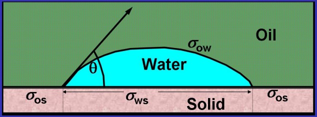
Multiphase Flow and Heat Transfer



Wettability

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- Usually, a liquid-vapor phase change is accomplished by transferring energy through the walls of a container or channel into or out of a two-phase system.
- The vaporization or condensation process ultimately takes place at the liquid-vapor interface.
- However, the contact through which the energy is transferred will strongly affect the resulting heat and mass transfer in the system.
- The performance of heat transfer equipment in which vaporization or condensation occurs may depend strongly on the way that the two phases contact the solid walls.

Wettability

- Liquids with weak affinities for a solid wall will collect themselves into beads while those with high affinities for solid will form film to maximize the liquid-solid contact area.
- The affinity of liquids for solids - **wettability of the fluid.**

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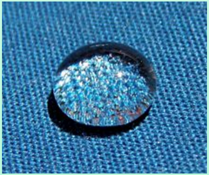
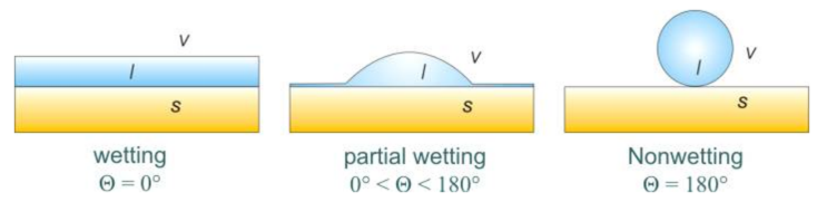
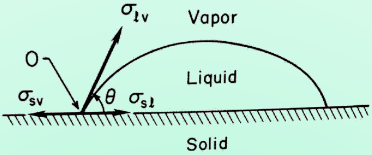




Neumann's Formula or Young's Equation



$$\sigma_{sv} = \sigma_{sl} + \sigma_{lv}\cos\theta$$

Vertical force $\sigma_{lv}\sin\theta$ must be balanced by a vertical reaction force in the solid.

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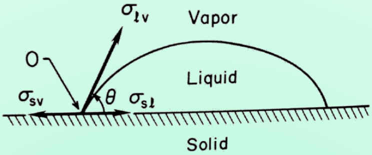

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Vertical force $\sigma_{lv} \sin\theta$ must be balanced by a vertical reaction force in the solid.

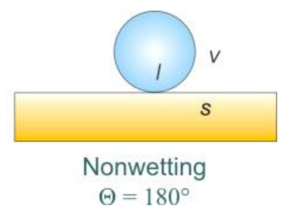
- Small and also modulus of elasticity of solid is high
- No deformation occurs

σ_{sl} and σ_{sv} are not available easily.

Neumann's Formula or Young's Equation

As $\theta \to 180^\circ$ (if g is negligible)

- Liquid droplet - sphere
- One point of contact on solid
- Completely non-wetting



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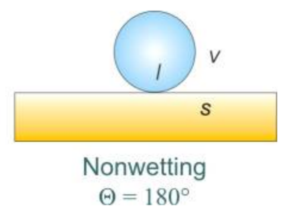

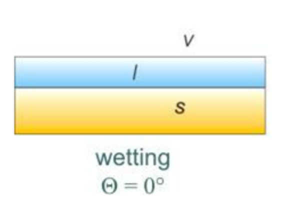

As $\theta \to 0^\circ$

- A thin film configuration
- Completely wet the solid

As $\theta \rightarrow 180^\circ$ (if g is negligible)

- Liquid droplet - sphere
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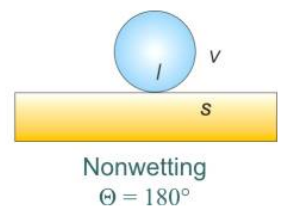
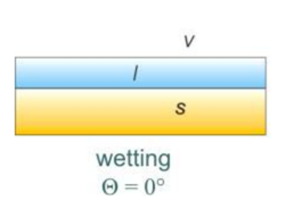




