IBC WORKSHOP · MSFC
SEPTEMBER 18, 2000

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- Liquid Behavior in Capillary Systems
  - Capillarity
  - Capillary-Driven Flow
  - Non-Circular Geometries
- Practical Design Considerations
  - Bubble Generation & Control
  - Environmental Control
- Mixing without Bouyancy
- Microfluidics

Bond Number

a measure of the relative strength of body forces (gravity) to that of surface forces (capillarity) on a fluid

$$Bo \equiv \frac{\Delta\rho g r^2}{\sigma}$$

$\Delta\rho$ - difference in densities
g - gravitational acceleration
σ - surface tension
r - characteristic length

$Bo \ll 1$ gravitational effects are negligible

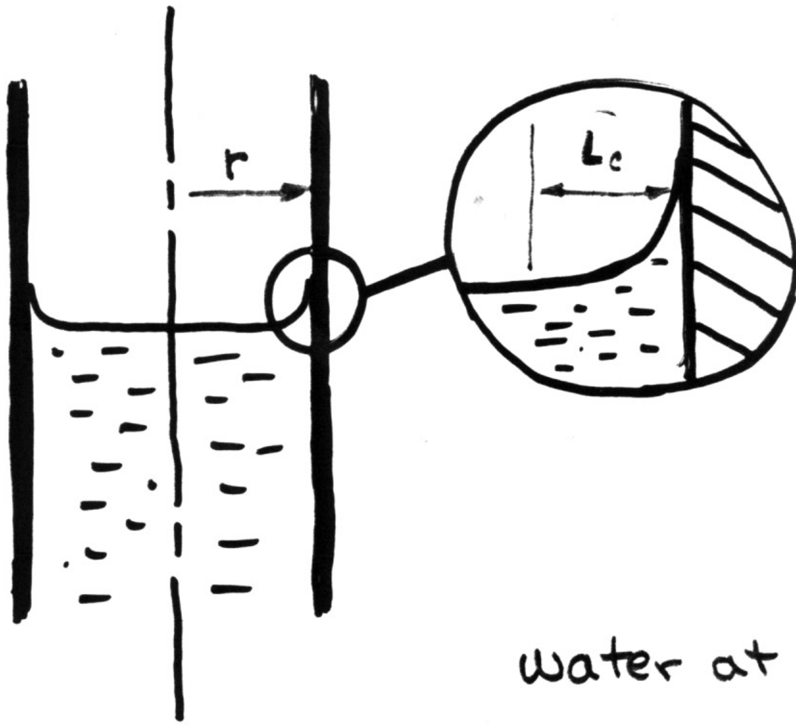
