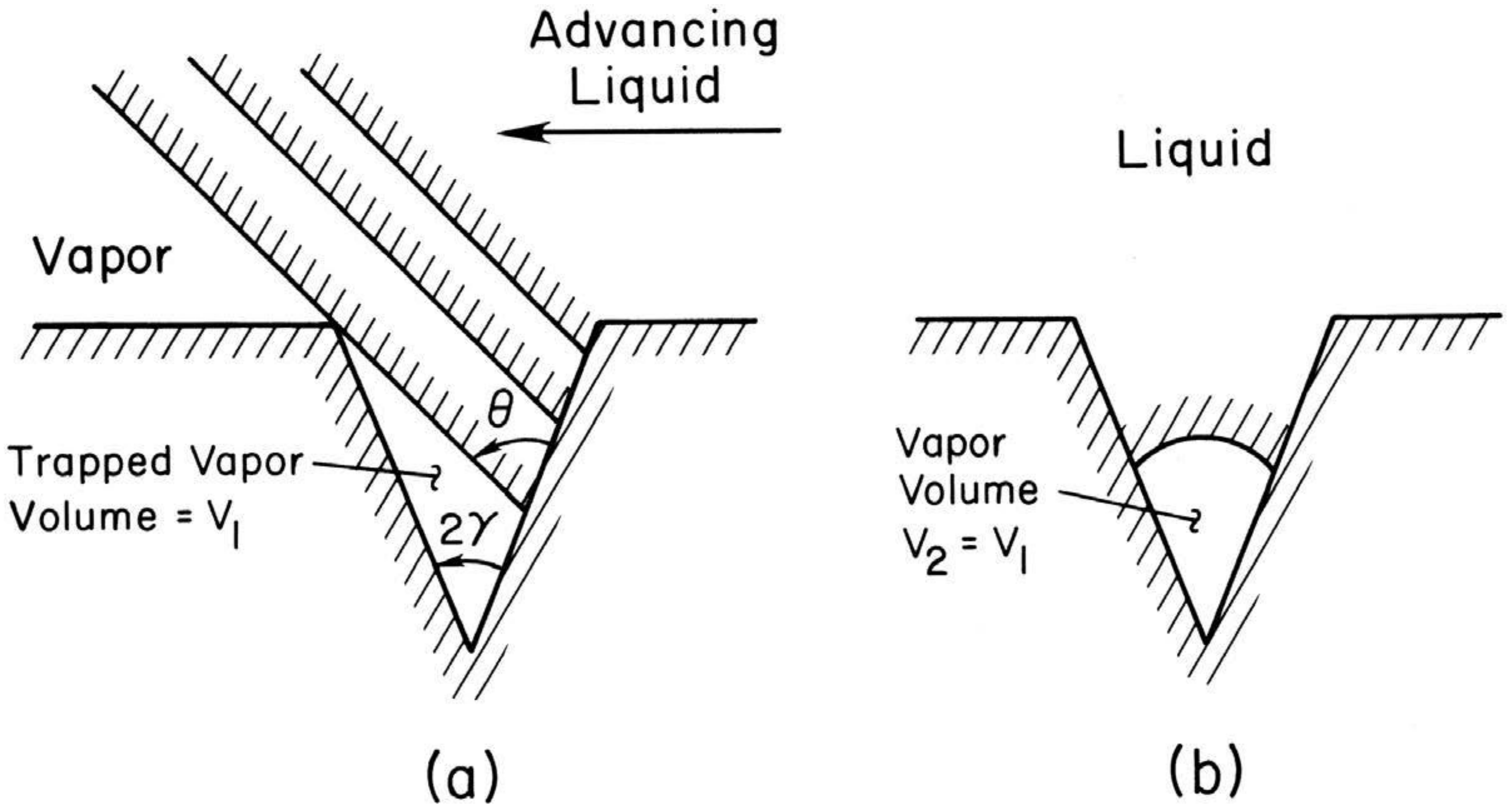
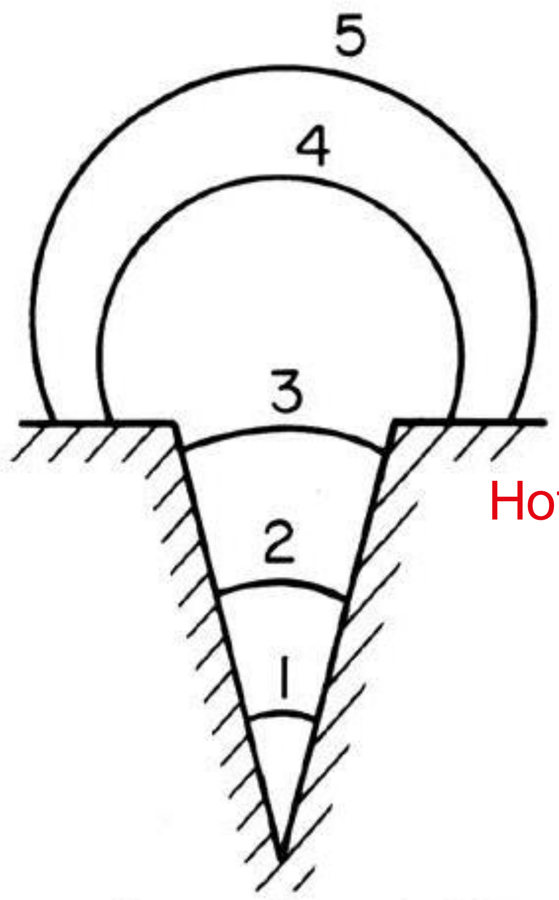


