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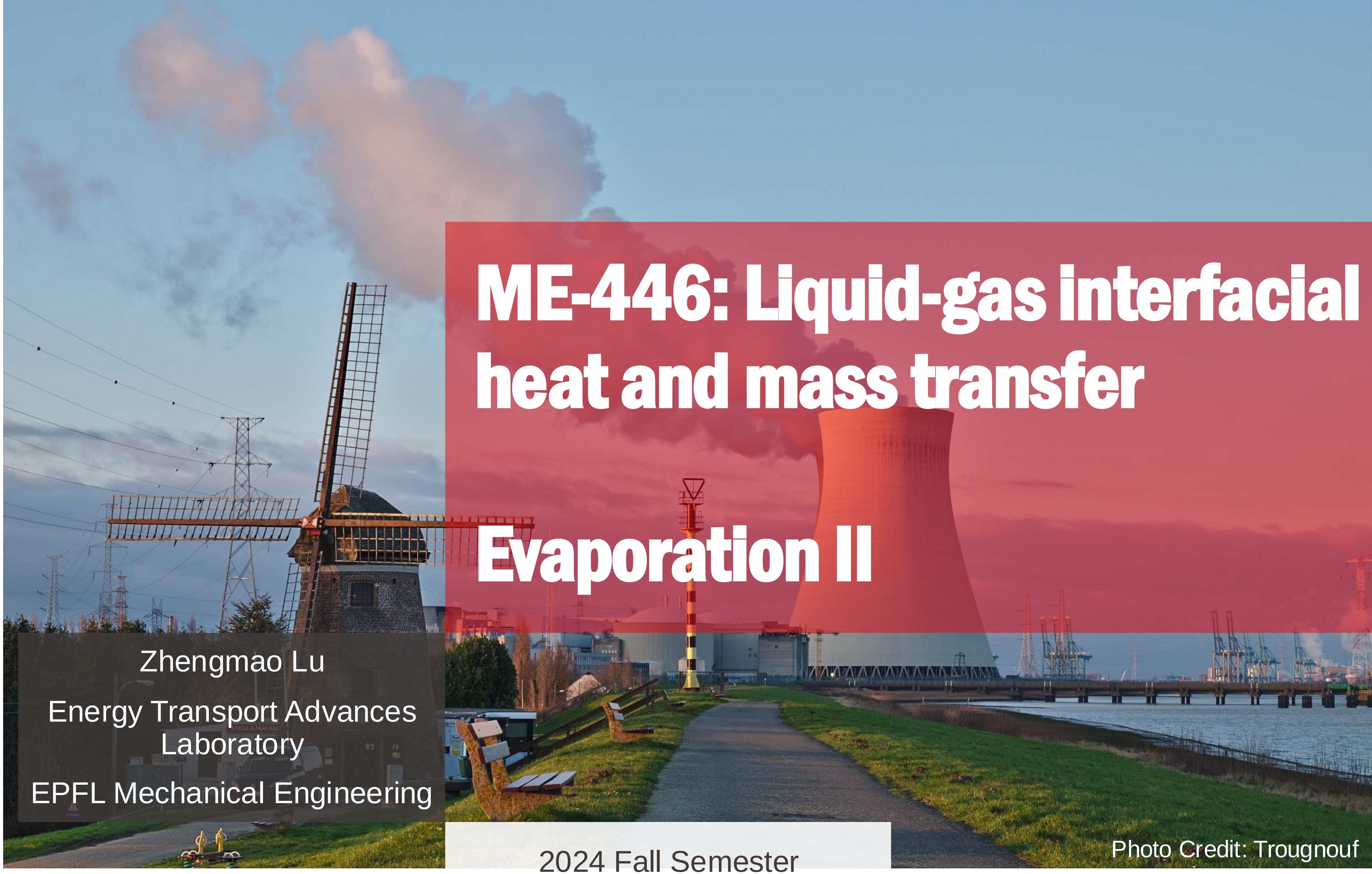
ETA-Lab
Energy Transport Advances



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

Evaporation II

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Energy Transport Advances Laboratory