As $\theta \rightarrow 0^\circ$

- A thin film configuration
- Completely wet the solid

- Wetting liquid: As $0^\circ < \theta < 90^\circ$
- Non-wetting liquid: As $90^\circ < \theta < 180^\circ$

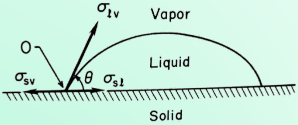
  one point of contact on solid

Neumann's Formula or Young's Equation

$$\sigma_{sv} = \sigma_{sl} + \sigma_{lv} \cos\theta; \qquad |\cos\theta| \ngtr 1$$

At equilibrium:

$$\left| \frac{\sigma_{sv} - \sigma_{sl}}{\sigma_{lv}} \right| < 1$$



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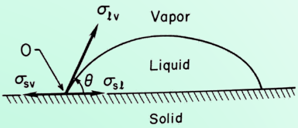

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If $\dfrac{\sigma_{sv} - \sigma_{sl}}{\sigma_{lv}} < -1$, σ_{sl} pulls the contact line, $\theta \to 180^\circ$

Never happens for a droplet surrounded by its vapor, but could happen for a liquid droplet in another immiscible liquid.

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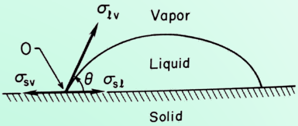

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Never happens for a droplet surrounded by its vapor, but could happen for a liquid droplet in another immiscible liquid.

If $\dfrac{\sigma_{sv} - \sigma_{sl}}{\sigma_{lv}} > 1,\ \sigma_{sv}$ pulls the contact line, $\theta \to 0^\circ$

Until the film becomes so thin that molecular interactions come into play.

Spreading Coefficient

$$\mathsf{Sp}_{ls} = \sigma_{sv} - (\sigma_{lv} + \sigma_{sl})$$

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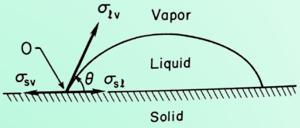

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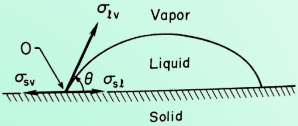

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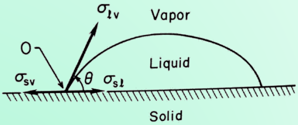

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These results are theoretical and no lack of σ_{sv} and σ_{sl}.

Work of Adhesion

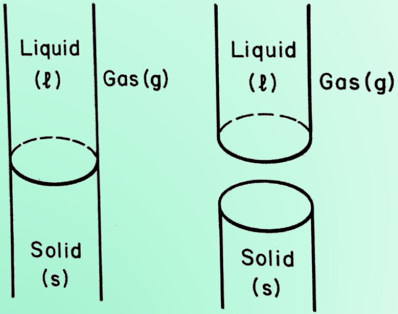
Cylindrical column formed by l, s and low density gas, g. The net reversible work required per unit of interface area:

$$w_{sl} = \sigma_{lg} + \sigma_{sg} - \sigma_{sl}$$

Essentially,

- Forming 2 new interfaces
- Breaking one interface

Adhesion: due to the minimum reversible work required to tear the liquid off the solid surface.



Work of Cohesion

Now consider, instead of solid-liquid column there is only one liquid column. To tear a single liquid column in half:

$$w_{ll} = 2\sigma_{lg}$$

Essentially, two interfaces are formed without breaking any interface.

