CHE 231

Transport Phenomena I: Fluids

Jeff Heys
Arizona State University

about this class...

- Make sure you have a copy of the syllabus and schedule even though the schedule is tentative.
- Syllabus Highlights:
  - Office Hours: M 3:00 – 4:00 and W 9:15 – 11:15
  - My office: ERC 287 (480-965-0874)
  - email: jheys@asu.edu
  - Make sure you have the prerequisites??
  - Text (New): J.O. Wilkes, Fluid Mechanics for ChE, 2nd Ed.
  - Grades: 20% HW (10), 50% Midterms (2), 30% Final

Schedule Highlights

- We have two midterms, currently scheduled for Feb. 20 and Apr. 7 (Tentative)
- Final is on Wed, May 7 at 2:40 (NOT Tentative)
- I'll be out of town on April 16 so we are unlikely to have class.
- I'm using a new book, so the schedule is likely to be changed, although the goal of getting through the first 8 chapters is unlikely to change

about me...

- I conduct research on computational fluid mechanics in tissues and other biological systems
- I'm married with one daughter, one son, and one cat....'Bleu'
- I like math and have taught it extensively so...prepare!
- I dislike proprietary file formats (e.g., *.doc and *.ppt) and lecturing with slides....

TA

- Brad Merchant
  - ERC 356
  - bmerchan@asu.edu
  - Office Hours: ?

Course Goals

- Model or analyze *static* fluid systems (Chpt. 1)
- Use *Macroscopic* balances (Integrals, Chpt. 2-4)
- Use *Microscopic* balances (Diff Eqs., Chpt. 5-6)
- Understand *dimensionless* quantities (Chpt. 4)
- Understand fluid properties (all, starting today)
- Experimentally measure fluid properties (all)

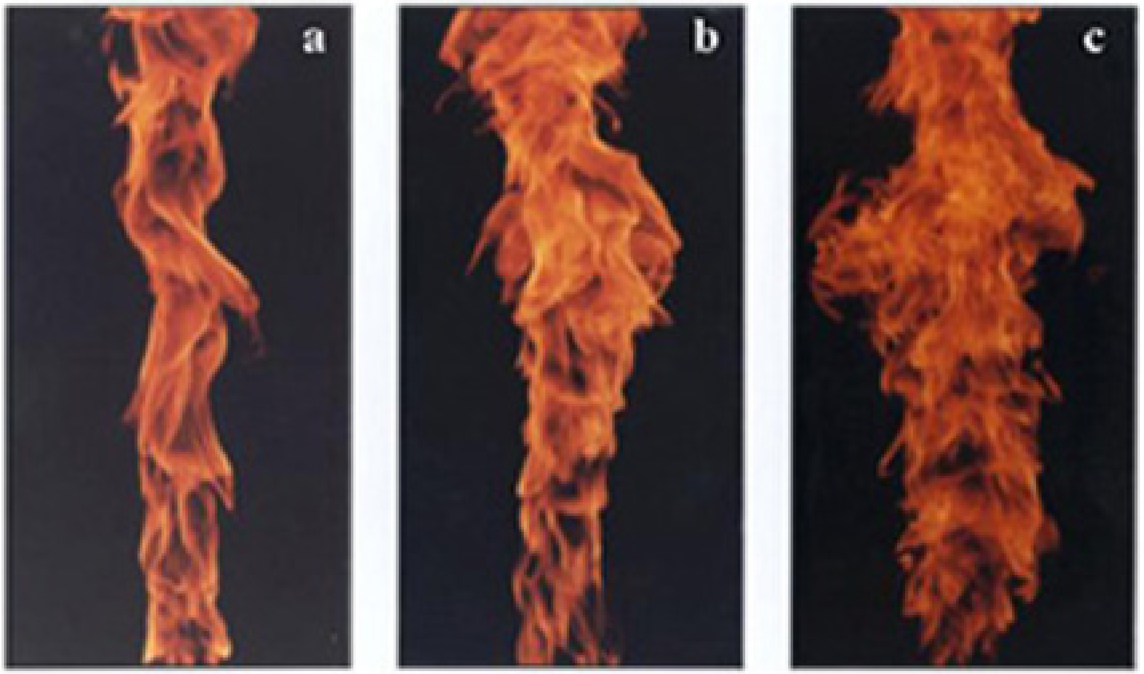
Introduction

- What's a fluid?