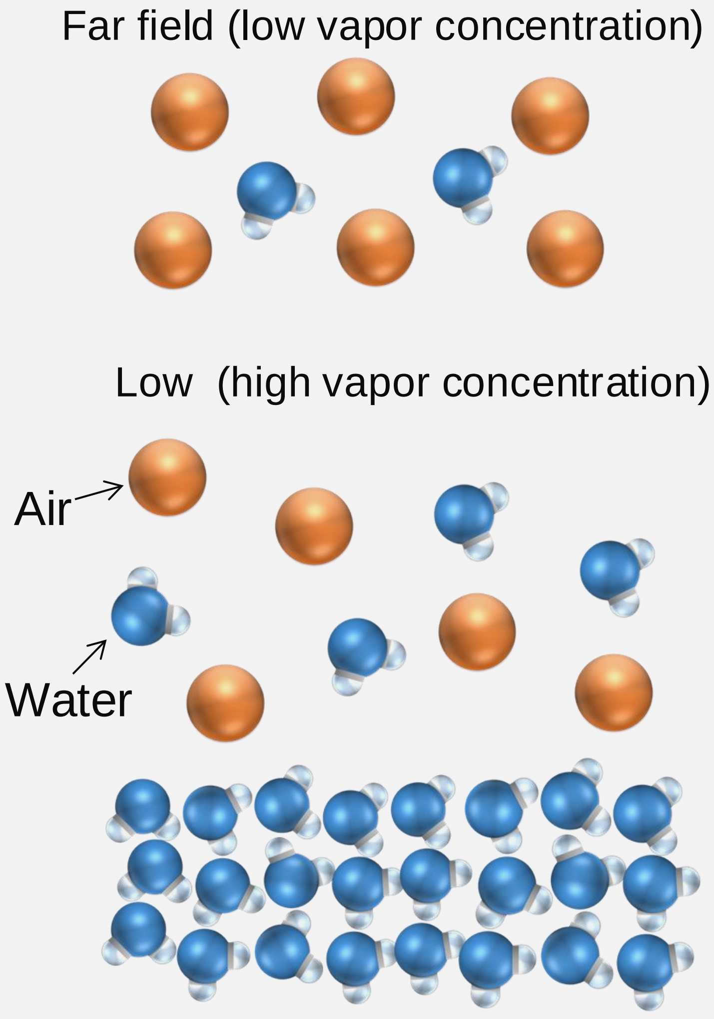
EPFL Mechanical Engineering

2024 Fall Semester

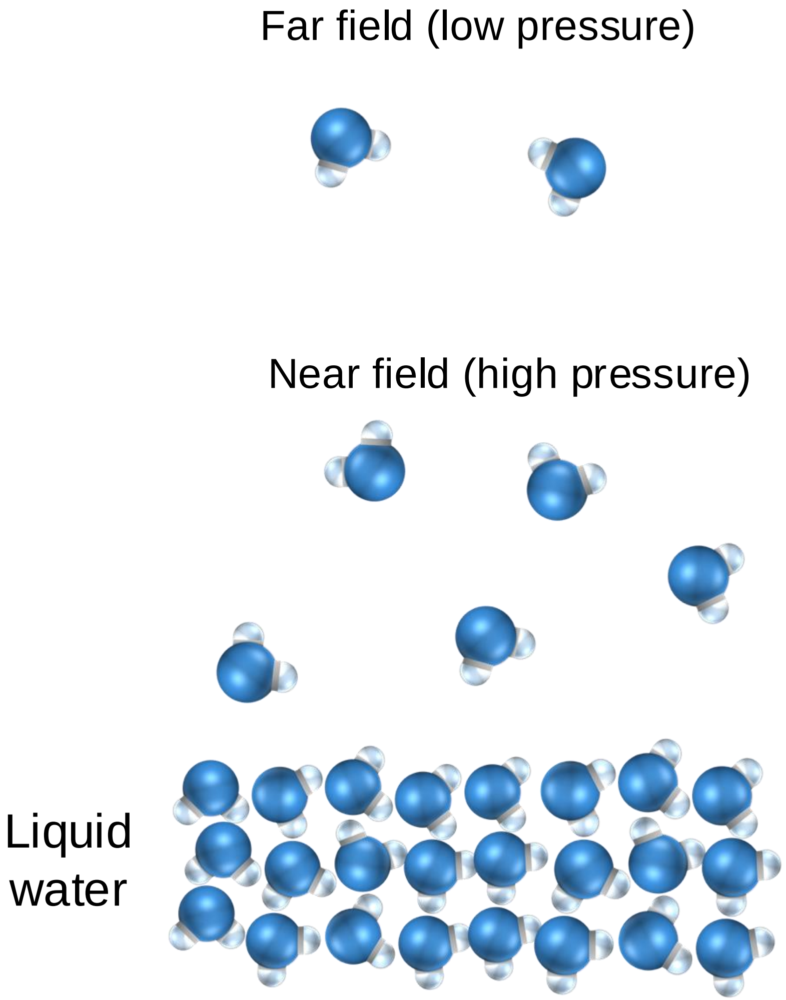
Photo Credit: Trougnouf

Last Week

Air → Diffusion Limited



Vapor → Kinetically Limited



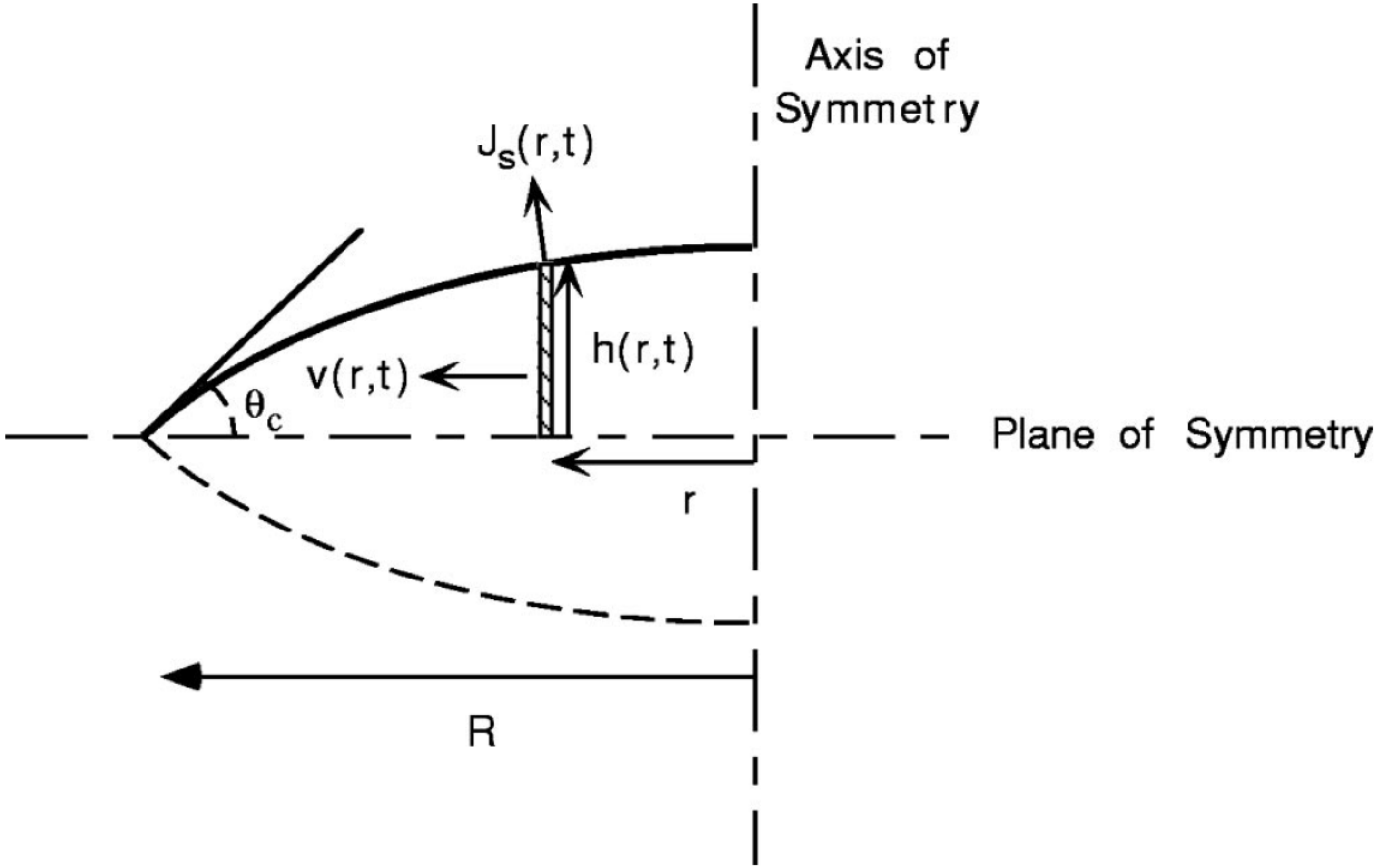
Last Week

- Fick's Law of Diffusion
  - Physical meaning of gradient and divergence operators