FIGURE 6.7

Entrapped Gas/Vapor Theory

- Clear correlation between locations of surface cavities and and those of bubble nucleation sites has been documented in literature
- When liquid is pressurized to dissolve entrapped gases before being heated, the required superheat to initiate nucleation is similar to the homogeneous case
- After the initial nucleation, surface cavities can be refilled with vapor to sustain nucleation
- During boiling, bubbles released from surface cavities carry away entrapped gases; when the system is subsequently cooled down, the cavities may no longer contain entrapped gas

Criteria for Nucleation Site Activation



- 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

Hsu's Model

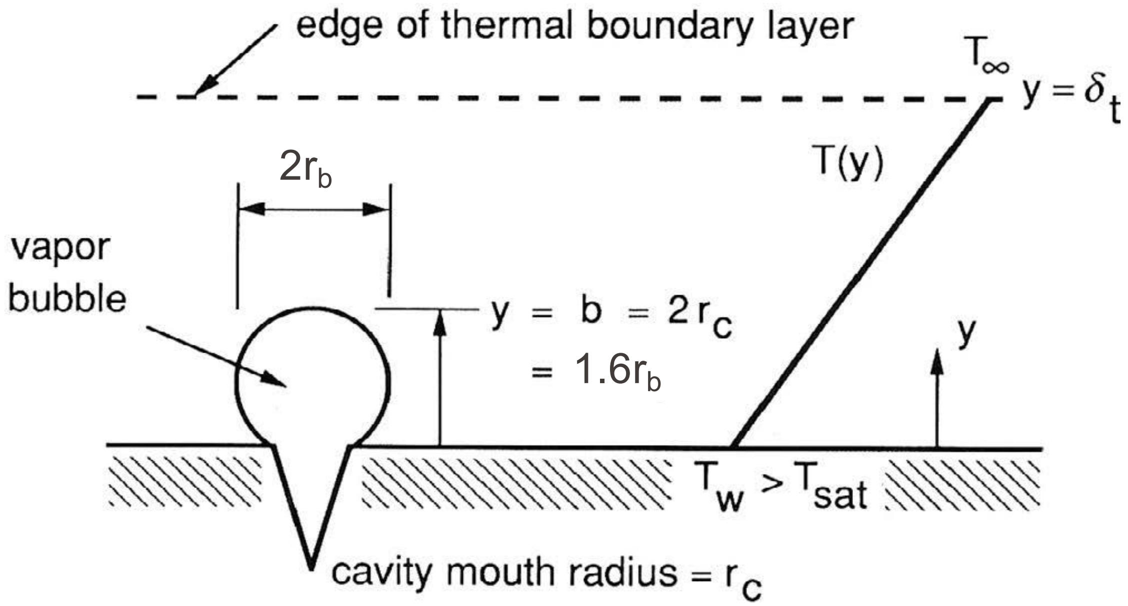


Figure 6.11 in Carey

A thermal boundary layer of fixed thickness δ_t is assumed to be adjacent to the wall

