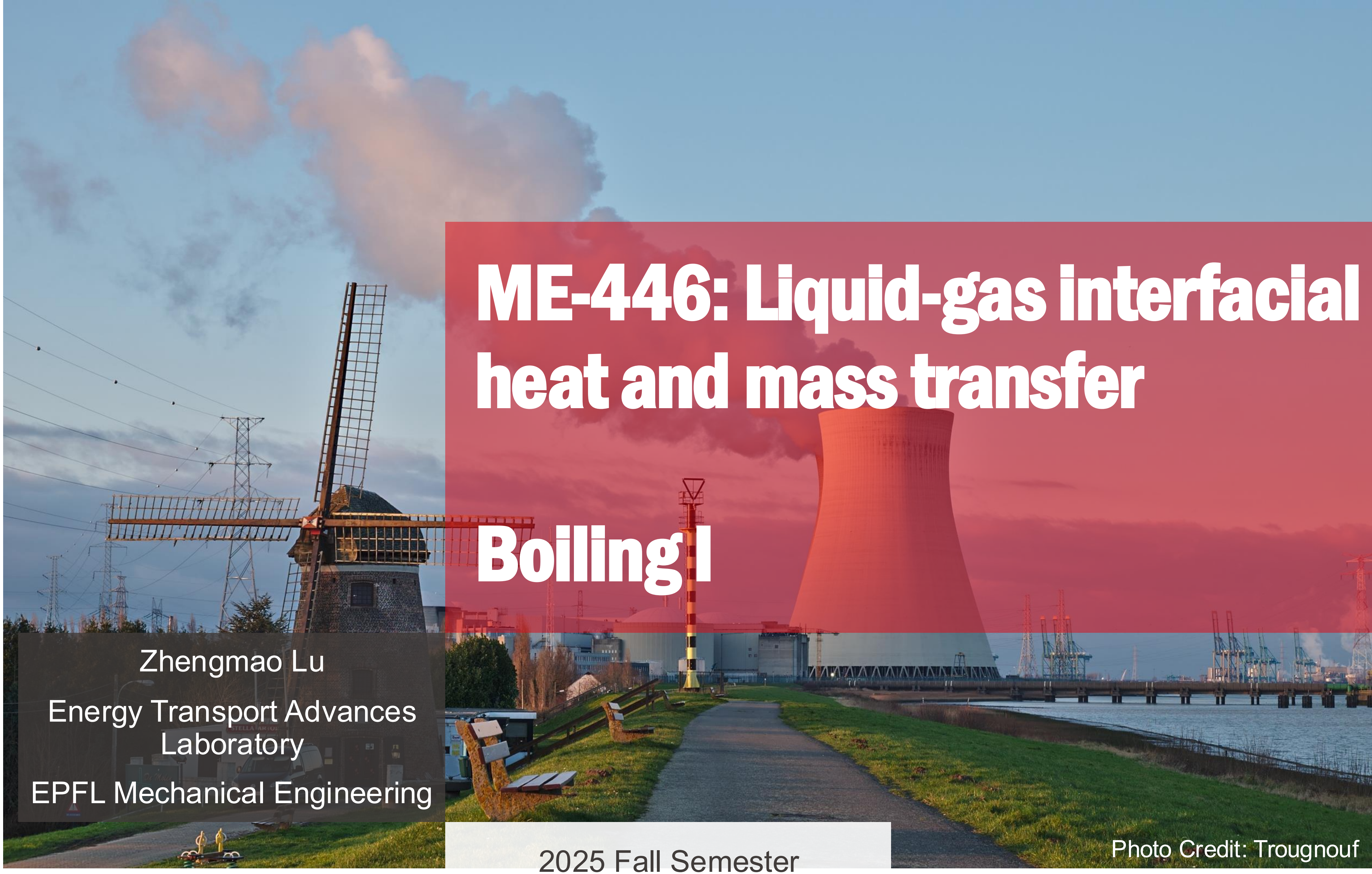

ME-446: Liquid-gas interfacial heat and mass transfer

Boiling I

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Energy Transport Advances Laboratory

