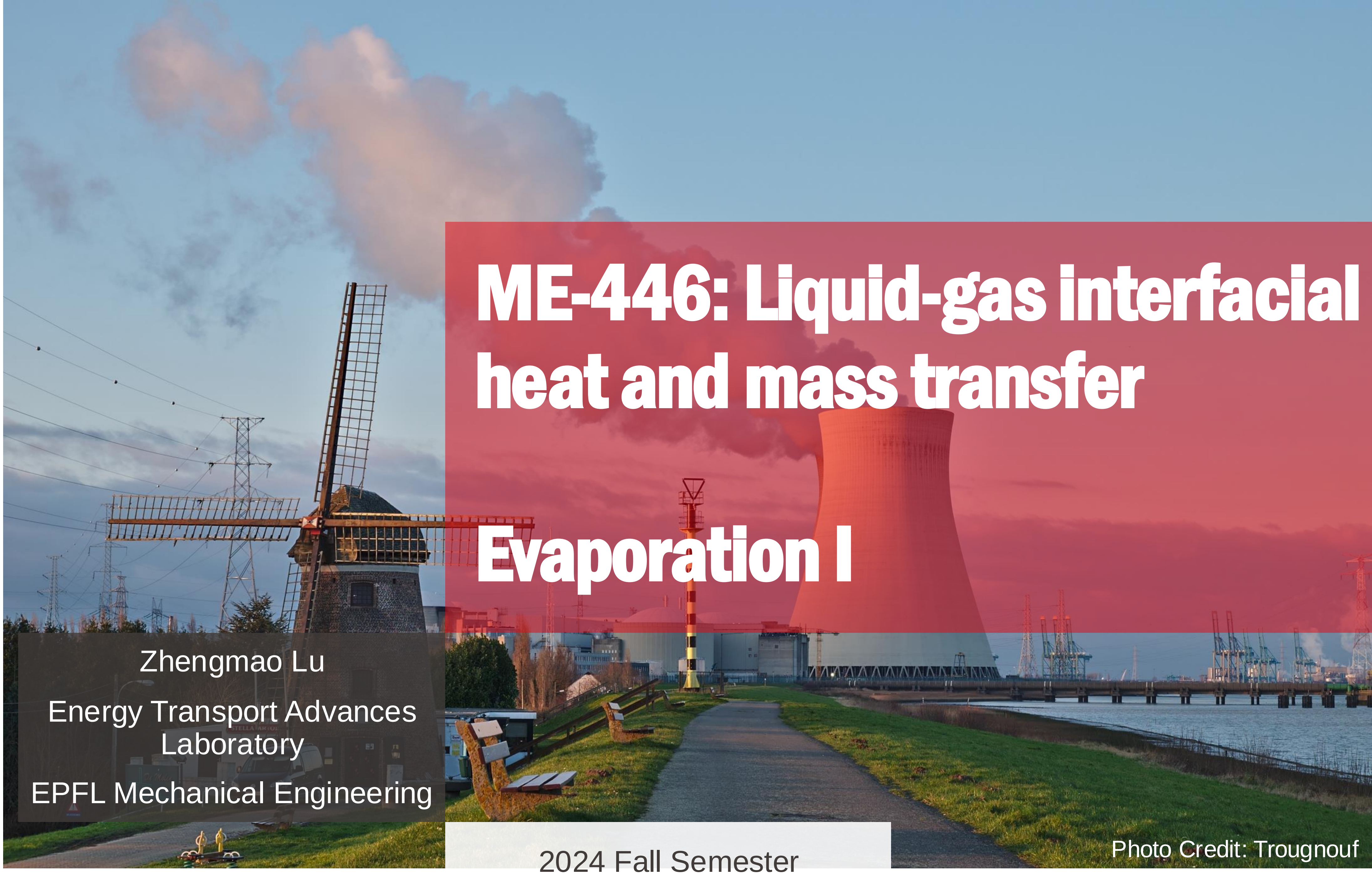
EPFL

ETA-Lab
Energy Transport Advances



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

Evaporation I

Zhengmao Lu

Energy Transport Advances Laboratory

EPFL Mechanical Engineering

2024 Fall Semester

Photo Credit: Trougnouf

Last Time

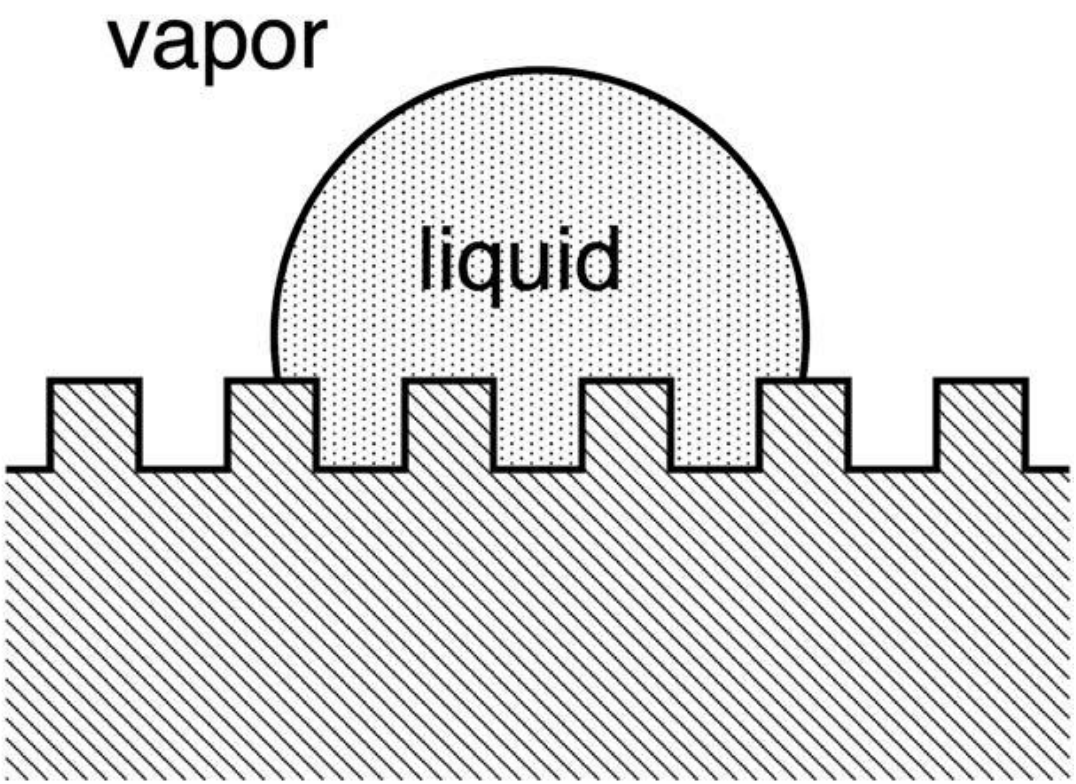
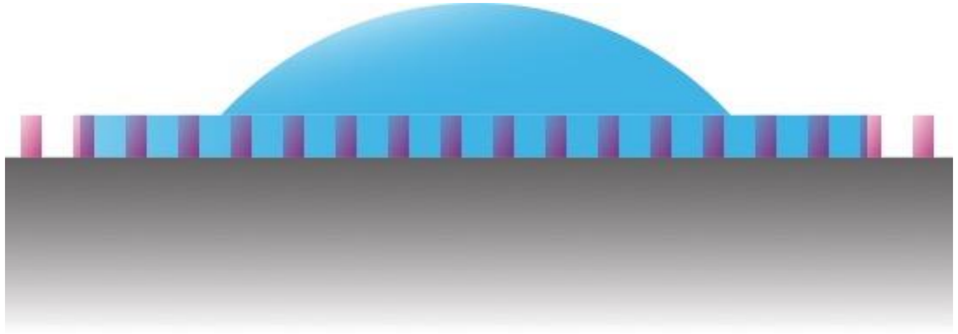