cup of coffee: $Bo \sim 35{,}000$

$\frac{\Delta\rho g}{\sigma}$ also known as <u>capilarity constant</u>

Capillary Length

length scale at which body forces & surface forces are comparable - **Bo = 1**

$$L_c \equiv \sqrt{\frac{\sigma}{\Delta \rho g}}$$



water at room temperature

$1g \rightarrow L_c \sim 1\,mm$

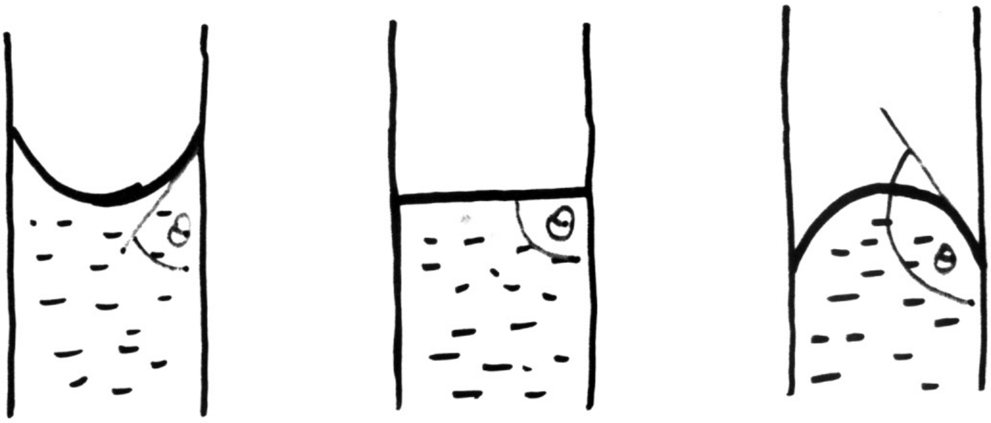
$10^{-4}g \rightarrow L_c \sim 1\,m$

MENISCUS

liquid surface whose shape is defined by a mean radius of curvature which is less than the capillary length

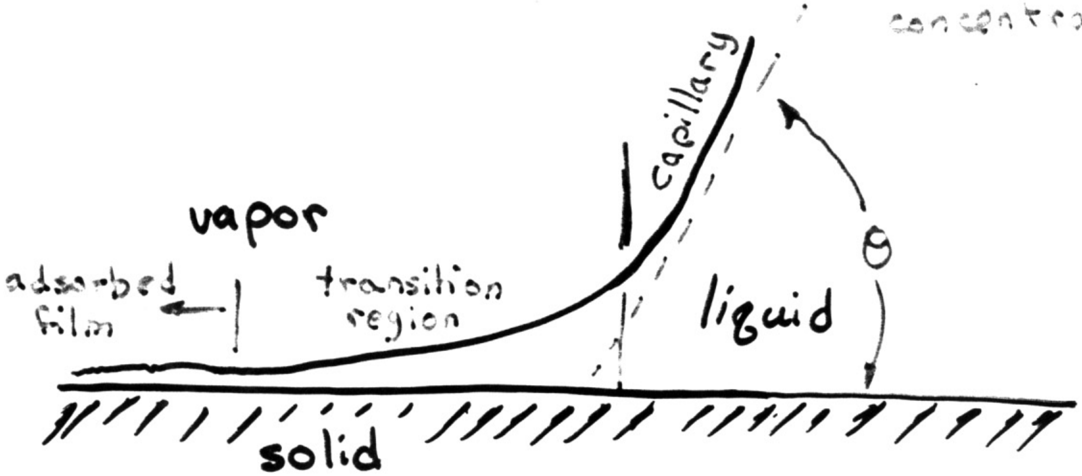
CONTACT ANGLE

$Bo \ll 1$

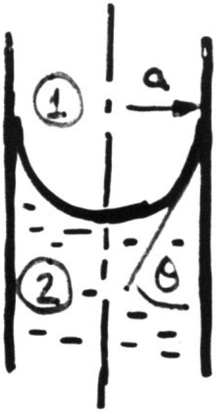


$\theta = 45°$ $\theta = 90°$ $\theta = 135°$

Contact Angle <u>may</u> be affected by temperature or concentration.