Hsu postulated the height of the embryo bubble b, the bubble radius r_b and the cavity mouth radius r_c follow

$$b = 2r_c = 1.6r_b$$

Hsu's Model

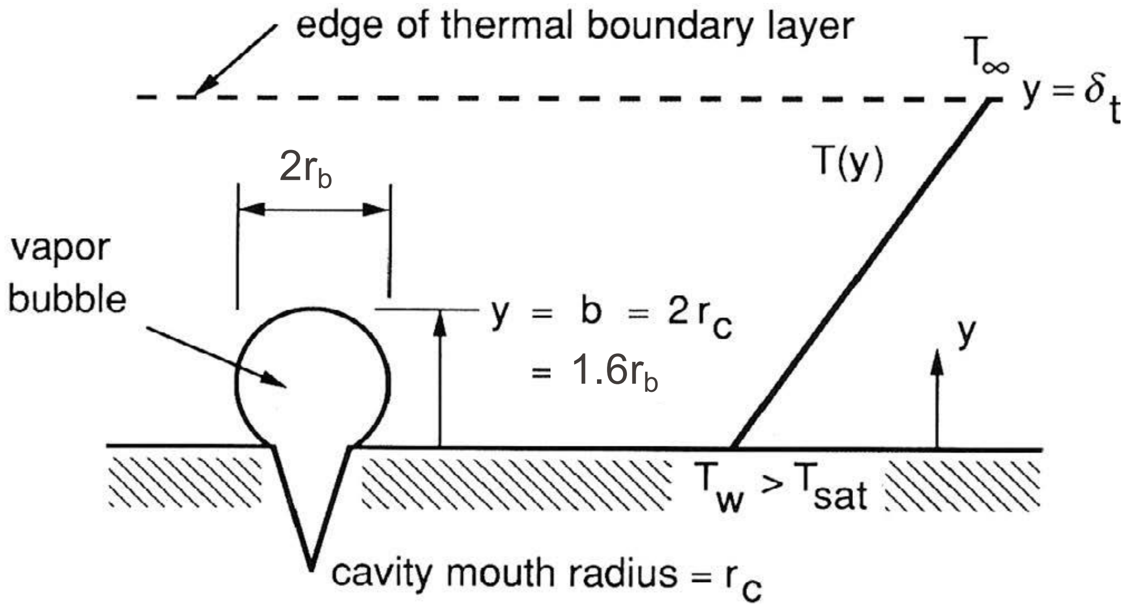
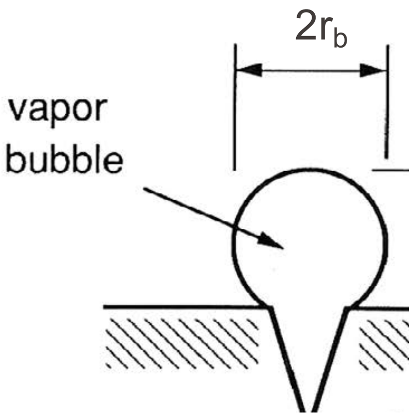
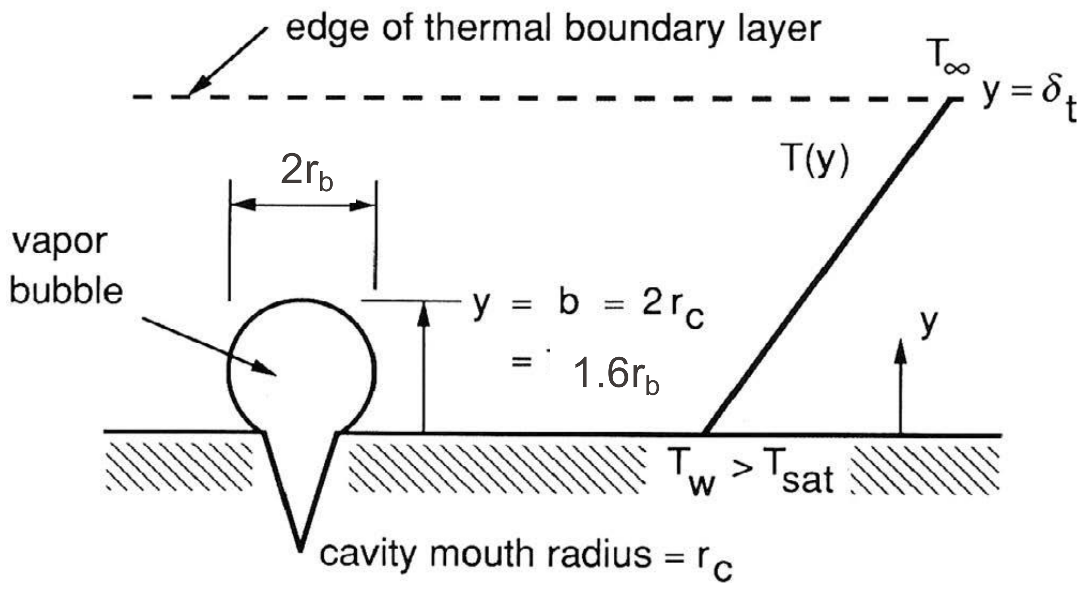