Figure 3.19 in Carey

Wenzel state

Liquid penetrates through the surface structure underneath the droplet, yet not spreading further

Hemi-Spreading State



Liquid penetrates into surface structures ahead of macroscopic contact lines

Cassie-Baxter State

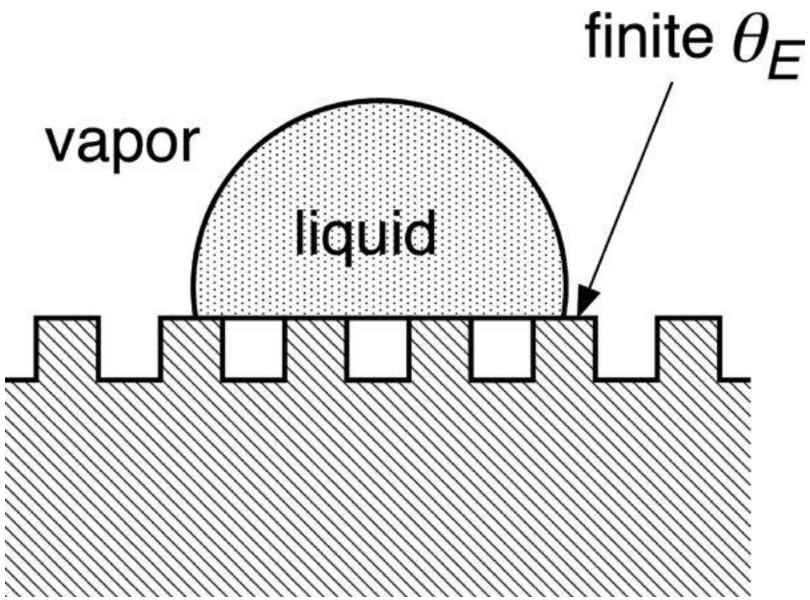
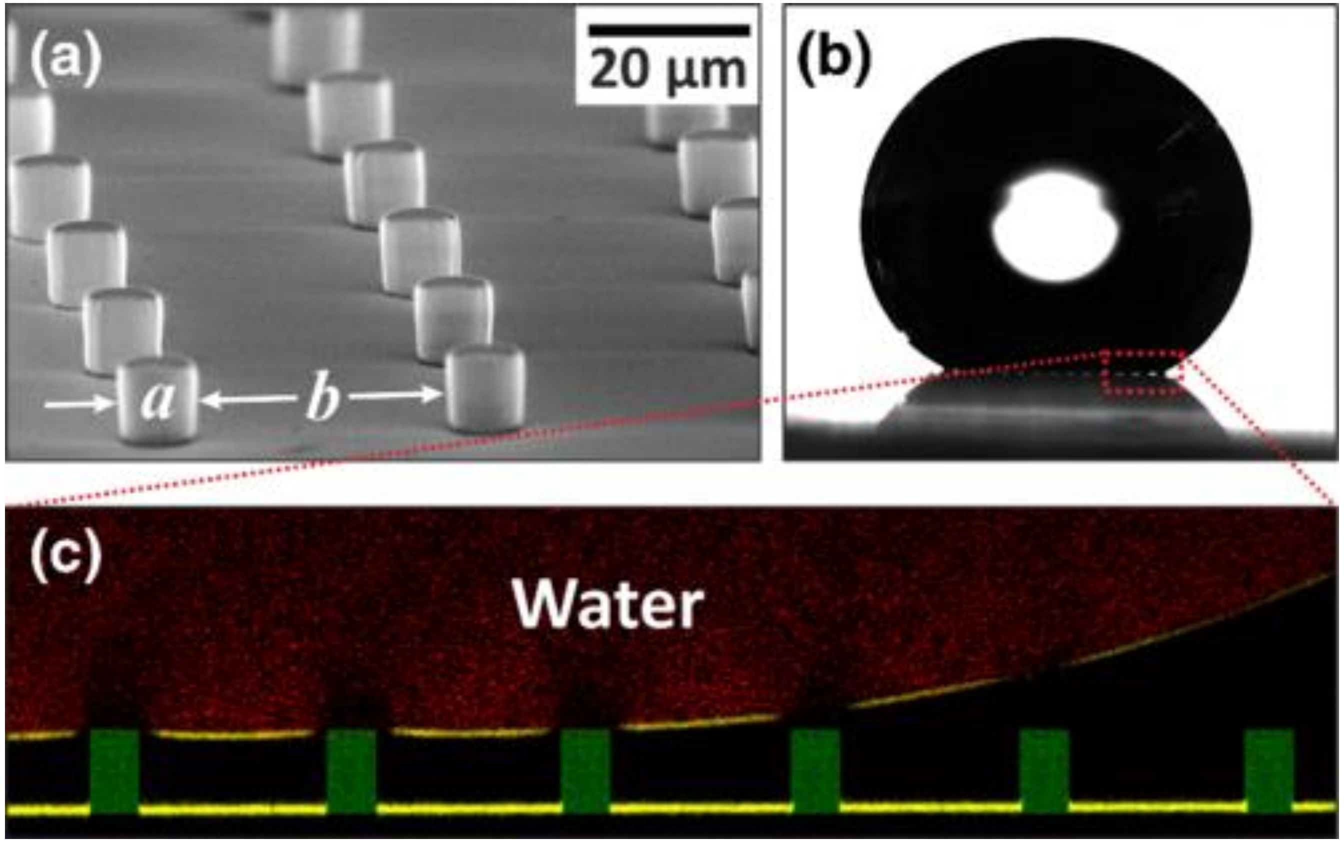