- Heat and mass transfer analogy

- Coffee ring effects

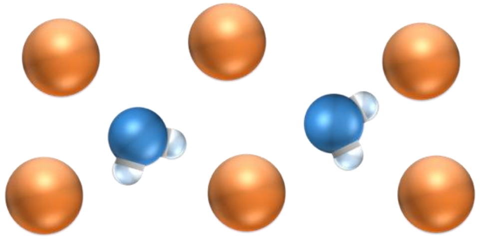
Coffee Ring Effects



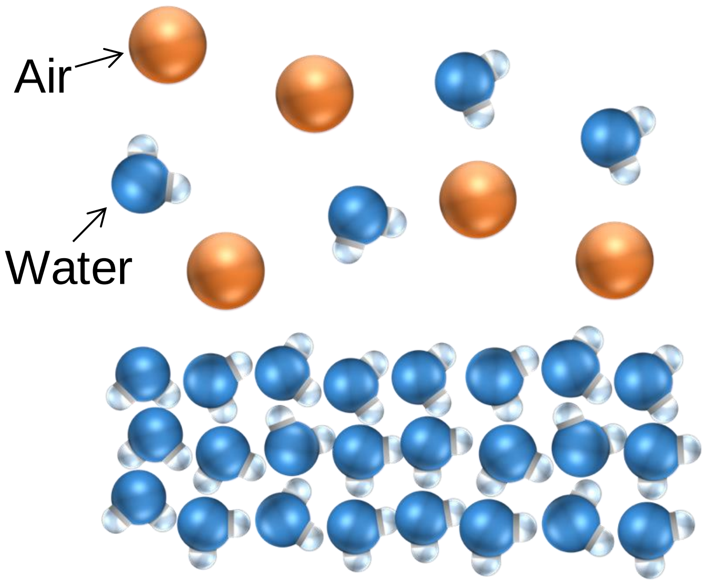
Fundamental Picture of Evaporation

Air → Diffusion Limited

Far field (low vapor concentration)



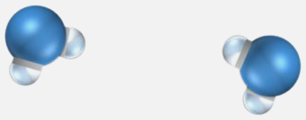
Low (high vapor concentration)