Figure 6.11 in Carey

Clausius-Clapeyron Relation



Bubble Nucleation Criteria



$$T_{top} = T_\infty + (T_w - T_\infty)\left(1 - \frac{b}{\delta_t}\right)$$

$$T_{le} = T_{sat}(P_l) + \frac{2\sigma T_{sat}(P_l)}{\rho_v h_{lv} r_b}$$

Bubble Nucleation Criteria

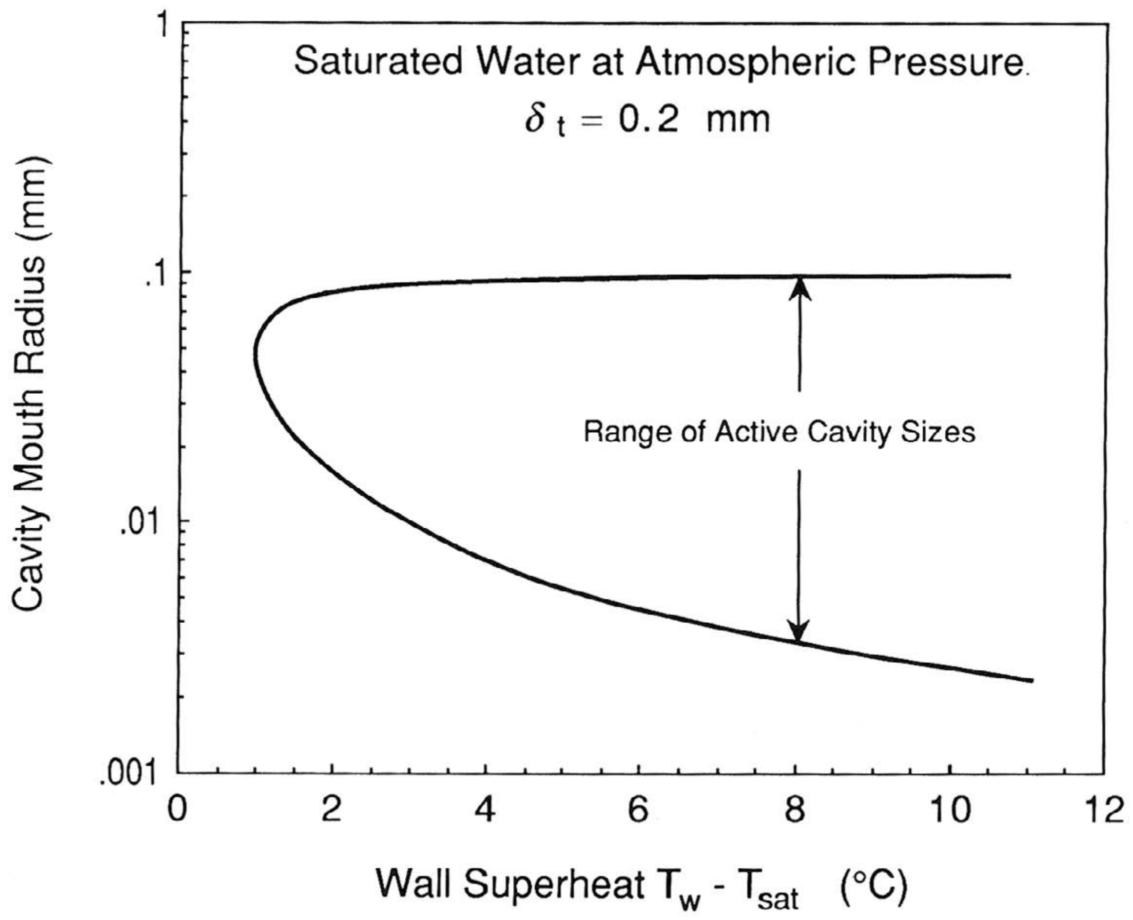
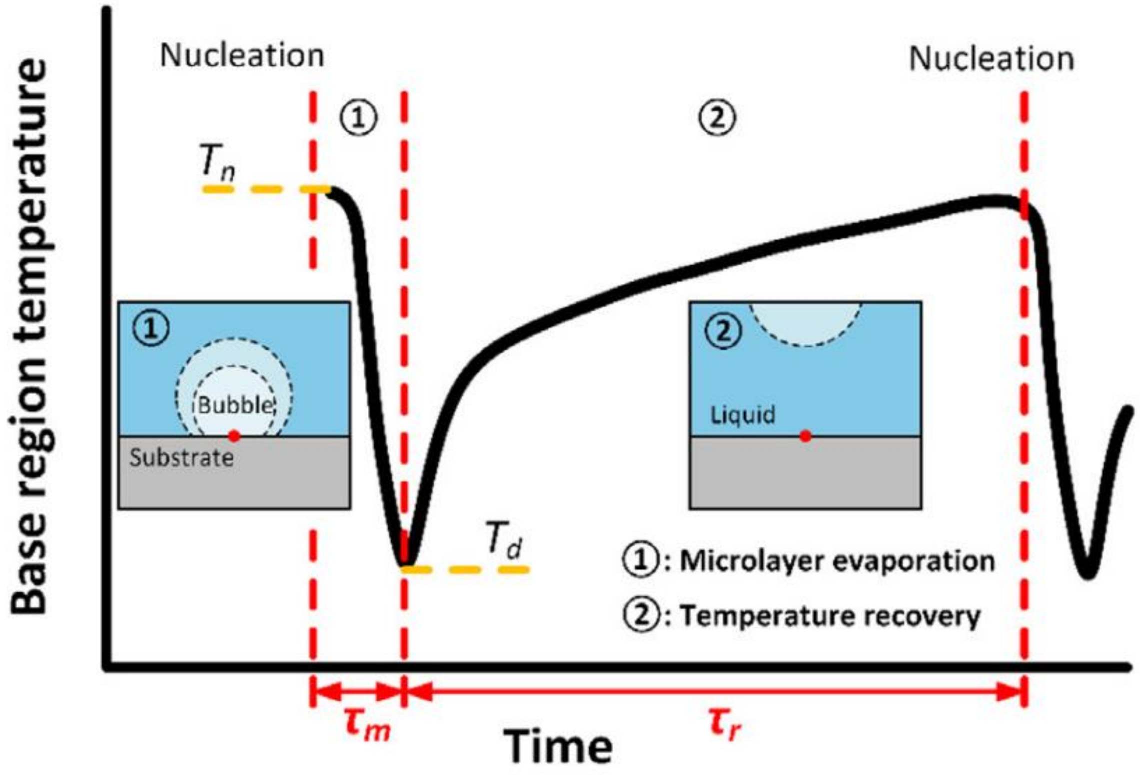