Figure 3.23 in Carey

Air/vapor trapped between the roughness elements underneath the droplet

Conditions for Air Pocket Formation



Schellenberger *et al.*, *Physical Review Letters* 2016

Capillary pressure preventing liquid from entering surface structures

Last Time

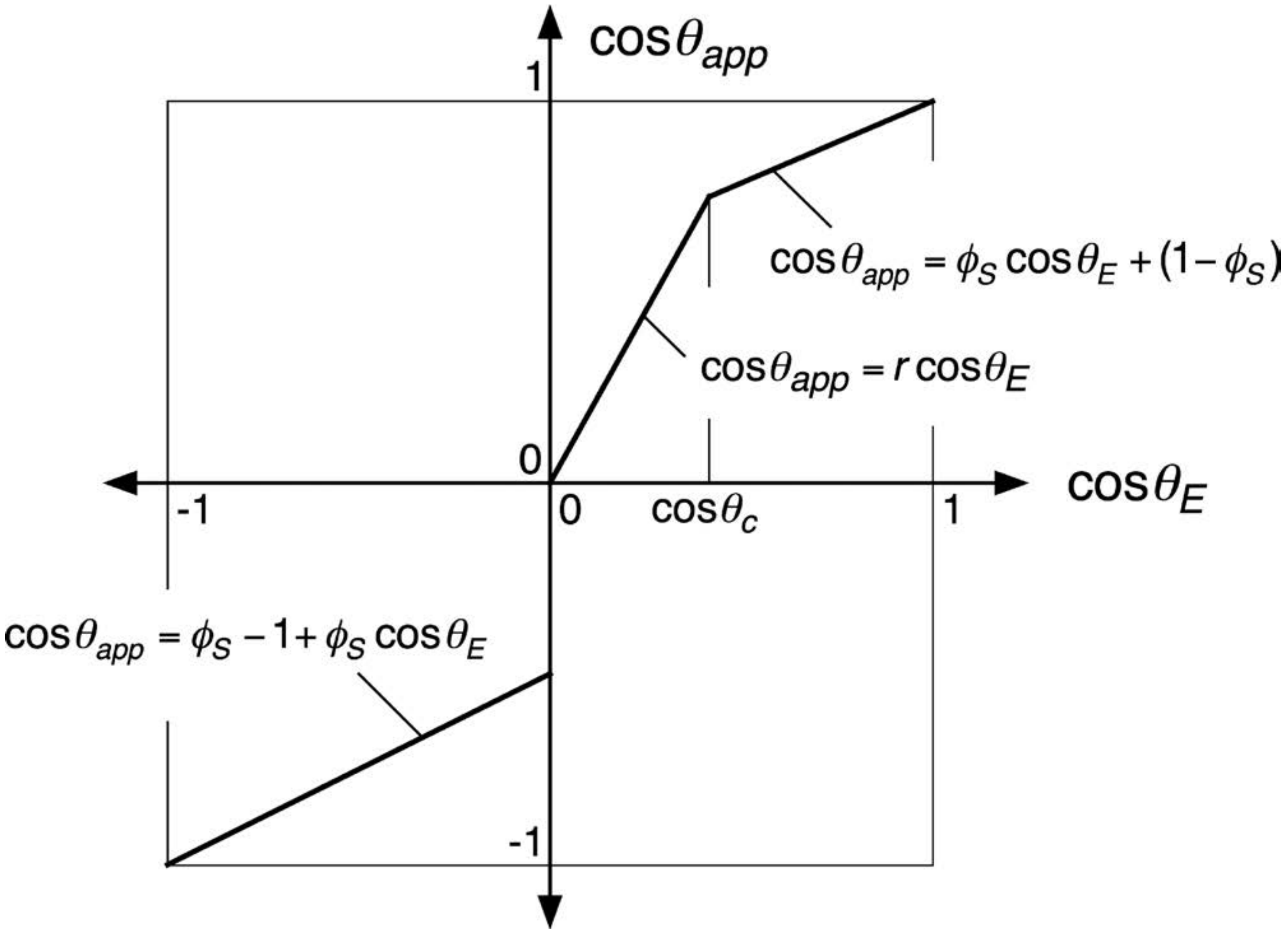
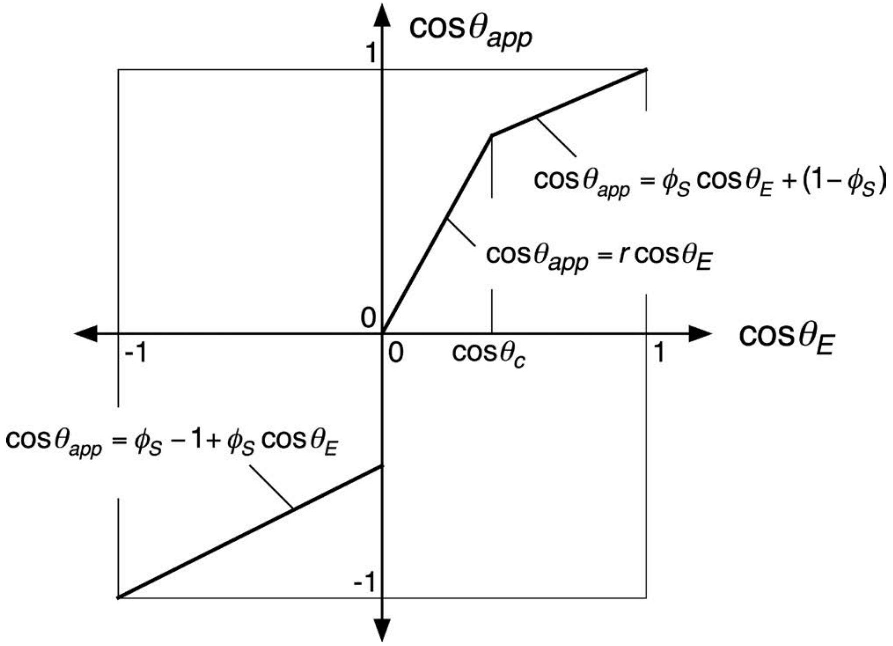