Pressure drop across a capillary interface

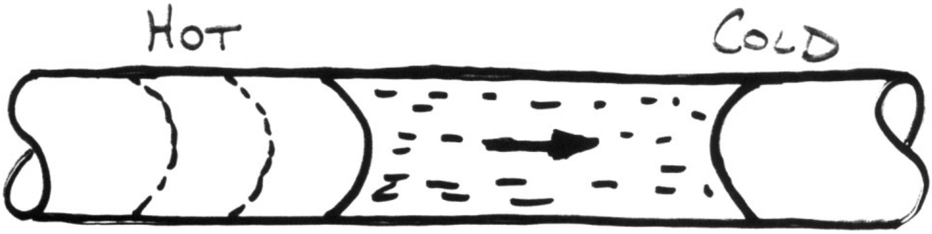


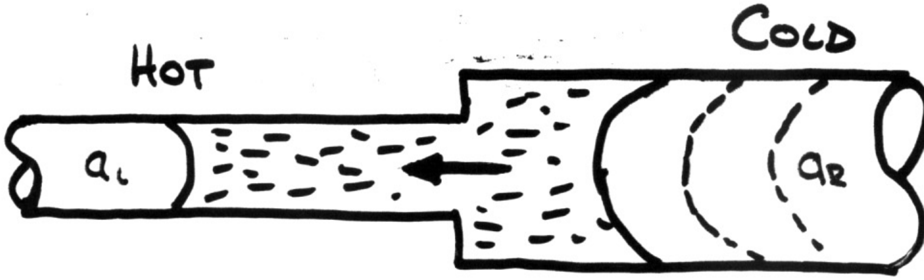
$$P_1 - P_2 = \frac{2\sigma\cos\theta}{a}$$

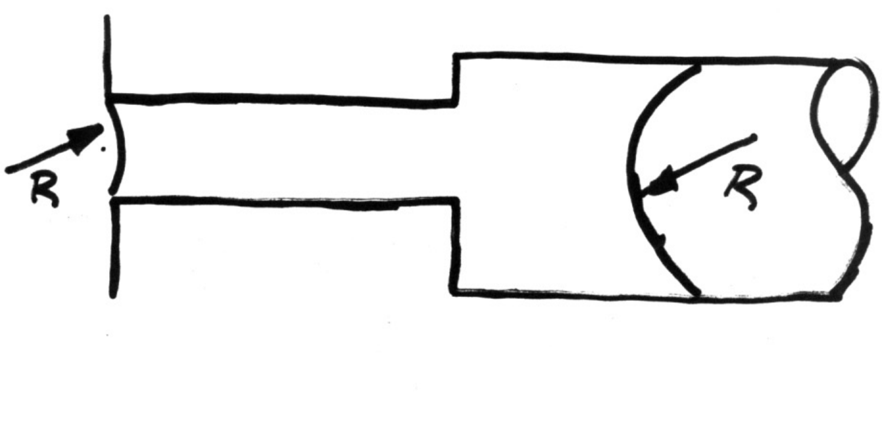
Motion of a Liquid Slug/Plug/Index/Drop/...

Liquid will remain stationary only when

$$\Delta P_L = \frac{2\sigma_L\cos\theta_L}{a_L} = \frac{2\sigma_R\cos\theta_R}{a_R} = \Delta P_R$$

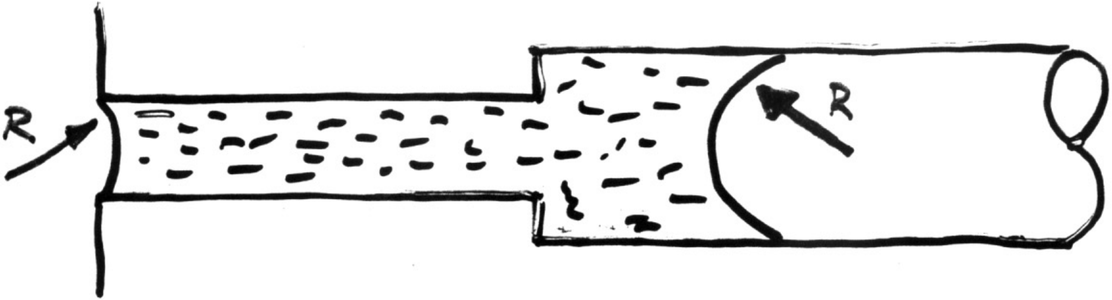






$$\Theta_L \neq \Theta_R : \frac{\bar{V}}{\cos\Theta_L - \cos\Theta_R} \cong a \cdot \frac{\sigma}{\mu}$$