Figure 6.13 in Carey

Beyond Nucleation

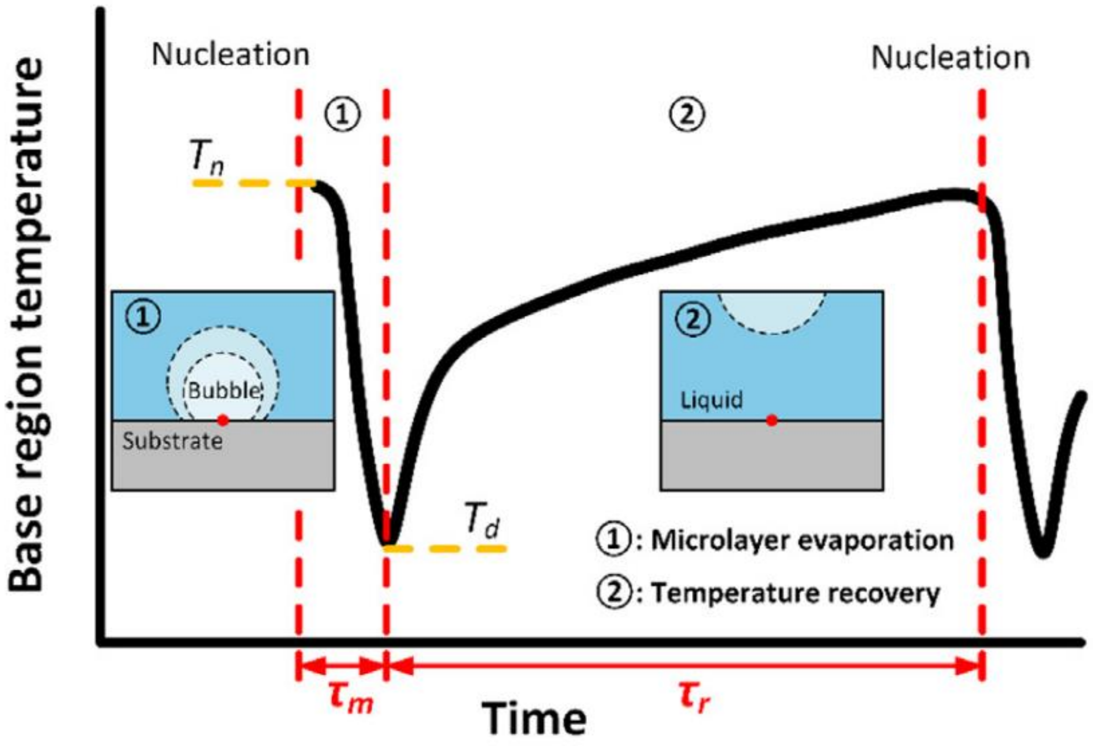


Zhang *et al.*, 2021

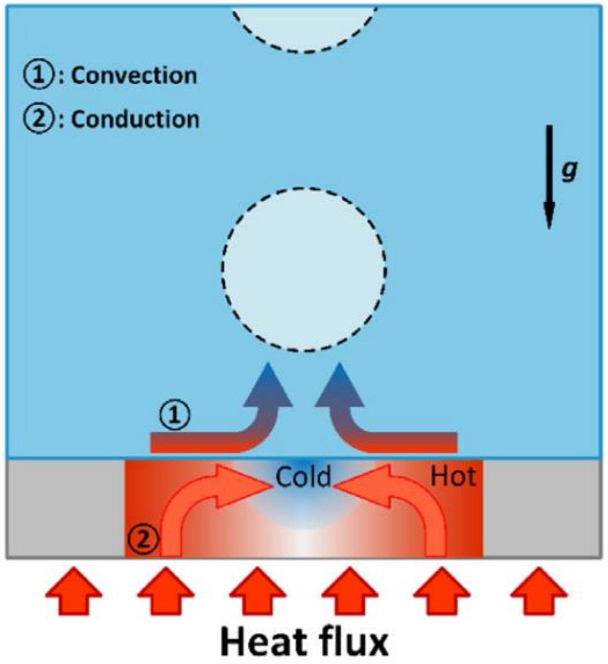
https://doi.org/10.1016/j.ijheatmasstransfer.2020.120640