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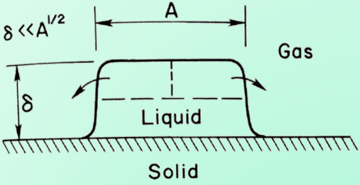
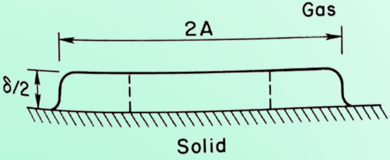
Adhesion - for dissimilar particles
Cohesion - for similar particles

Work per Unit Area Required for Spreading

Now lets march further. Lets say there is a liquid column of area A, and height δ. We are making it into a liquid column of area $2A$ and height of $\delta/2$.





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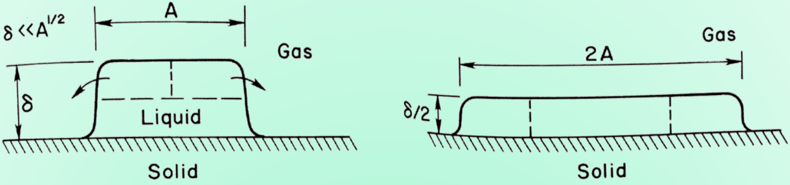

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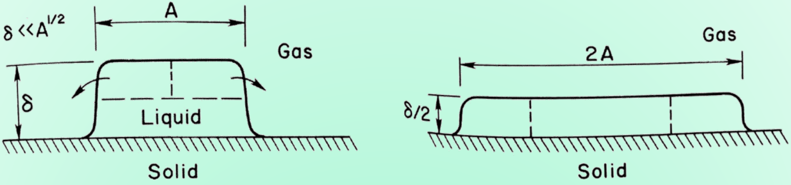

$$w_{sp} = \sigma_{lg} + \sigma_{sl} - \sigma_{sg}$$

$$= -\mathsf{Sp}_{ls}$$

Work interaction is negative (Sp_{ls} is positive for spreading). Work could be extracted if we can ($= \mathsf{Sp}_{ls}$).

Adhesion and Cohesion

$$\mathsf{Sp}_{ls} = -w_{sp} = w_{sl} - w_{ll}$$

Spreading coefficient = difference between $\begin{cases} \text{the work of adhesion} \\ \text{the work of cohesion} \end{cases}$

Sp_{ls} indicates the tendency of the liquid to adhere to the solid relative to its internal cohesive forces.

Surface Tension of a Mixture

$$w_{sl} = \sigma_{lg} + \sigma_{sg} - \sigma_{sl}$$

Applying it to any two solid or liquid phases a and b, and a low density gas or vapor phase g,

$$w_{ab} = \sigma_{bg} + \sigma_{ag} - \sigma_{ab}$$

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The work of adhesion is approximately given as:

$$w_{ab} \cong 2\left(\sigma_{ag}\sigma_{bg}\right)^{\frac{1}{2}}$$

$$\boxed{\sigma_{ab} = \sigma_{bg} + \sigma_{ag} - 2\left(\sigma_{ag}\sigma_{bg}\right)^{\frac{1}{2}}}$$

Problem

For water and hexane in contact with air at 20°C, σ_{wg} is 0.0728 N/m and σ_{hg} is 0.0184 N/m respectively. Use these data to estimate the interfacial tension between hexane and water. Compare this value to experimentally determined value of $\sigma_{wh} = 0.0511$ N/m.

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$$\sigma_{wh} = 0.0180 \text{ N/m}$$

This is 65% accuracy or 35% of the actual value.

$$\text{Sp}_{hw} = \sigma_{wg} - \sigma_{hg} - \sigma_{wh}$$

Problem

$$\mathsf{Sp}_{hw} = \sigma_{wg} - \sigma_{hg} - \sigma_{wh} = 0.0033 \text{ N/m}$$

- $\mathsf{Sp}_{hw} > 0$, hexane would spontaneously spread over the surface of water
- However, close to zero and so tendency is weak.
- Hexane is unlikely to form lens-shaped droplets.
- Spread out into a film, not aggressively covers the entire liquid surface.

Spread Thin Films

Spontaneous spreading of liquid helium over the walls of a Dewar flask