EPFL Mechanical Engineering

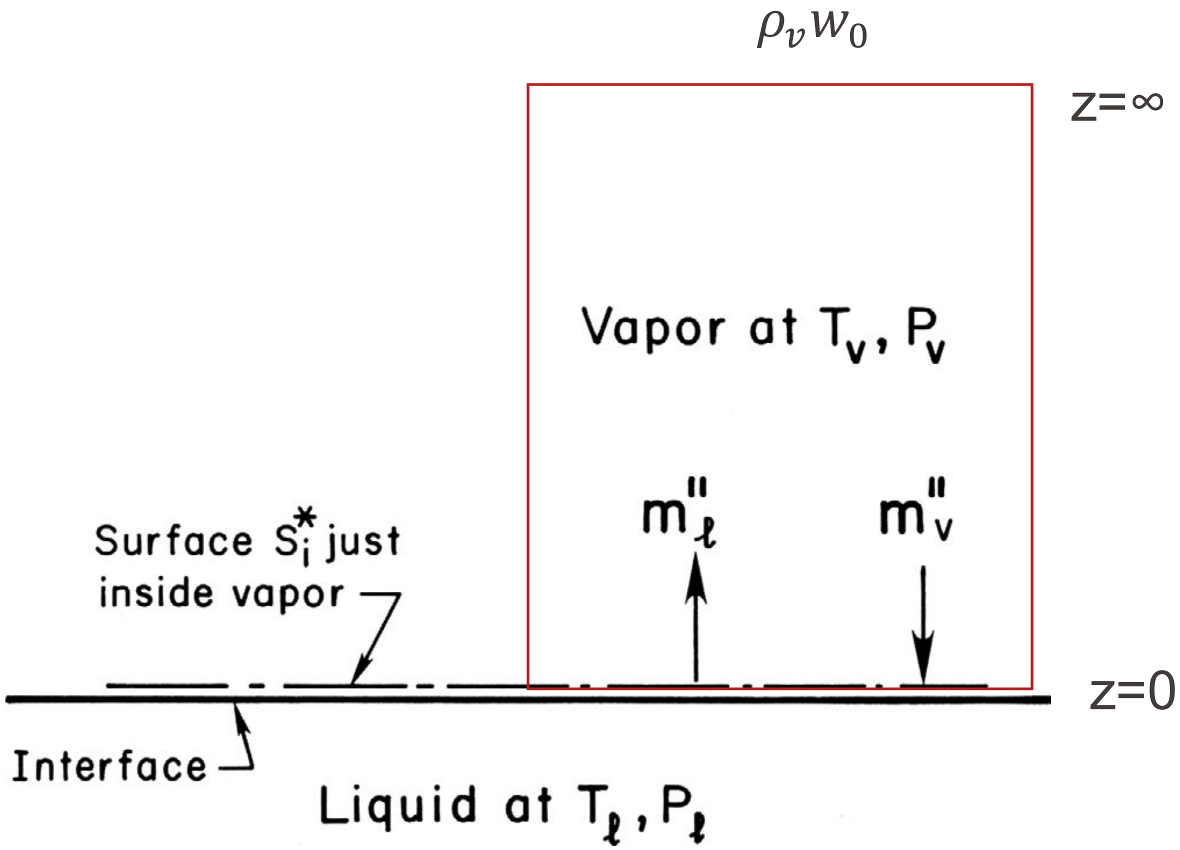
2025 Fall Semester

Photo Credit: Trougnouf

Last Time

- Velocity distribution function
- Relationship between macroscopic properties and velocity distribution
- Evaporation kinetics (Schrage equation)

Mass Balance



Mass balance

$$m_l'' - m_v'' = \rho_v w_0$$

$$m_l'' = \hat{\sigma} m_e'' + (1-\hat{\sigma}) m_v''$$

$$= \hat{\sigma} \frac{P_l}{RT_l} \left(\frac{k_B T_l}{2\pi m}\right)^{\frac{1}{2}} + (1-\hat{\sigma}) m_v''(w_0)$$

$$\hat{\sigma} \frac{P_l}{RT_l} \left(\frac{k_B T_l}{2\pi m}\right)^{\frac{1}{2}} - \hat{\sigma} m_v''(w_0) = \rho_v w_0$$

$$m_v''(w_0) = \rho_v \int_{-\infty}^{0} \left(\frac{m}{2\pi k_B T_v}\right)^{\frac{1}{2}} \exp\left(-\frac{m(w-w_0)^2}{2k_B T_v}\right) w dw$$