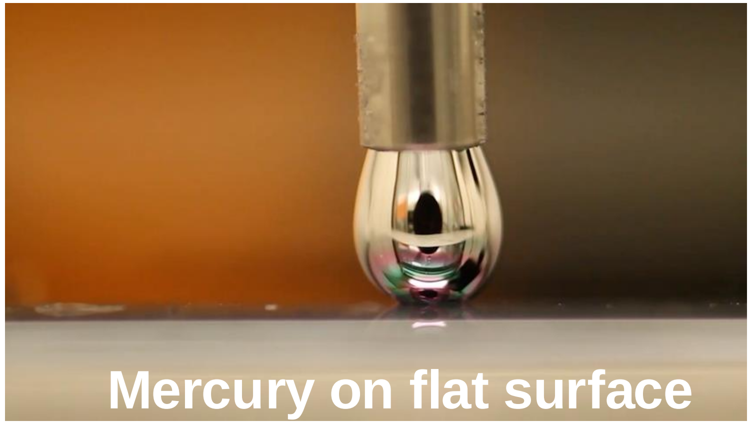
Figure 3.24 in Carey

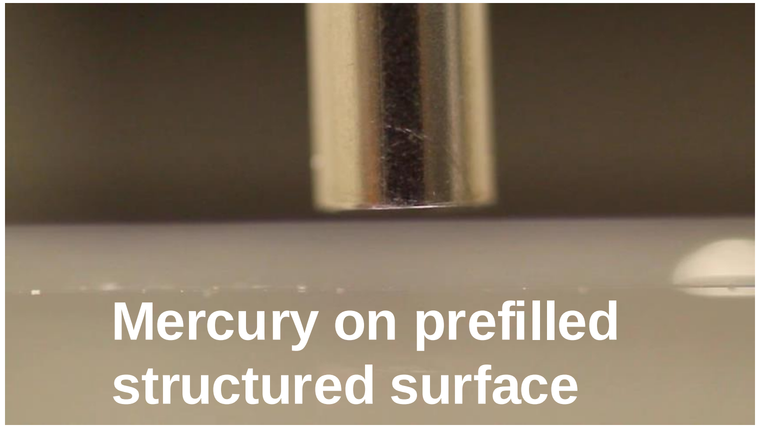
Omniphobic Surfaces



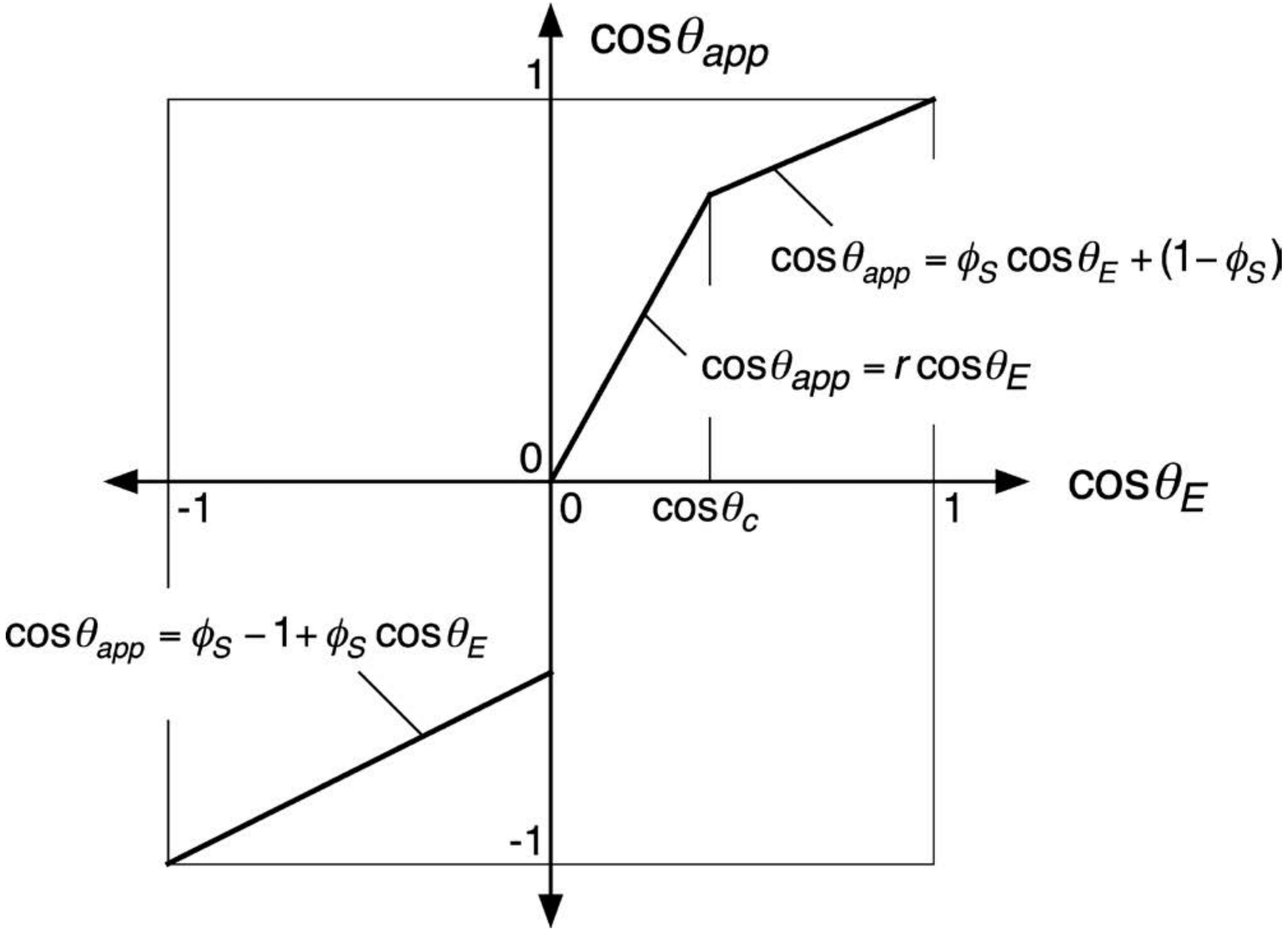
Liu *et al.*, *Science* 2014

Omniphilic Surfaces





Wilke *et al.*, *PNAS* 2021



Intended Learning Objectives Today

- Explain and apply the **Fick's Law of Diffusion**
- Apply heat and mass transfer analogy to **convective mass transfer**
- Explain the **coffee ring effect**