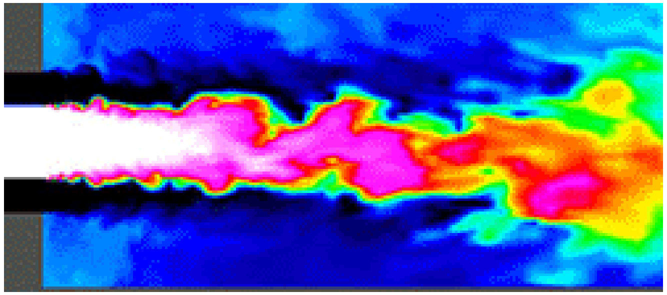
Introduction

- What's a fluid?
  - A material that cannot resist a shear stress by a *static* deflection.
  - Two classes: liquids and gases
  - Static is somewhat “subjective” because some fluids flow so slowly that they are considered static – e.g., asphalt (not glass)
  - the time scale for flow is related to the Deborah Number

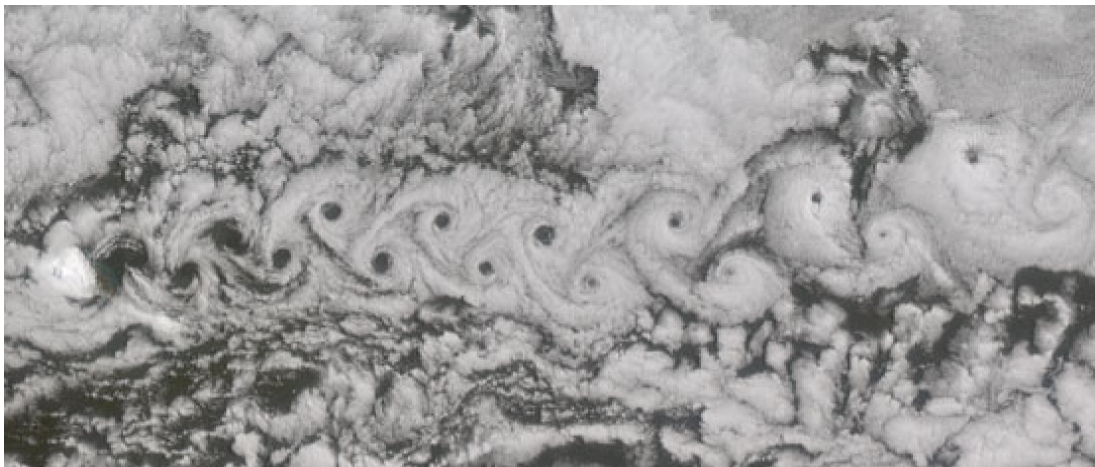
Images – Flames

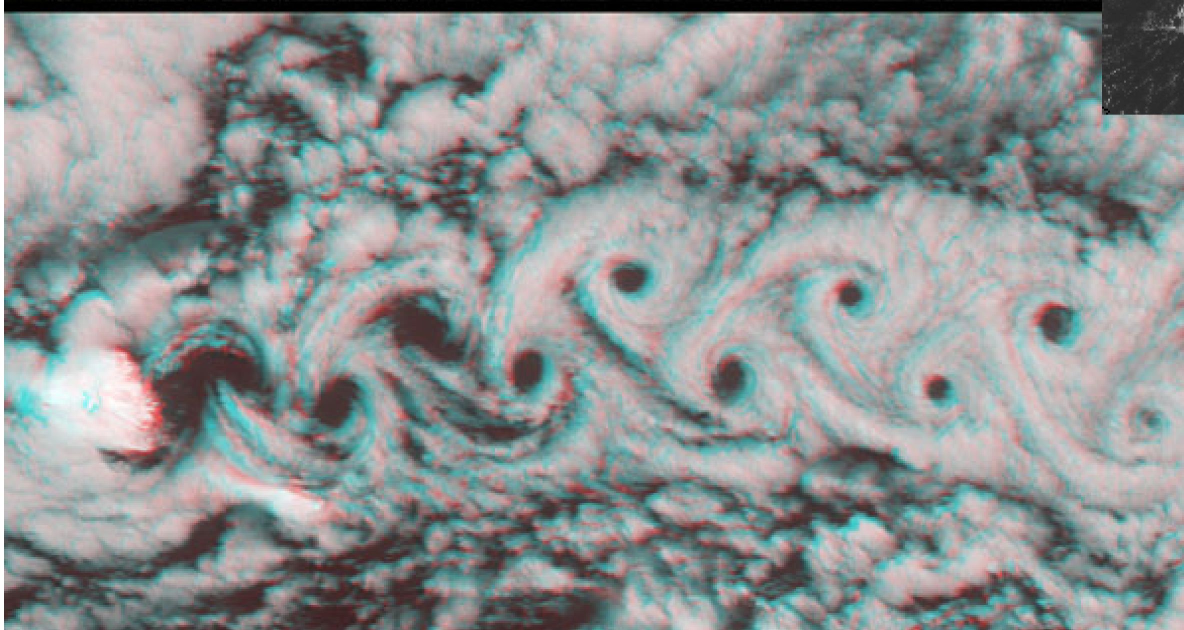


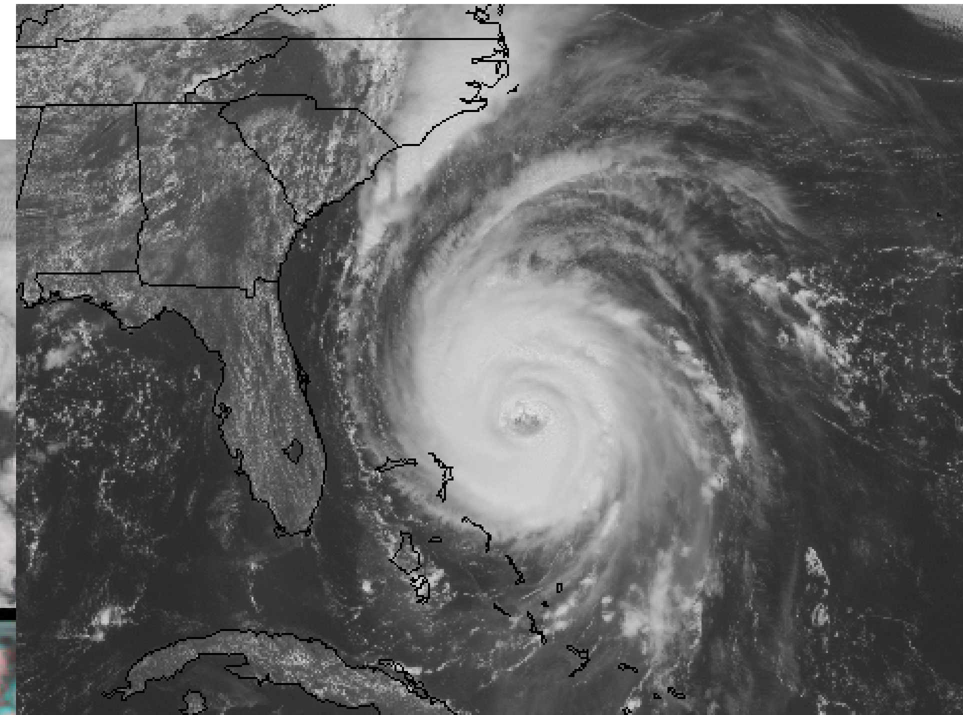
Different Re Numbers above and a simulation from a tailpipe below.



Images – Weather (Vortices)