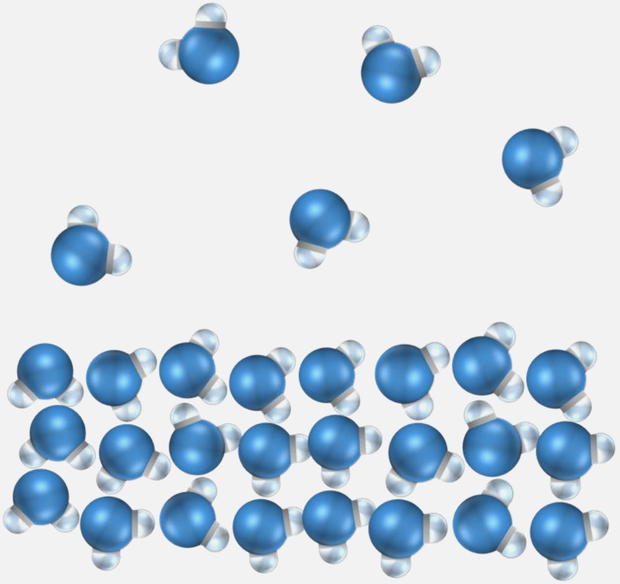
Liquid
water

Vapor → Kinetically Limited

Far field (low pressure)



Near field (high pressure)



Intended Learning Objectives Today

- Understand basic assumptions of the **kinetic theory of gases**
- Relate **macroscopic quantities** to microscopic molecular motion
- Derive and understand the limit of **Schrage equation** for evaporation

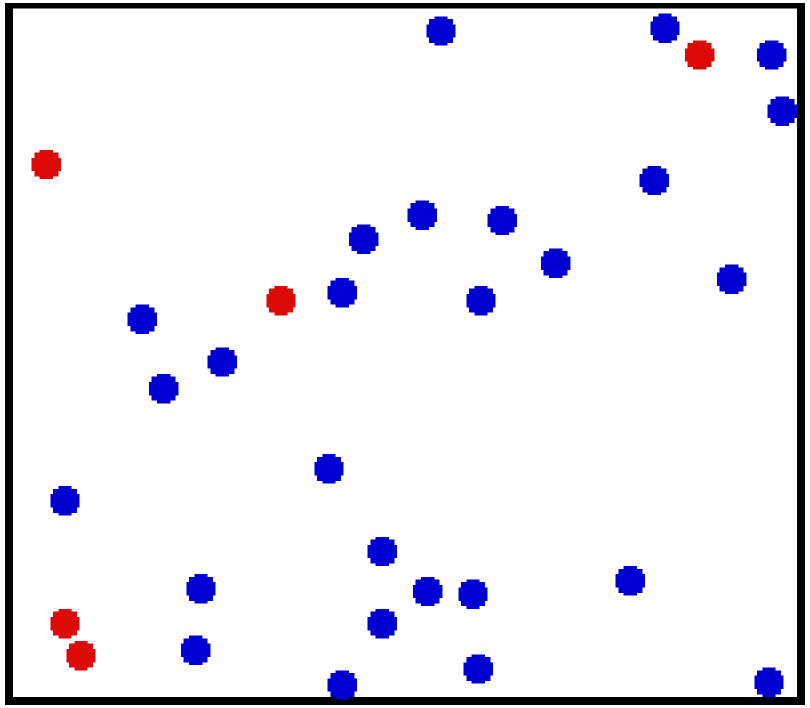
Reading materials: **Carey** Chapter 4.5, Appendix I

Crash Course on Kinetic Theory of Gases

- Consider gas as **a large number of randomly moving particles** that collide with one another every now and then

- Collisions are elastic: **kinetic energy is conserved** before and after

- Between collisions, particles are not affected by any force field



Credit: A. Greg

Velocity Distribution Function

Velocity Distribution Function

Average Properties

Temperature in Kinetic Theory

Maxwell-Boltzmann Distribution

Maxwell-Boltzmann Distribution

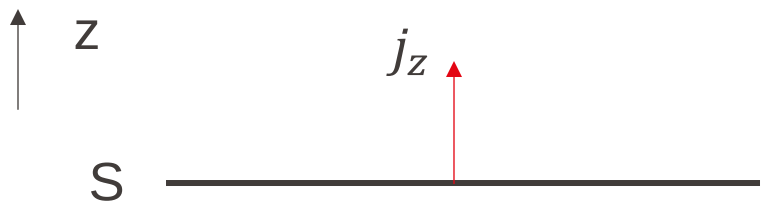
Maxwell-Boltzmann Distribution

Drifted M-B Distribution

In the case that the vapor is moving at a bulk velocity (u_0, v_0, w_0), but otherwise is in equilibrium, we can take the frame of reference that moves at the bulk vapor velocity.