Boiling


CC, BY

cooking


CC BY-CA

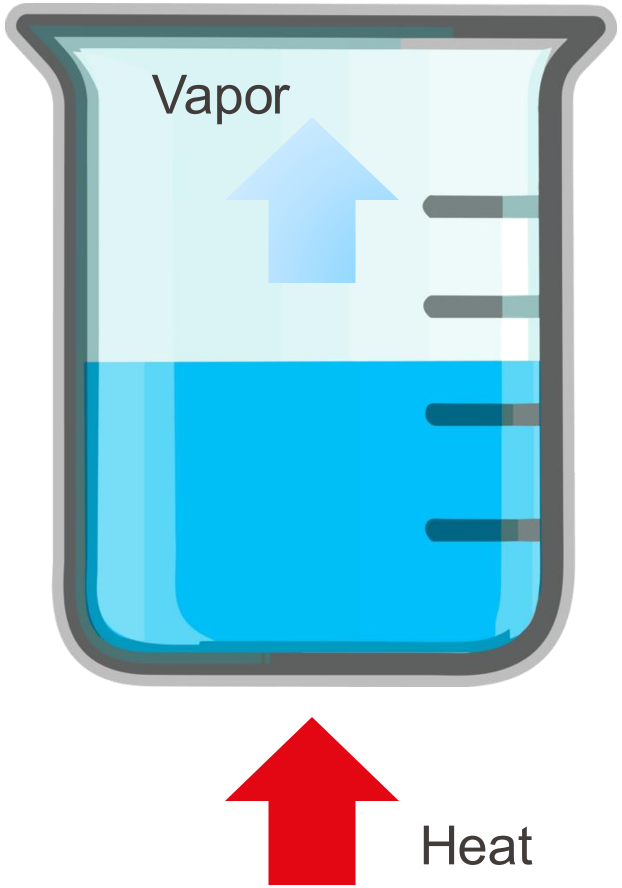
(nuclear) power plant


Microsoft

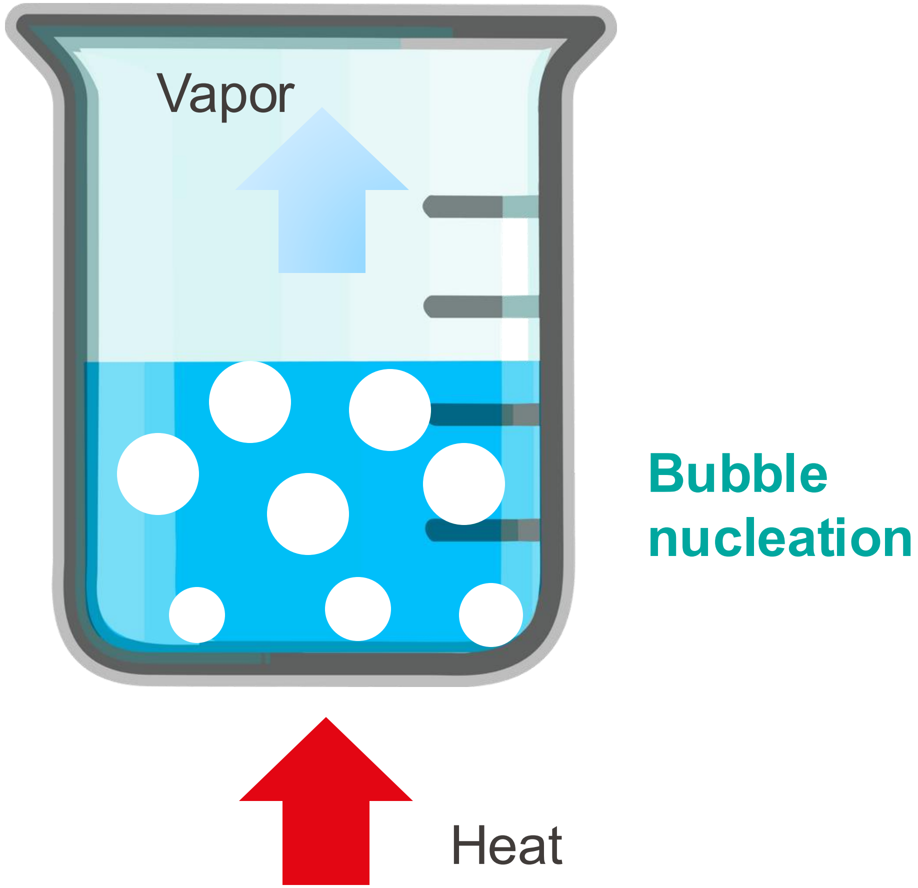
immersion cooling

Evaporation vs Boiling

Evaporation



Boiling



Intended Learning Objectives Today

- Analyze the free energy of vapor embryo (Thermodynamics)
- Understand the derivation of bubble growth kinetics at small sizes