Reading materials: **Lienhard** Chapter 11, **Bird** Chapter 17

Fundamental Picture of Evaporation in Air

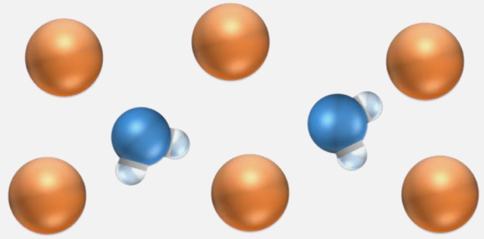
Fundamental Picture of Evaporation in Vapor

Vapor chamber cooler

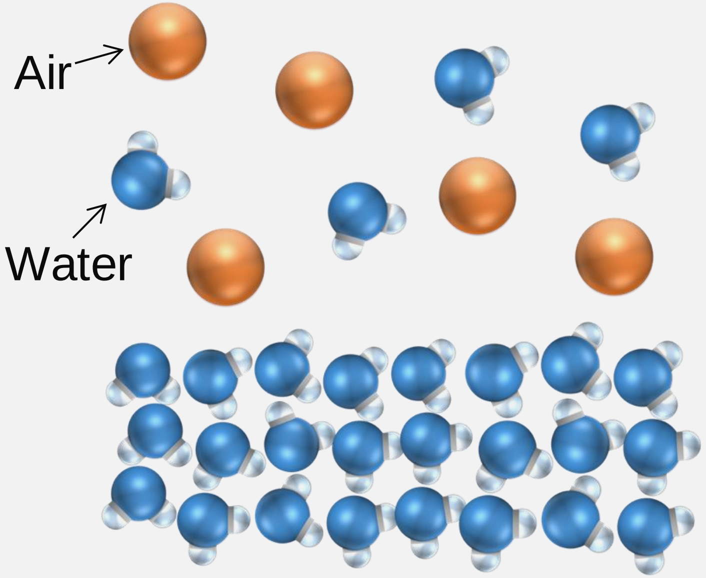
Fundamental Picture of Evaporation

Air → Diffusion Limited

Far field (low vapor concentration)



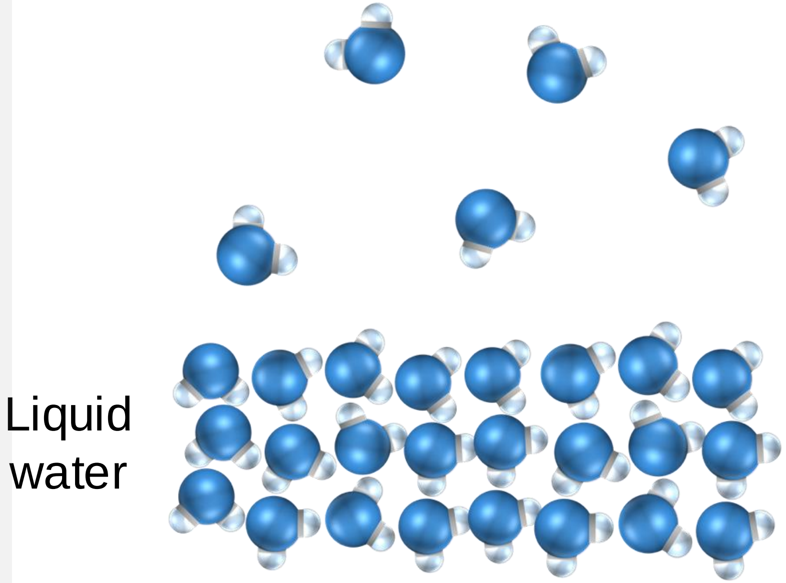
Low (high vapor concentration)



Vapor → Kinetically Limited

Far field (low pressure)

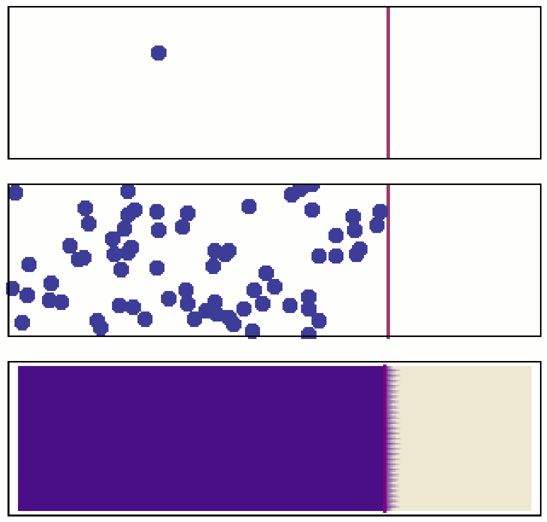
Near field (high pressure)



Transport of Water Vapor in Air

- Moist air modeled as a binary mixture: **water vapor + dry air**

- **Molecular diffusion**:

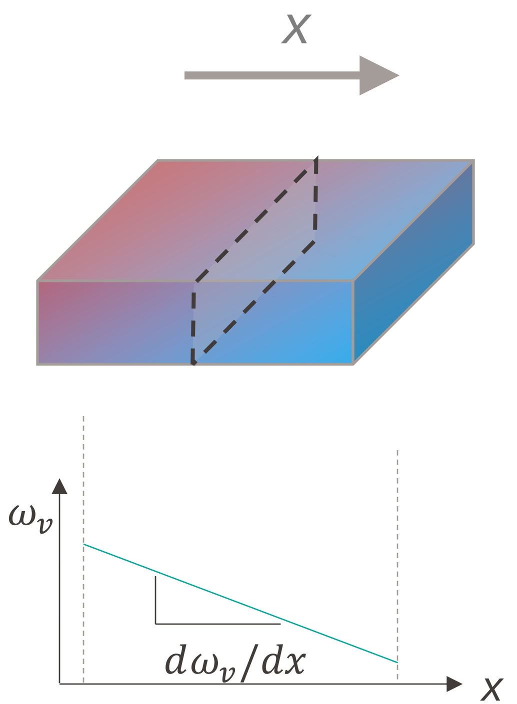


Fick’s law wiki page

Molecules in the mixture move around randomly

Spontaneous mass transfer from more concentrated region to less concentrated region