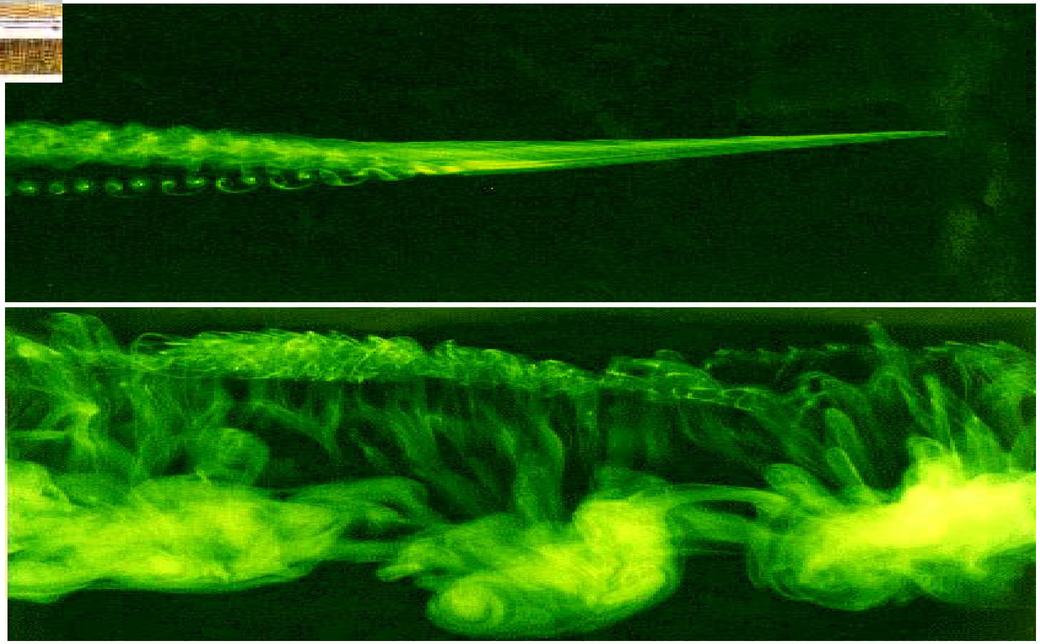




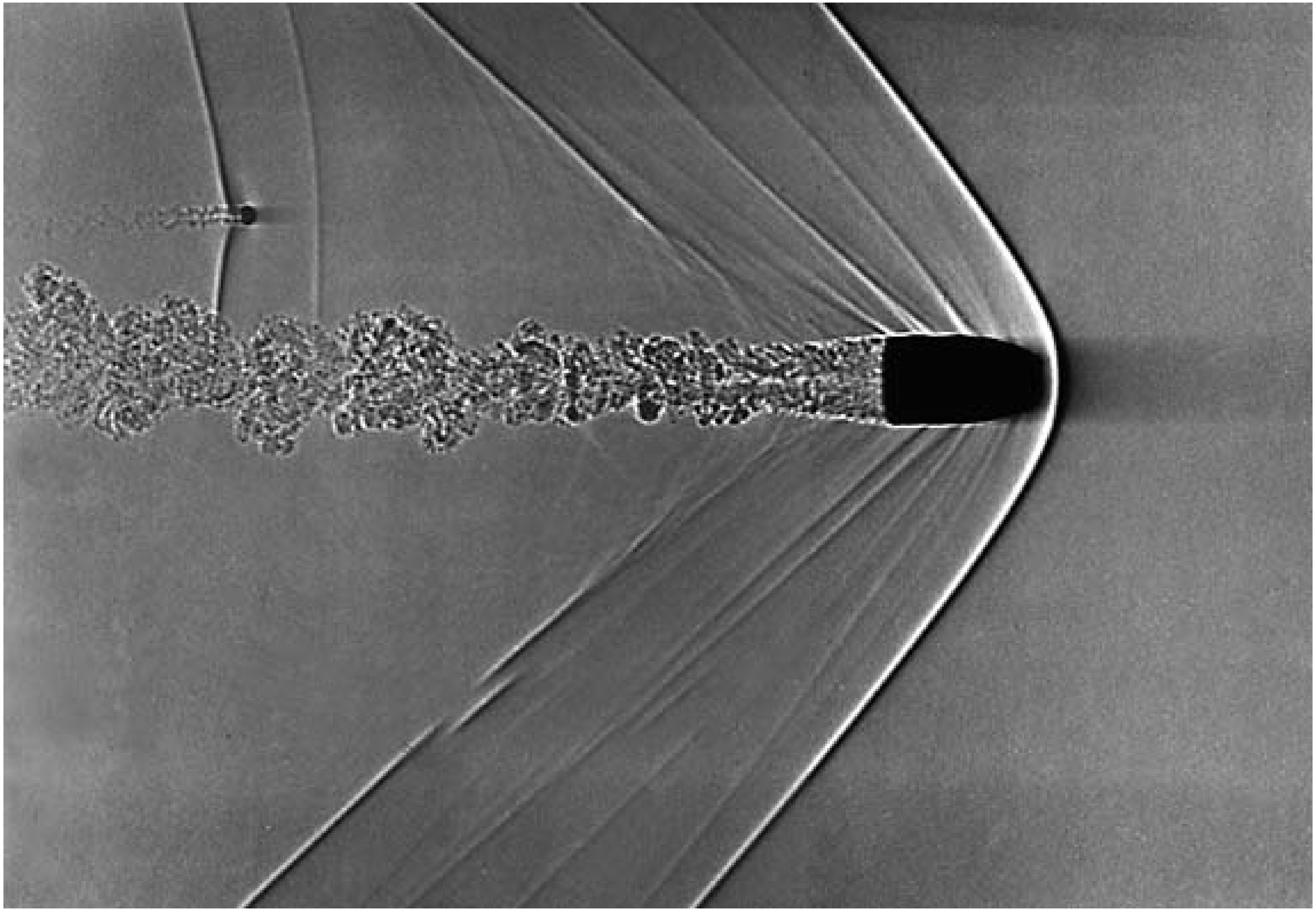


Images – Weather

Images – Aircraft



Images – Shock waves



Fluid Properties and Analysis

Fluid as a Continuum

- Even though fluids are made up of Quarks, atoms and molecules, we will assume they are continuous.
- Hence, nothing we learn can be applied to very small systems (microns or less).
- Density:

$$\rho = \lim_{\delta V \to \delta V^{o}} \frac{\delta m}{\delta V}$$

Dimensions

- Dimensions will be both useful and necessary in this class.
- We will use both SI and “British” Units
- In lectures we will sometimes use the generic:
  - M for mass (e.g., kilogram, lbm, or slug)
  - L for length (e.g., meter or foot)
  - T for time (e.g. second)
  - Θ for temperature (e.g. K or ^{o}F)

Dimensionality

- All answers must have units
- Theoretical equations ($F=ma$, $E=mc^2$) have consistent units and are dimensionally homogeneous (each term has the same units).
- Empirical (?) equations do not always have consistent units and special attention must be paid towards using the correct units (ex, Antoine's Eq).

Frames of reference

- Effects mass and energy balances and equations
- Eulerian
  - "On the shore" frame of reference
  - Used almost exclusively in fluid dynamics
  - Get pressure, p(x,y,z,t)
- Lagrangian
  - "In the boat" frame of reference
  - Used almost exclusively in solid mechanics
  - Get pressure, p(t)

Basic Properties

- Pressure – p
  - Units – Pa, lbf/ft^2
  - Pressure at sea level – 1 atm = 1.01325×10^5 Pa
- Density – ρ
  - Units – kg/m^3, lbm/ft^3
  - Water – 1000 kg/m^3 or 1 gm/cm^3 (know)
  - Air – 1 kg/m^3
- Temperature – T
  - Units – use absolute scale (K or ^oR)

Basic Properties

- Velocity (a VECTOR)

$$\underline{V}(x,y,z,t)=u(x,y,z,t)\underline{i}+v(x,y,z,t)\underline{j}+w(x,y,z,t)\underline{k}$$

- Magnitude of the velocity vector is the speed

Basic Properties

- Enthalpy, Entropy – secondary interest for us
- Specific Heats - ditto
- Transport properties:
  - Viscosity – μ (very important, more soon)
    - Units – M/(L Θ), P (poise)
    - Water – 2×10^{-5} P
    - Air – 1×10^{-3} P
  - Thermal conductivity – ditto

Property Variation

- Gases:
  - Ideal gas law: $p=\rho RT$
- Liquids
  - Density is nearly constant
  - Variation is approximated over a limited range by fitting data with a polynomial or something else...

Stresses

- FORCE/AREA (*Newton's Law, F=ma, still applies to `blobs' of fluid)

- Normal Stress – tensile or compressive
  - Includes PRESSURE

- Tangential Stress – called “Shear Stress”

Viscosity

- Measure of a fluids resistance to flow
- High viscosity means high resistance – e.g., honey, tar, heavy oil, Karo syrup
    - SAE 30 oil is 300 times more viscous than water
- Low viscosity means low resistance – e.g., air
- The Viscosity is a function of many things -
    - Temperature
    - Velocity at which the fluid is moving
    - Shear stresses within the fluid (τ).