In this reference frame, the bulk vapor is static and M-B applies

Mass Flux Across a Surface



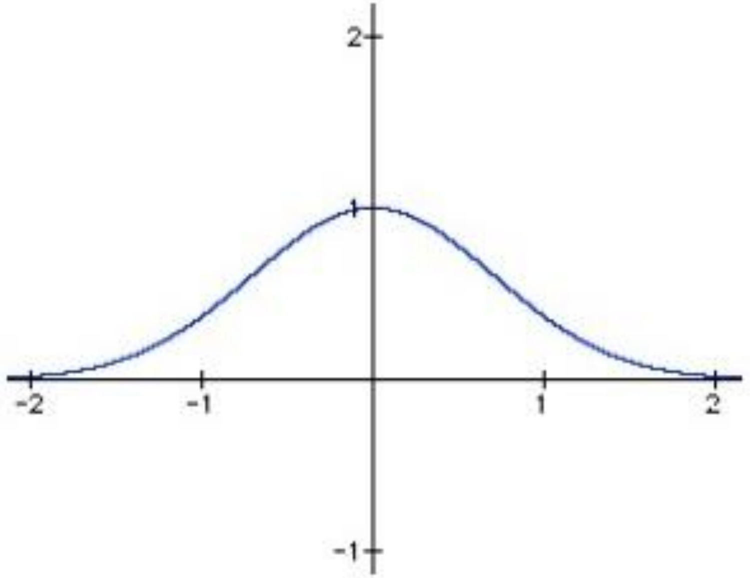
How to determine the molecular flux across a surface if the velocity distribution function is known

j_z : the rate at which molecules pass through surface S per unit area

What matters is velocity distribution in the direction perpendicular to the surface

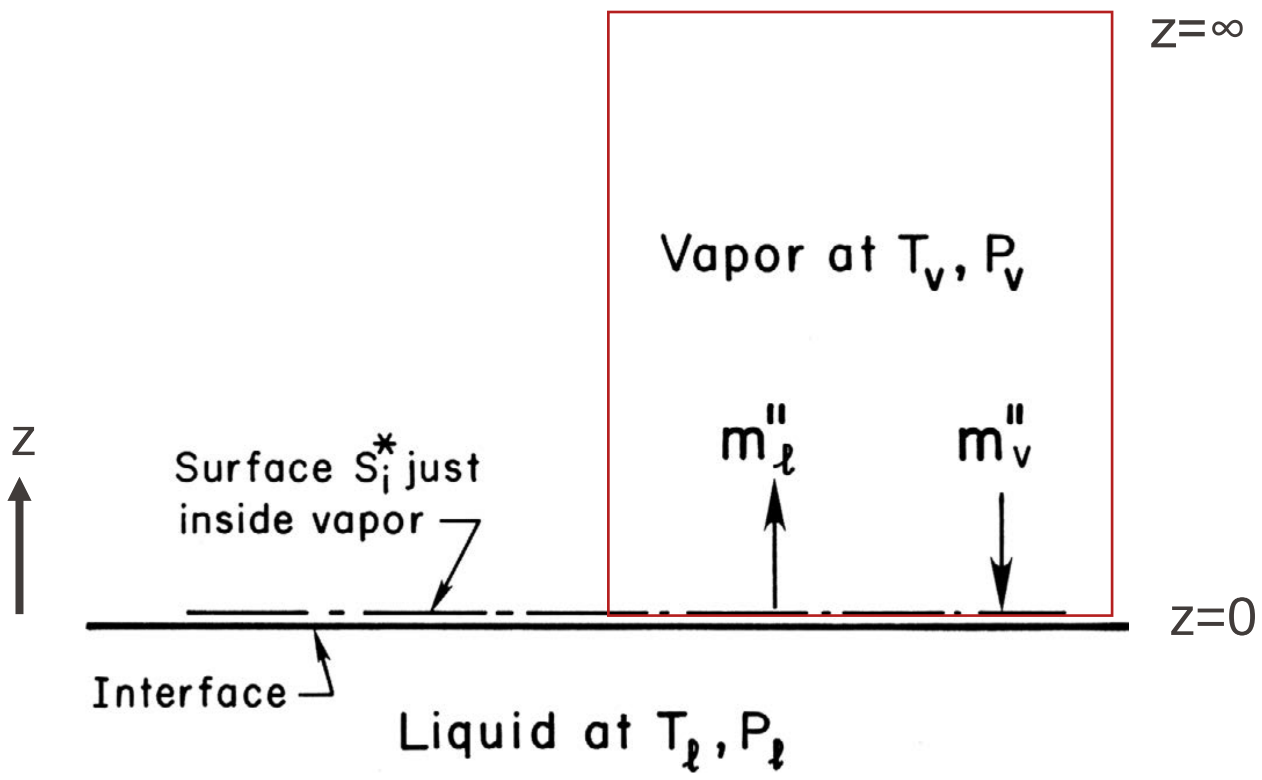
The molecular flux due to molecules with z-velocity between w and w+dw is