Fick's Law of Diffusion for Moist Air



Diffusion Coefficient

$$j_{\mathrm{vd}} = -\rho D_{\mathrm{va}} \frac{d\omega_{\mathrm{v}}}{dx}$$

Mixture Mass Average Velocity

Fick’s Law in 3D

Applying the gradient operator ∇ onto a scalar field gives you the direction and in which the scalar value increases most quickly

The magnitude determines how fast the increase is in that direction

Molar Form

What Affects D_{va}

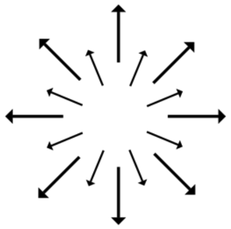
- Temperature
- Total gas pressure
- Composition of the mixture
- Correlation can be found in literature (Eq. 11.34 in Lienhard)

Convective Mass Transfer

Convective Mass Transfer

Applying the divergence operator $\nabla\cdot$ onto a vector field gives you the local sink term for the field flux:

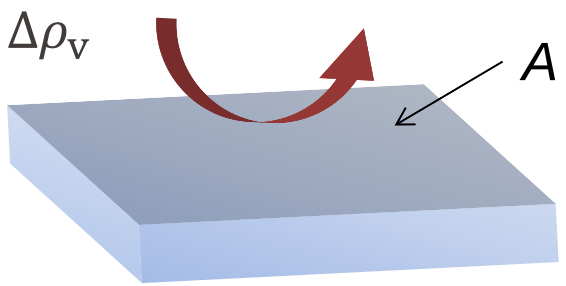
$\nabla\cdot$ $(\mathbf{Mass\ flux})$ = local mass “outgoingness”
$\nabla\cdot$ $(\mathbf{Energy\ flux})$ = local energy “outgoinness”

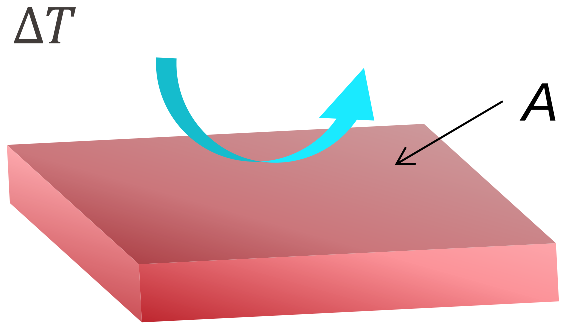


Convective Mass Transfer

$$\nabla \cdot \left(\psi \vec{A}\right) = \psi\left(\nabla \cdot \vec{A}\right) + (\nabla \psi) \cdot \vec{A}$$

Heat and Mass Transfer Analogy





Heat and Mass Transfer Analogy

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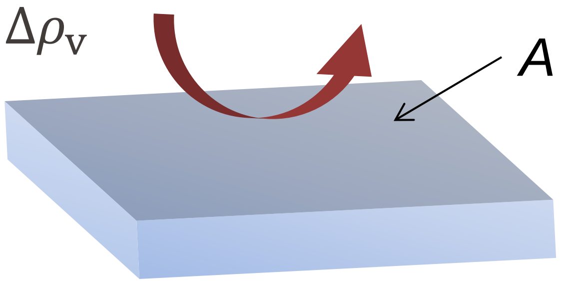
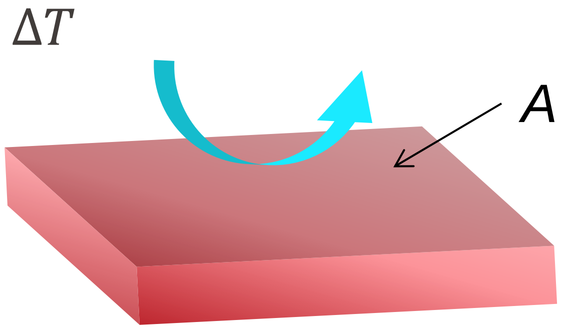
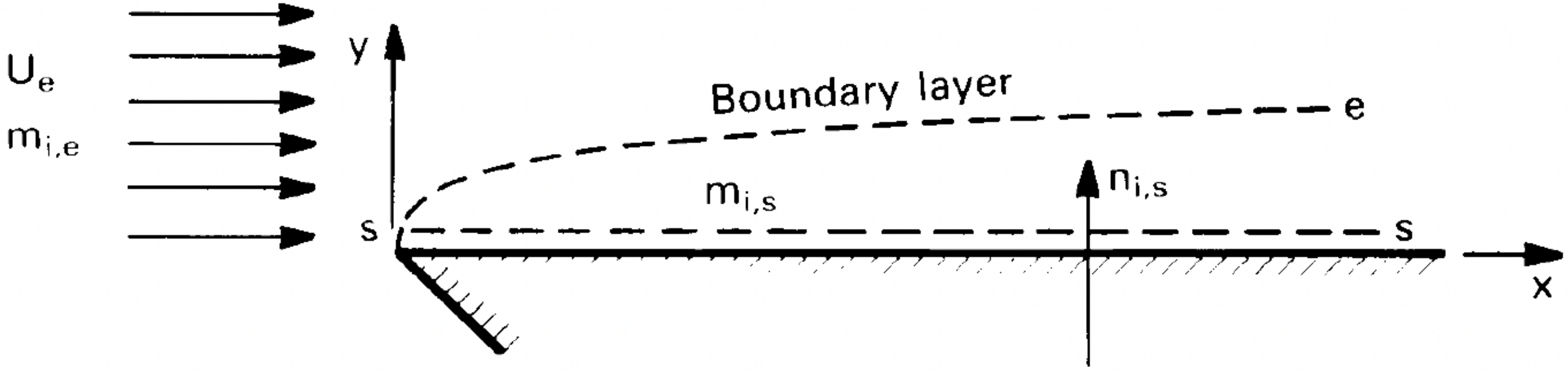
Heat and Mass Transfer Analogy