  - Reading materials: **Carey**, Chapter 5.2, 5.3

Formation of a Vapor Embryo (Homogeneous Nucleation)

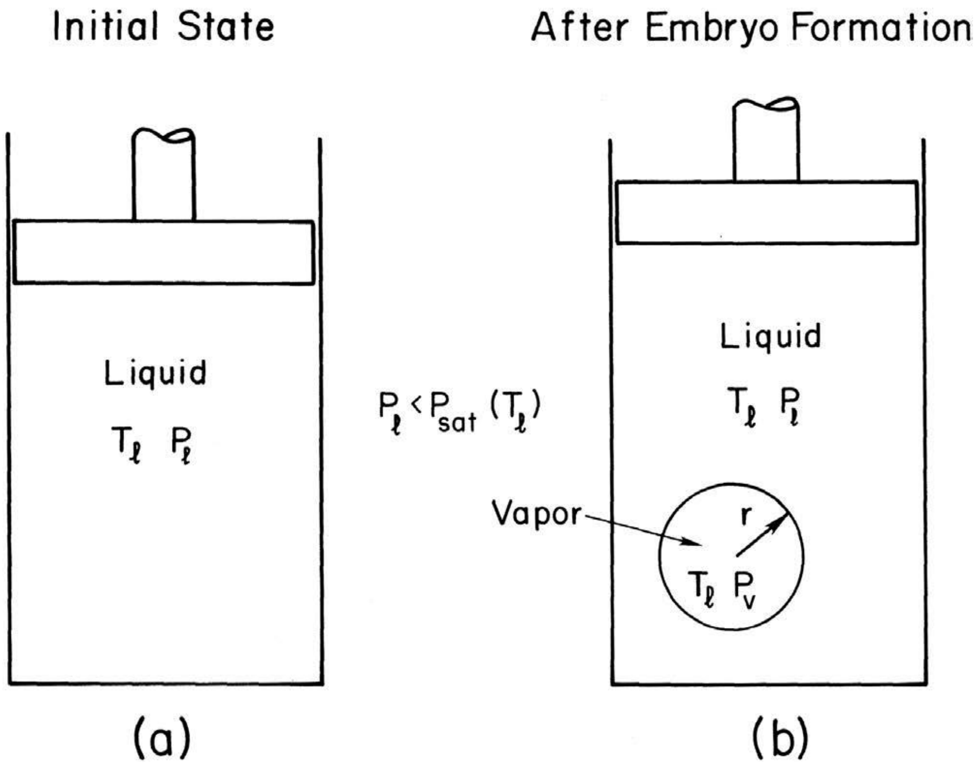
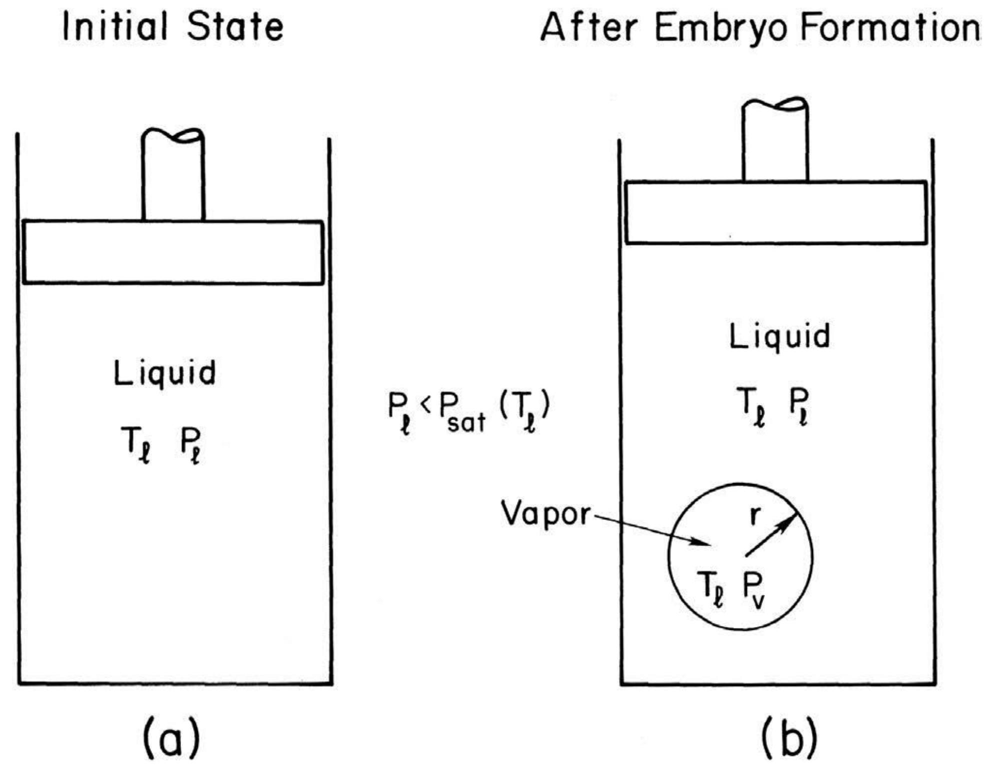