One Way Mass Flux



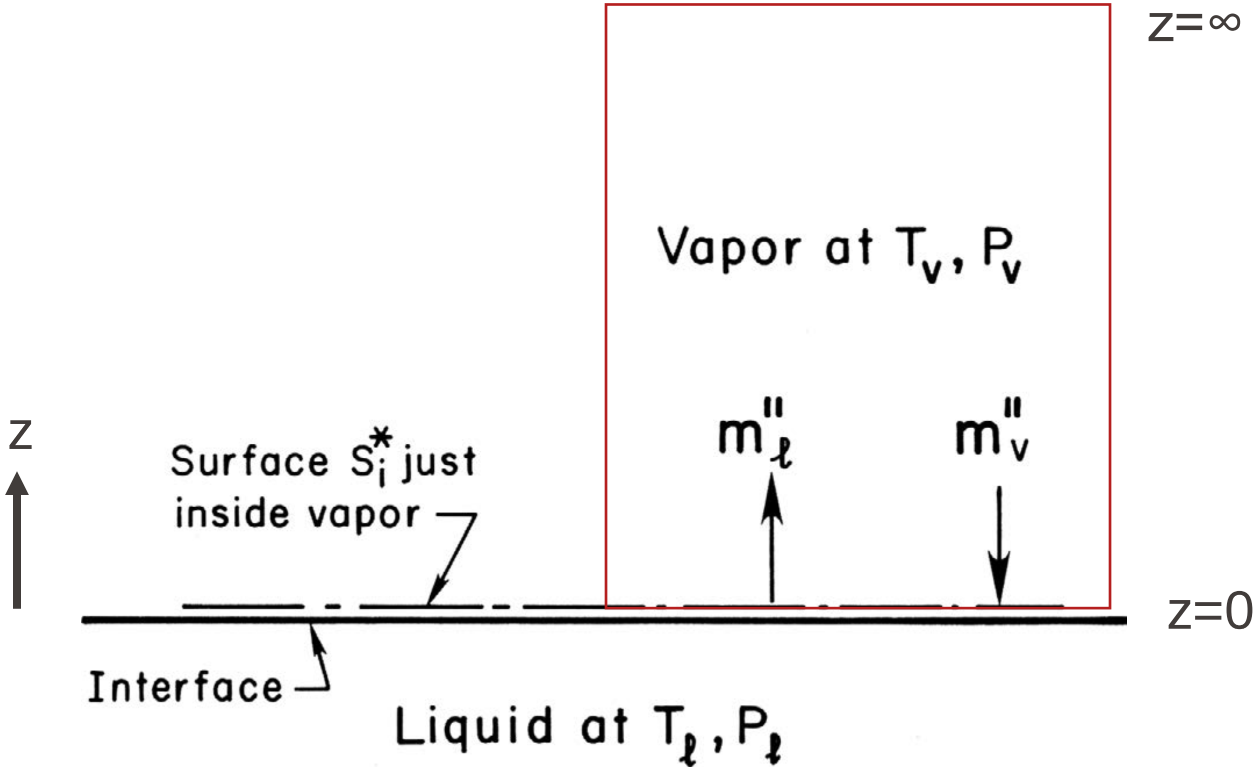
With symmetric velocity distribution such as M-B, although the net molecular flux is zero is zero, there are two one-way molecular fluxes negating each other.

Liquid-Vapor Interfacial Transport



z-direction opposite to Figure 4.10 in Carey

Liquid-Vapor Interfacial Transport



At surface S_i^*, m_l'' is due to
1) molecules emitted from liquid surface

one-way flux from equilibrium vapor at z = 0, with evaporation coefficient $\hat{\sigma}_e$