Heat and Mass Transfer Analogy

Example



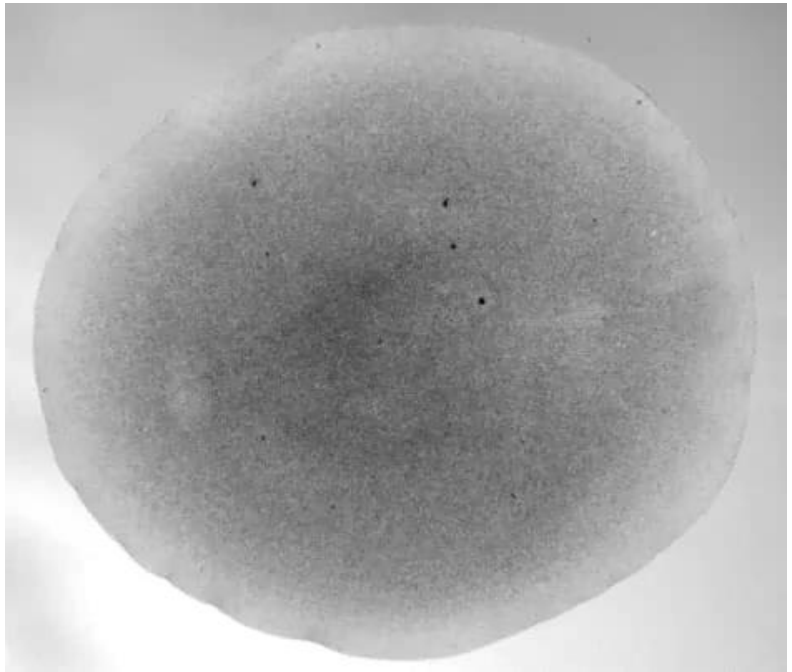
Lienhard, Figure 11.12

$$\mathrm{Nu}_x = 0.332\sqrt{\mathrm{Re}_x}\sqrt[3]{\mathrm{Pr}}$$

$$\mathrm{Sh}_x = 0.332\sqrt{\mathrm{Re}_x}\sqrt[3]{\mathrm{Sc}}$$

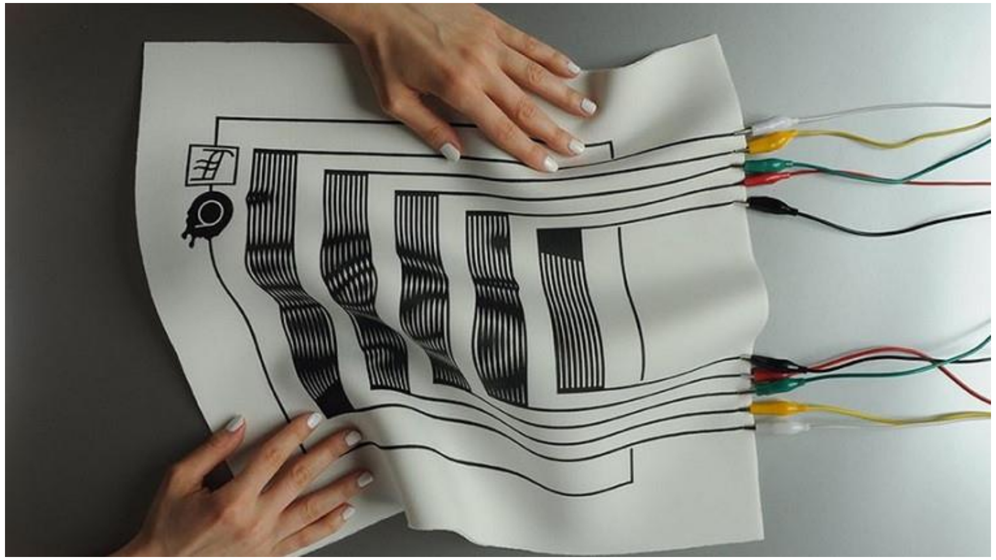
Coffee Ring Effect

Coffee Ring Effect



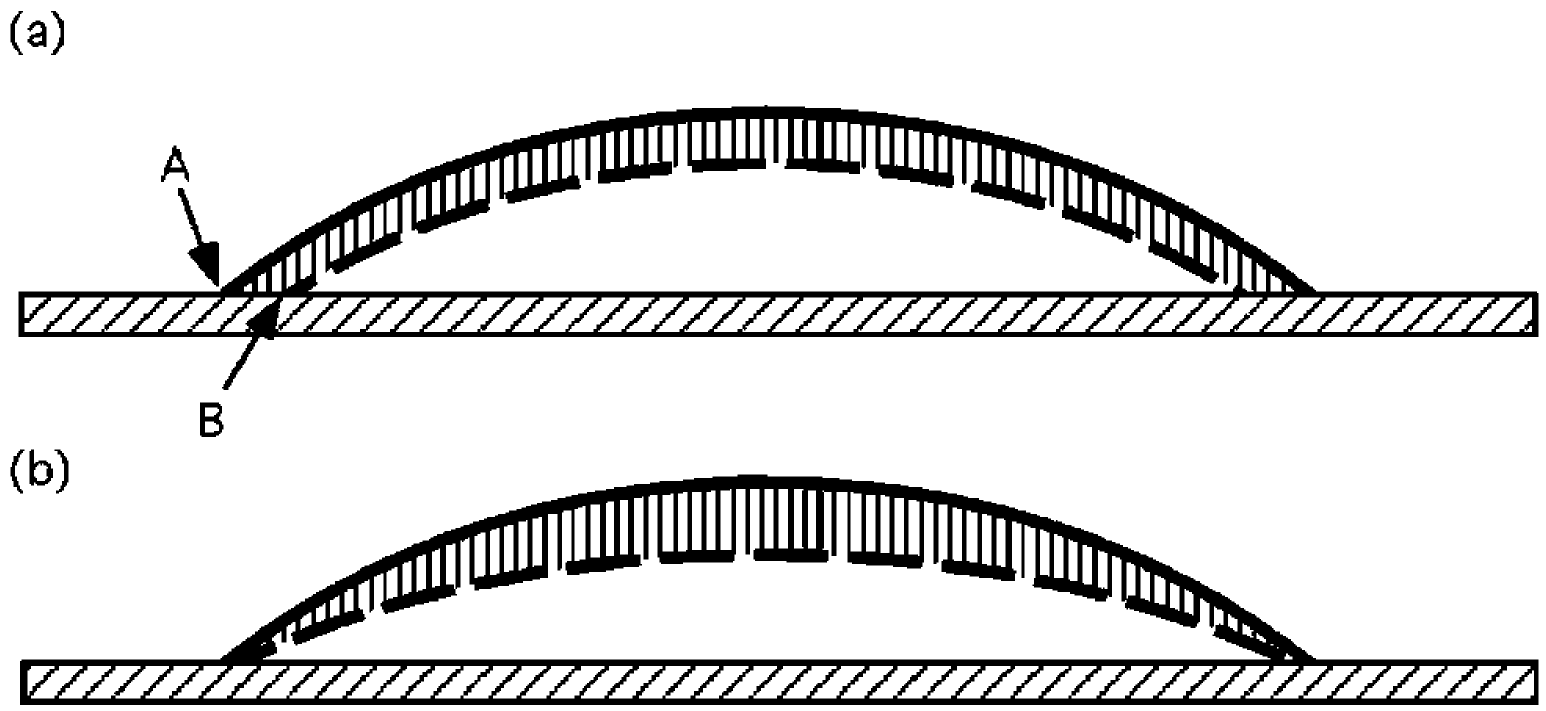
Yunker *et al.*, *Nature* (2011)