Figure 5.7 in Carey

Homogeneous Nucleation



Gibbs Free Energy Change

$$\Delta G = \widehat{N}_v(\hat{g}_v - \hat{g}_l) + (P_l - P_v)V_v + 4\pi r^2\sigma_{lv}$$

Considering T_l and P_l as fixed values, assuming mechanical equilibrium is always satisfied

ΔG can be considered as a function of r, to which we can apply Taylor expansion near r_e

Gibbs Free Energy Change

$$\frac{d\Delta G}{dr} = \frac{d\widehat{N}_v}{dr}(\hat{g}_v - \hat{g}_l) + 4\pi r^2\left(\frac{2\sigma_{lv}}{r} + P_l - P_v\right)$$

Gibbs Free Energy Change

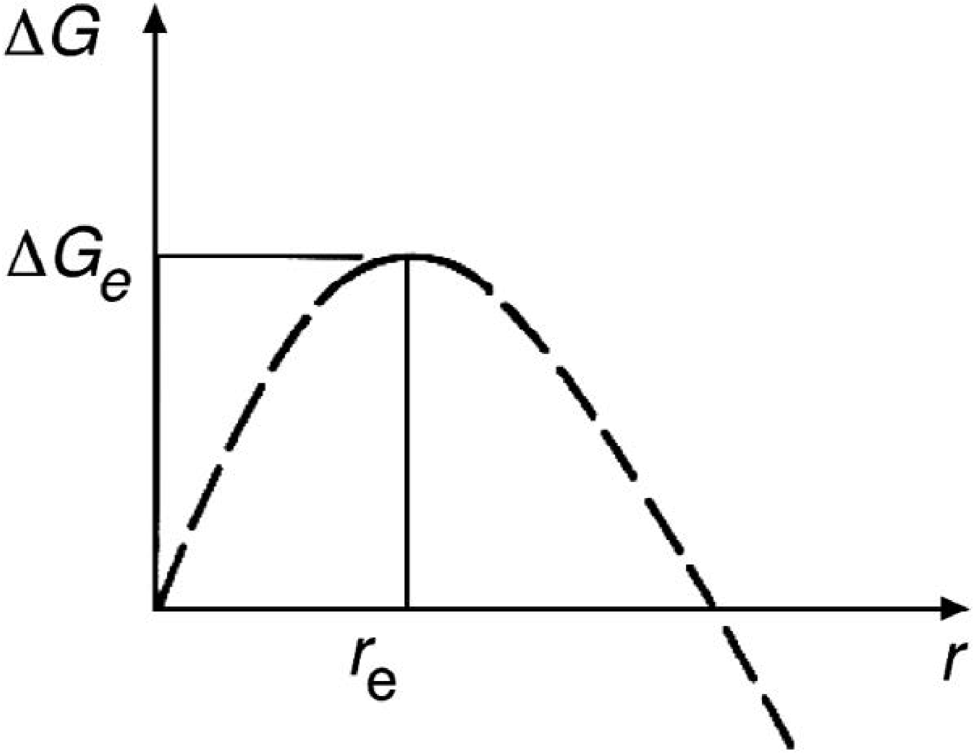
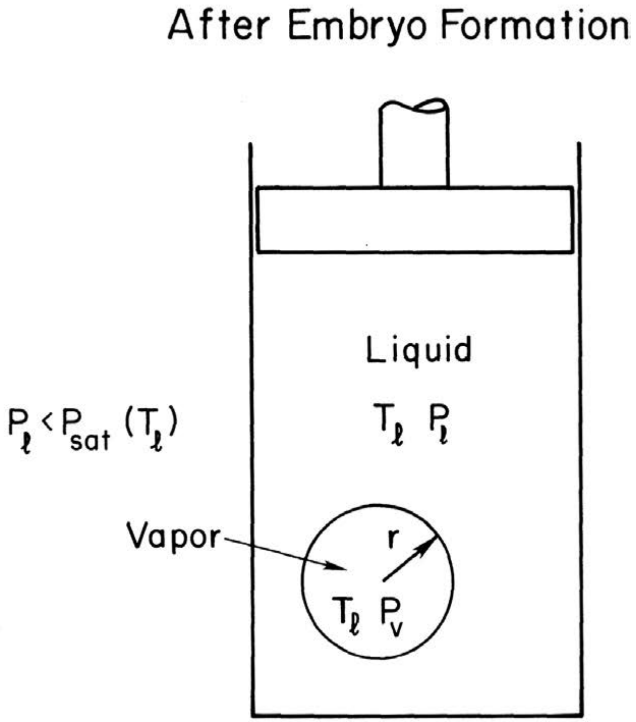