- 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

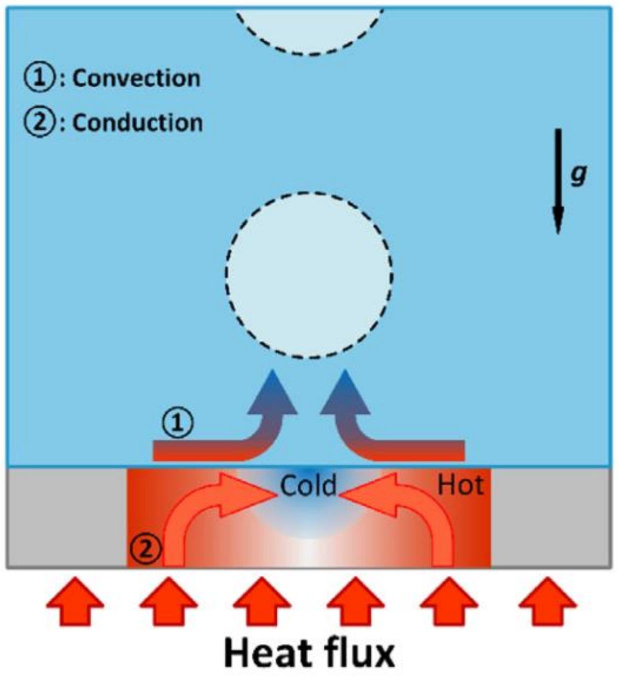
Timescale Analysis



Temperature Recovery Mechanism

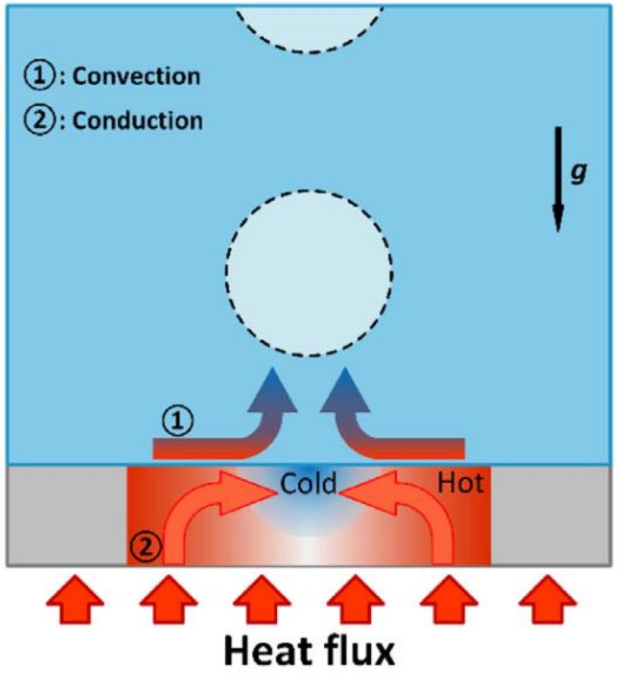


Timescale Analysis



① Rewetting of surrounding superheated liquid

Timescale Analysis

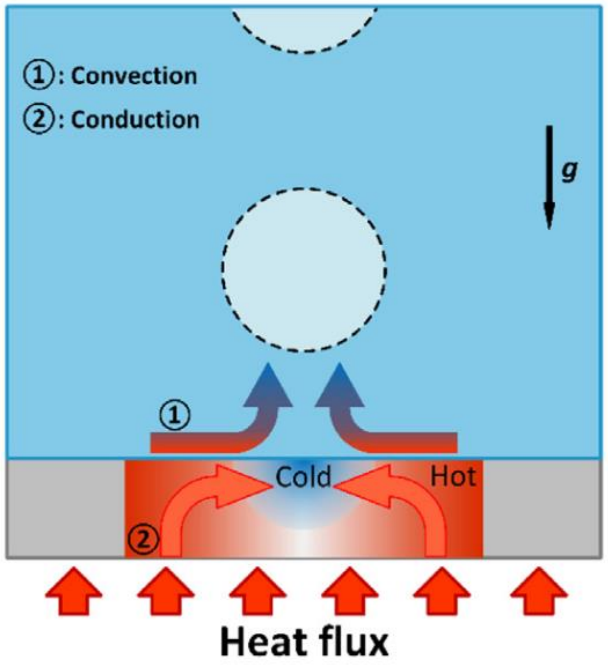


① Rewetting of surrounding superheated liquid