Printed electronics



Karim *et al.*, *Scientific Reports* (2019)

Contact Line Pinning

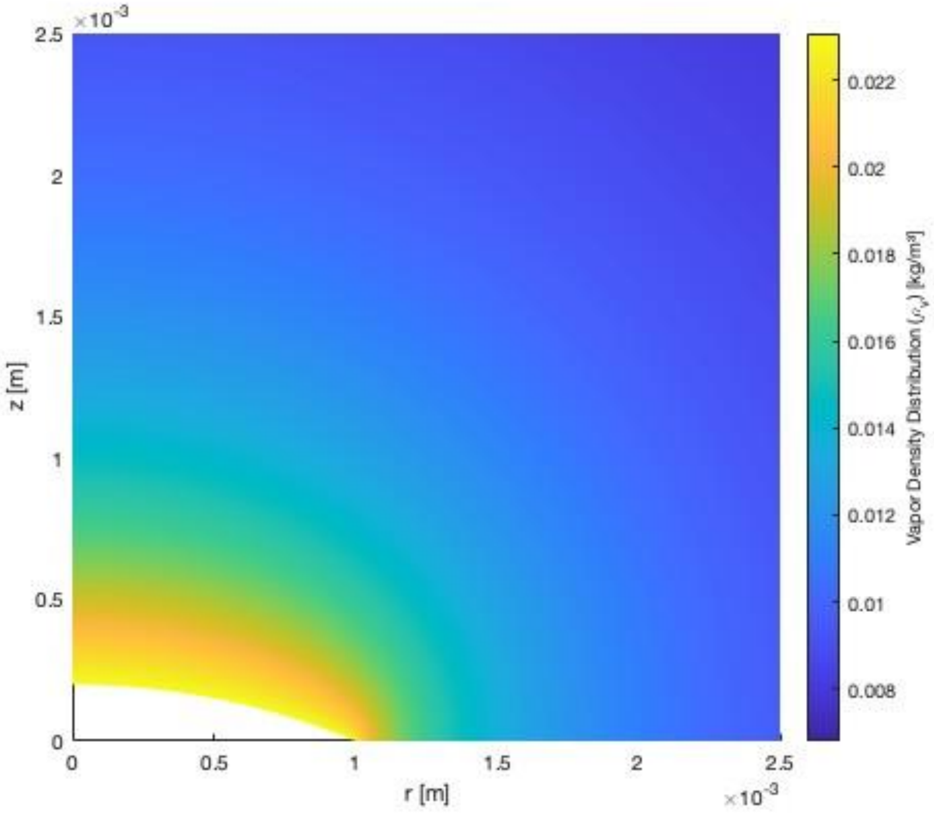


Deegan *et al.*, *Physical Review E* (2000)

Evaporative Transport

Lightening rod

Evaporative Transport



Lightening rod

Mass Conservation

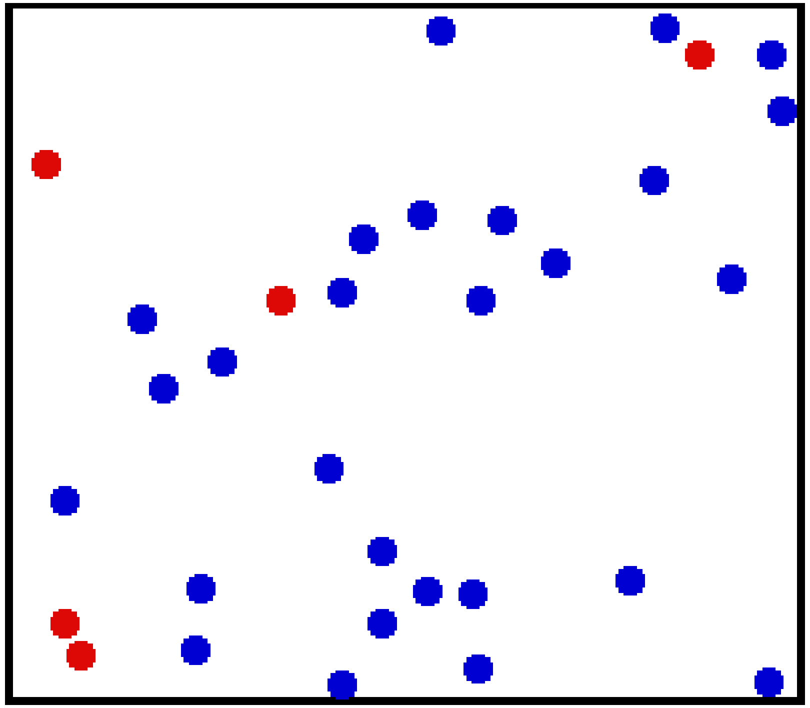
Fluid Flow

What We Learned Today

- Fick’s Law of Diffusion
- Heat and mass transfer analogy
- Coffee ring effect

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
- **Ideal gas**: molecules with negligible sizes and not interacting with each other other than collision



Credit: A. Greg