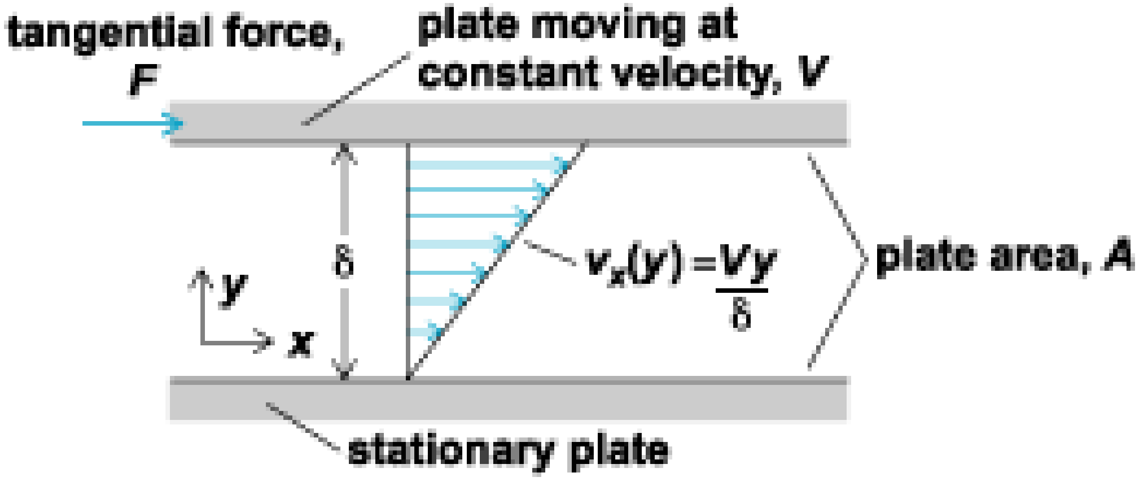
Newtonian Fluids

- Common fluids, like air, water, and oil have a simple relationship between STRESS and DEFORMATION (i.e., velocity profile)

$$\tau=\mu(dv/dy)$$

- The shear stress is proportional to the strain rate (i.e., velocity gradient or rate of change in velocity).
- The constant of proportionality is the viscosity
- Fluids that follow this relationship are called Newtonian fluids (more on nonNewtonian fluids later)

Page 14



- $dv/dy = V/\delta$
- $\tau = F/A = \mu\, V/\delta$

More on viscosity

- Varies with pressure (weakly) and temperature (strongly).
- Often, the kinematic viscosity is reported: $\nu = \mu/\rho$
  - Just the viscosity divided by density
  - Units: L^2/Θ
- Variation with temperature: $\mu = \mu_0(T/T_0)^n$
  - The so called power law where n changes between gases, many other correlations (curve fits) are available.

Nonnewtonian Fluids

- Shear thickening fluids increase thickness with increasing strain rate
- Pseudoplastics (shear thinning) fluids decreases resistance with increasing strain rate.
- Bingham plastic – require a finite stress before flow (toothpaste)

Surface Tension

- Applies only to liquids
- Molecules near the surface are attracted to each other, so increasing the surface area requires a force
- The coefficent of surface tension, σ, is the force per length of surface tension (0.073 N/m, air-H_2O), or, equivalently the energy per area (J/m^2)
- Can also be thought of as the surface energy per unit area at the interface
- A pressure drop (force per area) is required to curve a surface: $\Delta p=2\sigma/R$ (sphere), $\Delta p=\sigma/(R_1+R_2)$ (general)

Vapor Pressure

- The pressure at which a liquid boils for a given temperature. (or the equilibrium pressure for a given temperature)
- One important aspect for fluid mechanics occurs when the ambient pressure falls below the vapor pressure – resulting in boiling or cavitation.
- Cavitation number: $Ca=2(p_a-p_v)/(\rho V^2)$.

Boundary Conditions

- When a fluid is in contact with a solid surface, molecular interactions cause the fluid in contact with the surface to seek momentum and energy equilibrium with that surface. Two consequences:
- $V_{fluid} = V_{wall}$ (typically zero) *NO SLIP
  - States there is a very thing layer of fluid molecules near the solid surface moving at the solid velocity.
- $T_{fluid}=T_{wall}$ *no temperature jump condition

Flow Analysis

- Flows must satisfy three basic laws of mechanics
  - Conservation of mass (very important)
  - Conservation of momentum (very important)
  - Conservation of energy (only important if temperature is changing)
- Constitutive relationships
  - Ideal gas law
  - Newton's law of viscosity
- Boundary conditions (hard to get).

Flow Visualization

- Streamline: line everywhere tangent to the velocity vector. (instantaneous)
- Pathline: the actual path traversed by a given fluid particle (temporal, one particle)
- Streakline: locus of particles that have earlier passed through a prescribed point. (temporal, many particles)
- Timeline: a set of fluid particles that form a line at a given instant. (instantaneous)
- First three identical in steady flow!

Experimental Flow Visualization

- Dye, smoke, or bubble discharges (most common)
- Neutral-density particles
- Luminescent fluids or bioluminescence
- Particle image velocimetry
- Doppler shift with a laser
- Ultrasound (echocardiography)

Computer Software

- Options
- Matlab
- Excel
- “Engineering Equation Solver”
- I'm reluctant to require everyone to use a specific option
- I'll likely use Excel (i.e., Open Office Calc)