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

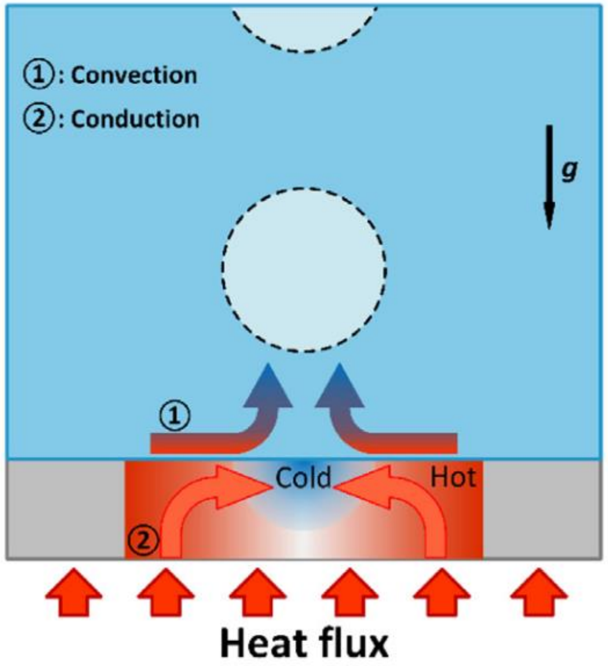
How to determine *h*

Timescale Analysis



② Heat conduction from surrounding solid region

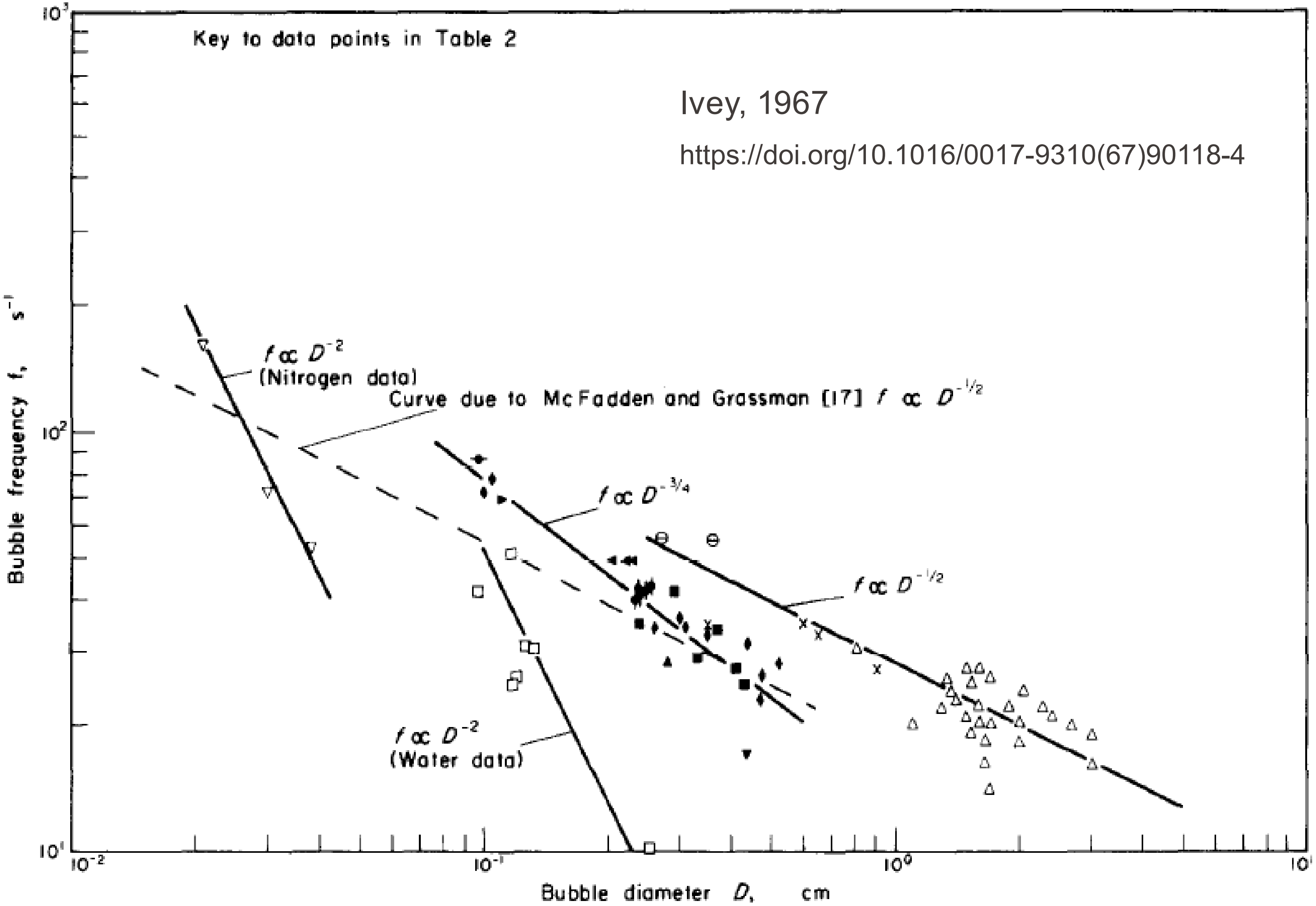
Timescale Analysis



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

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

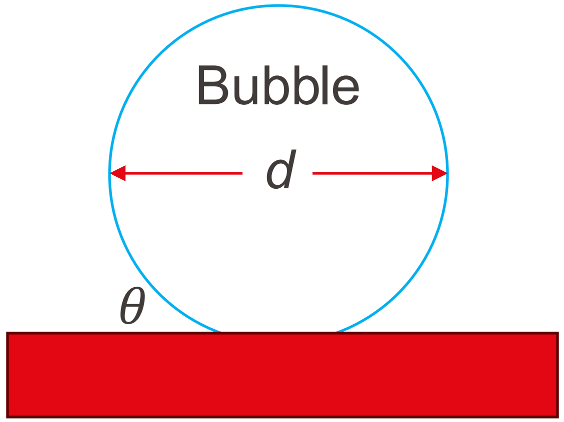
Comparison to Experiments



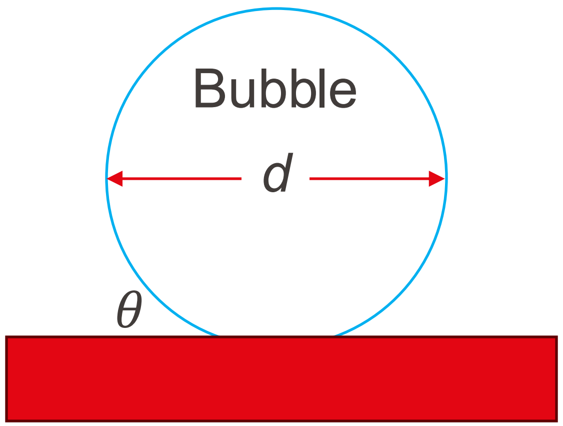
Ivey, 1967

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

Bubble Departure Diameter



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

Summary

- Entrapped gas/vapor theory
- Onset of nucleation coupled with thermal boundary layer
- Timescale analysis for bubble growth and departure cycle