Figure 5.9 in Carey

Equilibrium Bubble Radius



Embryo Size Distribution

Consider the number of embryos consisting of n molecules per unit volume N_n

For an embryo of size n, define j_{ne} as the evaporating molecular flux and j_{nc} as the condensing molecular flux [$m^{-2}s^{-1}$]

Embryo Size Distribution

Embryo Size Distribution

Embryo Size Distribution

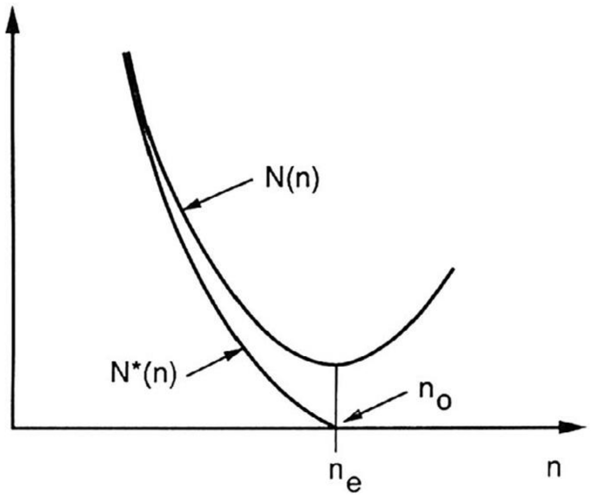
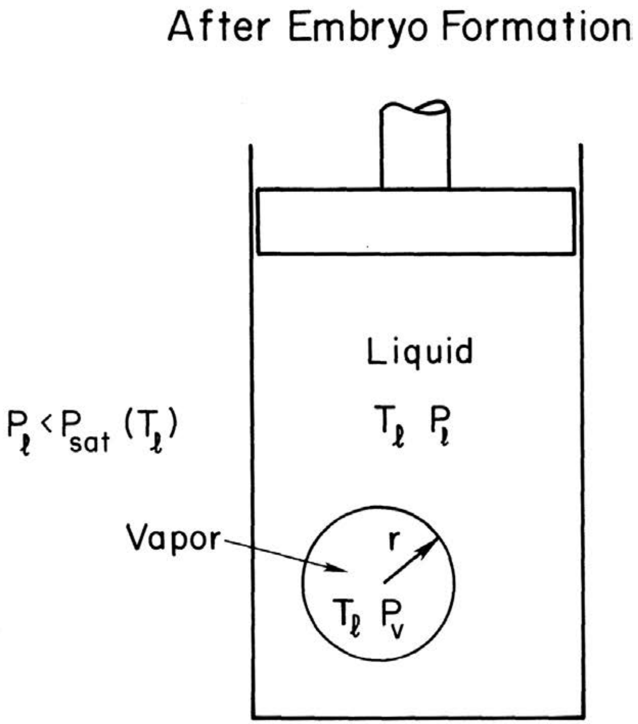