2) vapor molecules reflected from liquid surface

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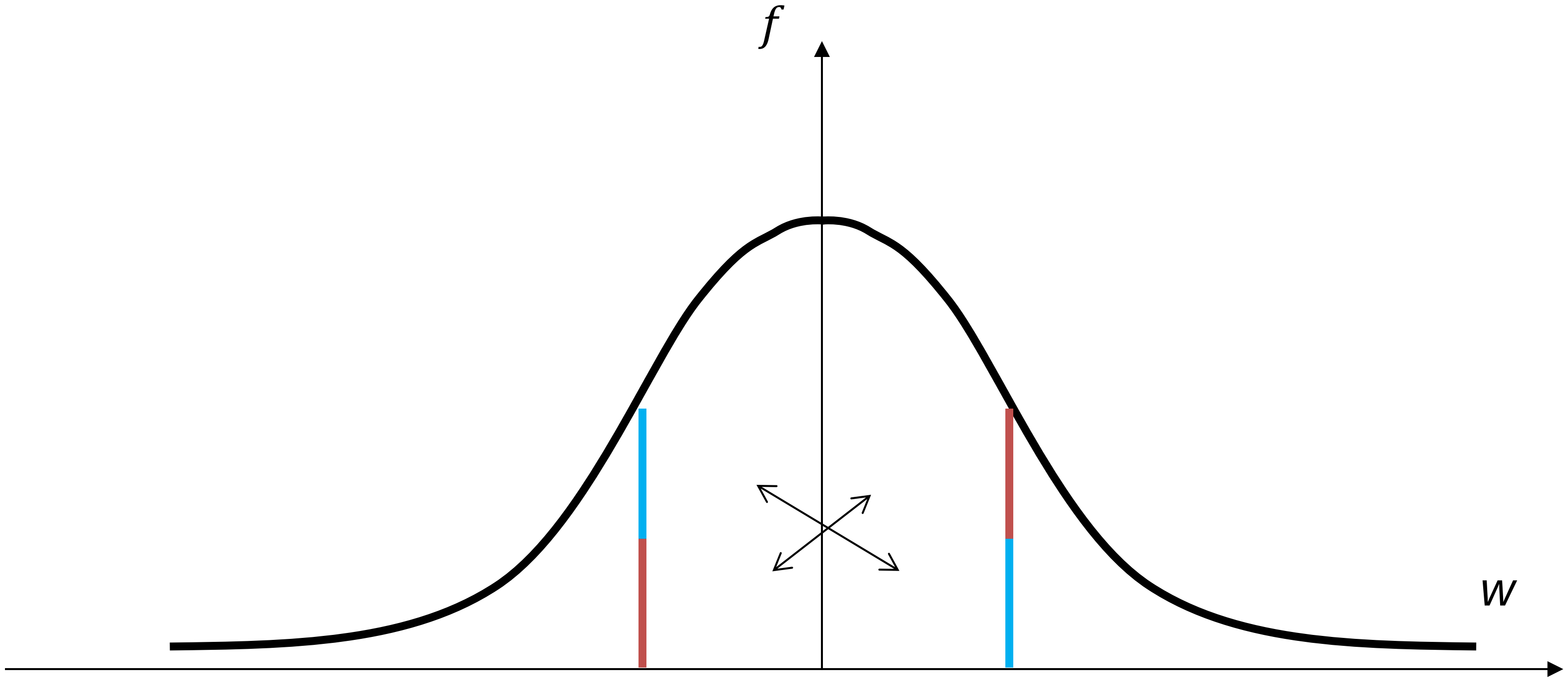
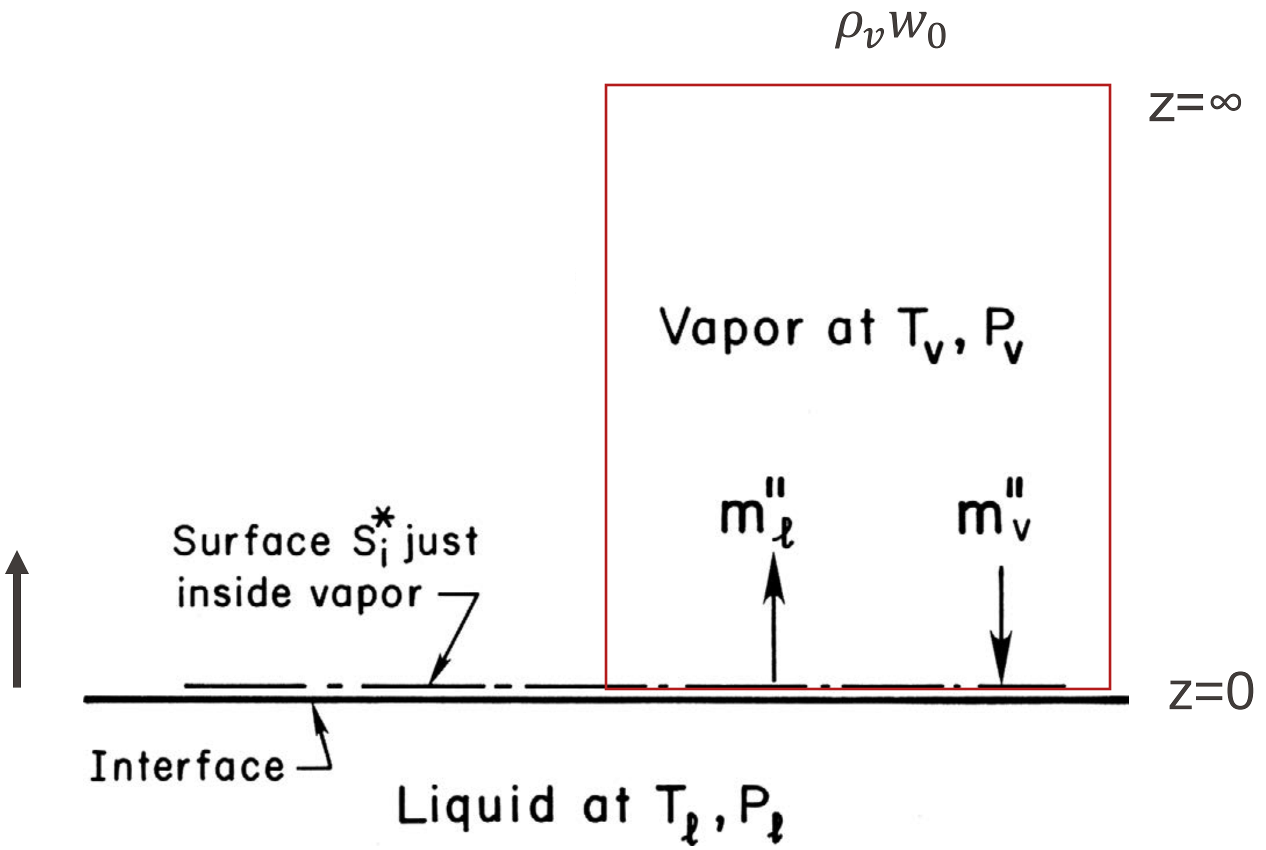
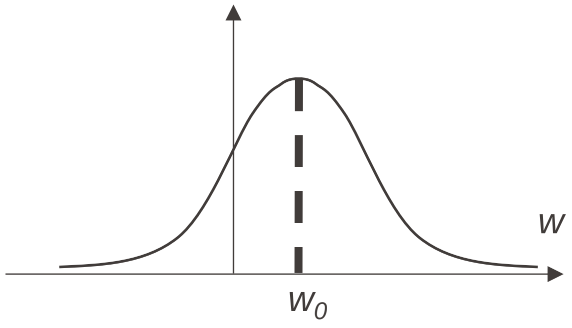
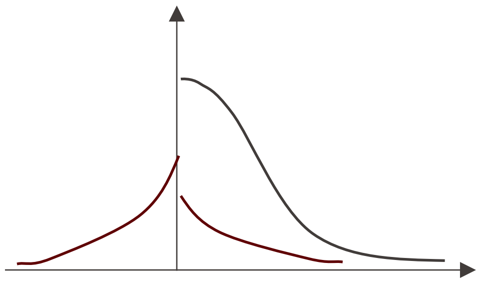
Evaporation/Condensation Coefficient