PINNING EDGE



Important Parameters in Capillary-Driven Flow

$$We \equiv \frac{\rho R V^2}{\sigma}$$ **Weber Number**

for $Bo \ll 1$, $We > 1$ implies that the surface will break up due to convective flows

$$Ca \equiv \frac{\mu V}{\sigma}$$ **Capillary Number**

for $Bo \ll 1$, Ca is a measure of surface deformation due to viscous effects

for capillary-driven flows, $V \sim \frac{\sigma}{\mu}$

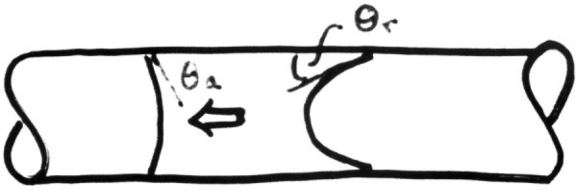
$$\therefore \; Su \equiv \frac{\rho \sigma R}{\mu^2}$$ **Suratman Number**

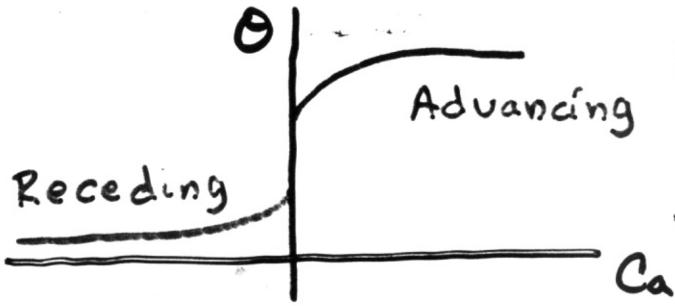
for $Bo \ll 1$, Su is a measure of inertia in a capillary system

"Significant inertia is perhaps the most distinguishing characteristic of low-g capillary flows with constant properties." (Weislogel, 1998)

Dynamic Contact Angle

$\theta_{static} \neq 0$





small Ca limit

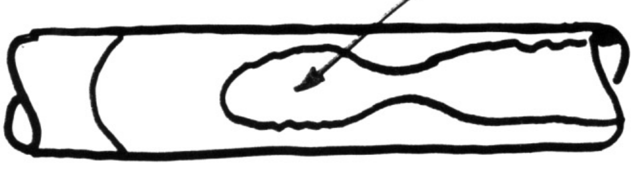
Liquid Film Deposition

large Ca

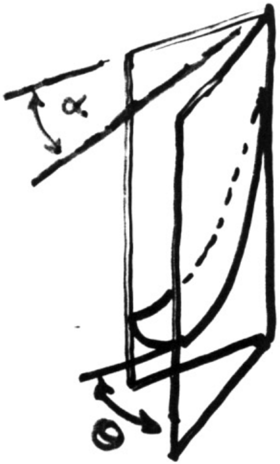
deposited (left behind) liquid film is unstable

- if the film thickness > 0.1 R, then "pinch-off" may occur

bubble formation eminent



Flow in a corner - Critical Contact Angle



Concus-Finn Condition

If $\theta < \frac{\pi}{2} - \alpha$, then liquid will wick into the corner.

α - half-angle of corner

θ - contact angle

- *Equilibrium Capillary Surfaces*, Robert Finn
  Springer-Verlag, New York, 1986

- *Low-Gravity Fluid Mechanics*, Myshkis, Babskii, Kopachevskii, Slobozhanin, & Tyoptsov, translated by R.S. Wadhwa, Springer-Verlag, Berlin, 1987

- *Thermocapillary Flow with Evaporation and Condensation and its Effect on Liquid Retention in Low-G Fluid Acquisition Devices*, George R. Schmidt, NASA TP-3463, 1994

- "Capillary Flow in an Interior Corner", Mark Weislogel and Seth Lichter, *J. Fluid Mechanics*, vol. 373 (1998)

- *Fluid Interface Phenomena in a Low-Gravity Environment: Recent Results from Drop Tower Experimentation*, Mark Weislogel, *Space Forum*, vol. 3 (1998)