FIGURE 5.10 Carey

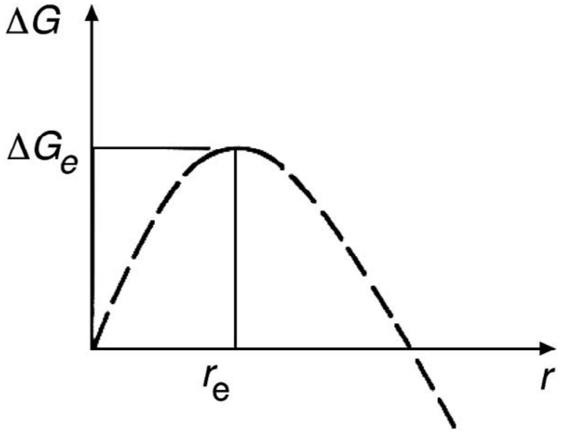
Embryo Size Distribution

Embryo Size Distribution

Embryo Size Distribution



Embryo Size Distribution



Physical Meaning of J

J represents the rate at which embryo bubbles grow from n to n + 1 molecules per unit volume [$m^{-3}s^{-1}$]

Generation Rate of Bubble of Critical Size

(Homogeneous case)

$$J = \rho_{N,l}\left[\frac{6\sigma_{lv}}{\pi m\left(2-\frac{P_l}{P_{ve}}\right)}\right]^{1/2}\exp\left(-\frac{4\pi r_e^2\sigma_{lv}}{3k_BT_l}\right)$$

increases sharply with temperature

There exists narrow range of temperature below which nucleation does not occur, and above which it occurs almost immediately.