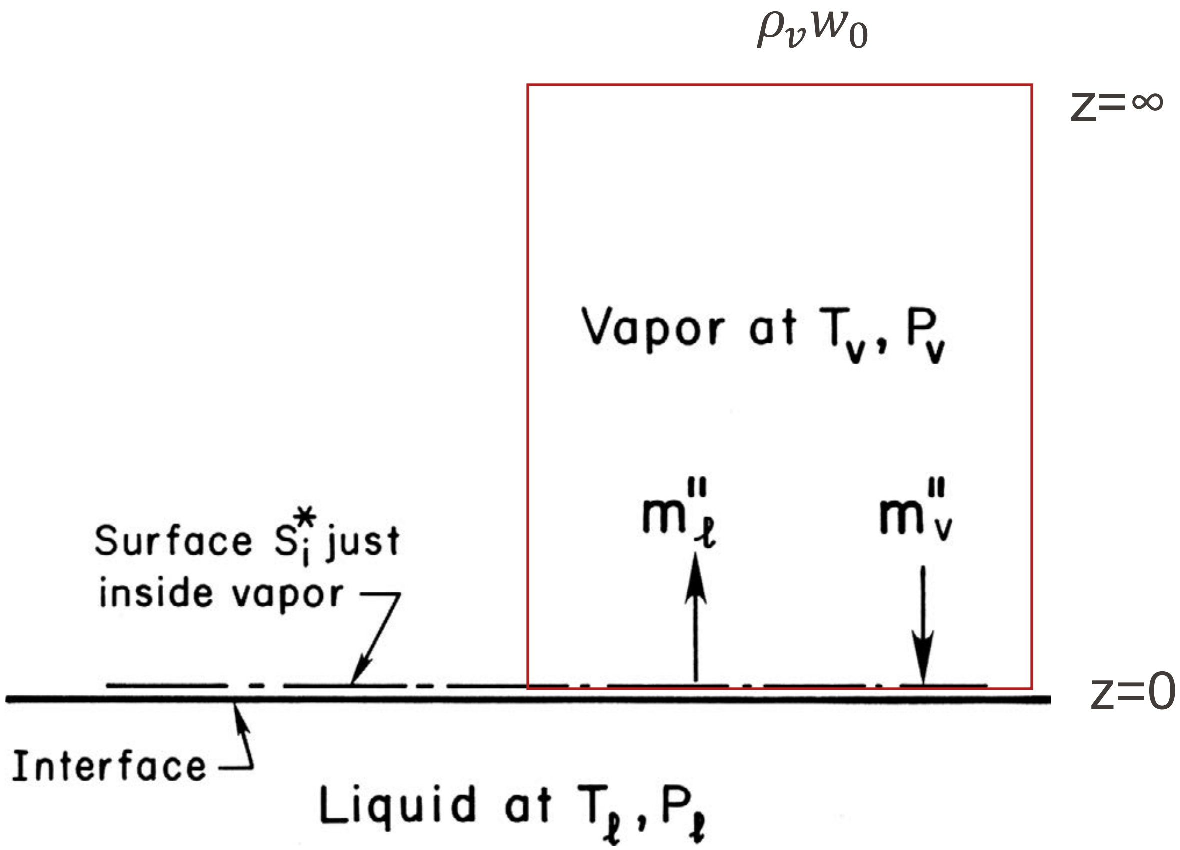
Key Assumption in Schrage Equation







Mass Balance



Schrage Equation

When $\frac{1}{2}mw_0^2 \ll k_B T_v$, the evaporation heat flux can be written in a closed form

$$q''_{evap} = \left(\frac{2\hat{\sigma}}{2-\hat{\sigma}}\right) h_{lv} (2\pi R)^{-\frac{1}{2}} \left(\frac{P_l}{\sqrt{T_l}} - \frac{P_v}{\sqrt{T_v}}\right)$$

z-direction defined differently from Carey

When $\hat{\sigma} = 0$, liquid surface is like an impermeable wall and there is no evaporation

Additional comment: Schrage's assumption about the velocity distribution has implications in energy and momentum balance as well (which will result in three equations with one unknown, causing inconsistencies)

Summary

- Understand basic assumptions of the **kinetic theory of gases**
- Relate **macroscopic quantities** to microscopic molecular motion
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Reading materials: **Carey** Chapter 4.5, Appendix I