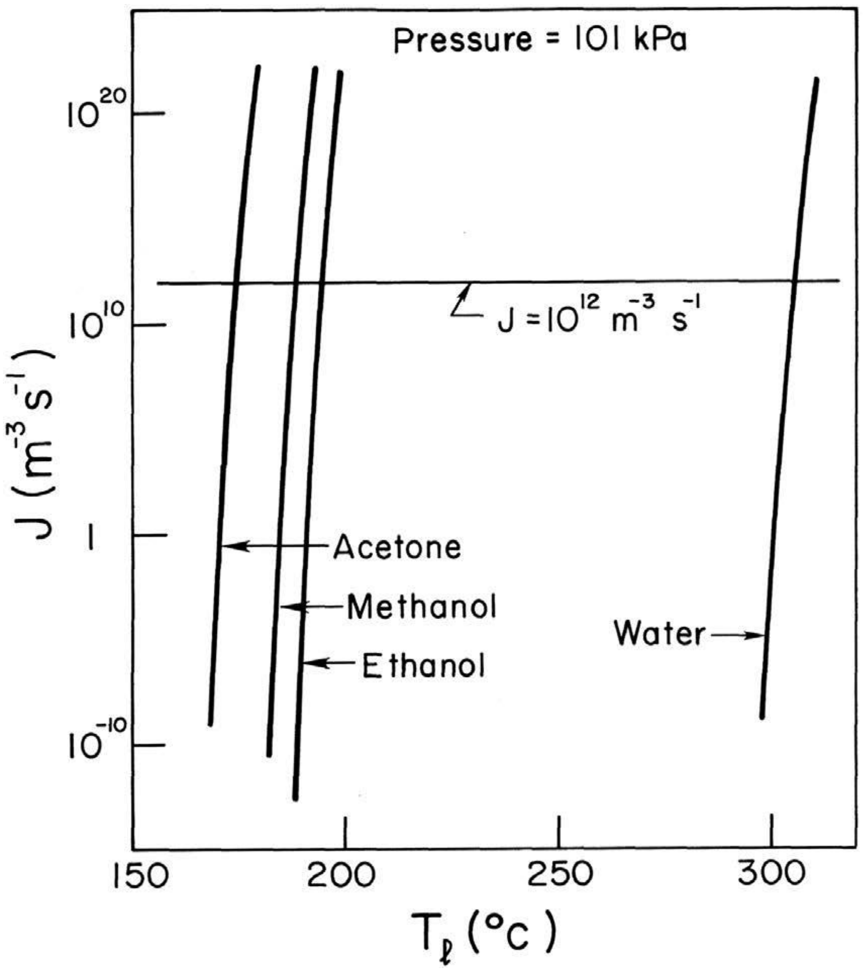


FIGURE 5.12, Carey

Measured Superheat Limit Data

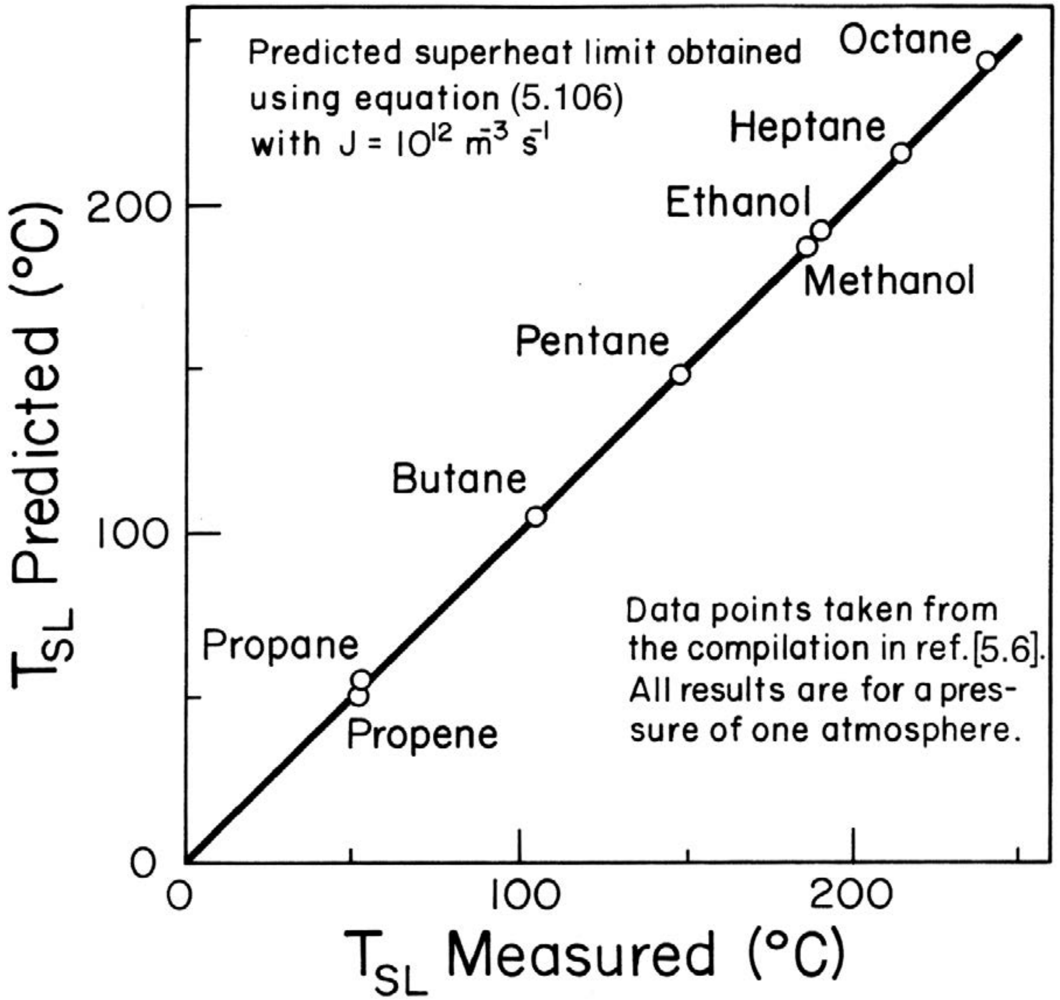


FIGURE 5.13

Great agreement was found for low surface tension liquids

For water, the predicted superheat limit is about 300 ℃ while the measured one is 250-280 ℃

When homogeneous nucleation does occur, vapor is generated at an extremely rapid rate

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