

Course Introduction

Larry Caretto
Mechanical Engineering 390
Fluid Mechanics

January 22 and 24, 2008

Today's Class

- First class day items: roll, outline, etc.
- Class goals and learning objectives
- Assessment quiz
- Discussion of dimensions and units
 - Physical quantities have dimensions
 - Several units measure same dimension
 - Use SI system of units (meter, kilogram, ...
 - Also use engineering units (feet, pounds ...

Thursday Class

- Fluid properties
 - Density
 - Bulk modulus
 - Viscosity
 - Vapor pressure
 - Viscosity
 - Surface Tension
- Start discussion of fluid statics on using next set of notes

Basic Information

- Larry Caretto, Jacaranda (Engineering) 3333, lcaretto@csun.edu, 818.677.6448
- Office hours Monday and Wednesday, 4:30 to 5:15 pm; Tuesday and Thursday 2:45 to 3:45 pm; other times by email, phone, drop-in, or appointment
- <http://www.csun.edu/~lcaretto/me390>
- Munson, Young, and Okiisii, *Fundamentals of Fluid Mechanics* (fifth edition), Wiley, 2006.

Email

- Campus policy requires students to monitor their CSUN email addresses
 - These addresses will be used class email list me390-c@csun.edu
- Setup your CSUN email account if you have not done so already
- If desired, forward CSUN email to another address

Course Learning Objectives

- Understand the and be able to formulate and solve problems using basic fluid properties: density, specific weight, viscosity and mechanical quantities: pressure, velocity, force and stress
- solve problems to determine pressures in static fluids and manometers
- understand limits of and solve problems with Bernoulli equation

More Learning Objectives

- understand definition and be able to use concepts of system and control volume
- use continuity equation to use mass conservation in problem solving
- solve problems to determine forces in moving fluids using control volumes
- use dimensionless parameters and apply the concept of similitude for fluid mechanics experimentation

Still More Learning Objectives

- understand the differences between laminar and turbulent flows and be able to determine if a flow is laminar or turbulent based on the Reynolds number for the flow
- solve problems in laminar and turbulent flows in pipes
- be familiar with the basic ideas of boundary layers and irrotational flows outside these boundary layers

Learning Objectives Concluded

- solve problems of lift and drag in external flows
- understand the important variables used to solve problems in open channel and compressible flows
- solve problems in one of the following areas (a) compressible flows (b) open channel flows

Thermodynamics

- Often a prerequisite for fluids, but not presently a prerequisite at CSUN
- Students advised to complete ME 370 prior to taking ME 390
- Instead of a 370 review this course will use “just-in-time” Thermodynamics
- Cover specific topics as required for course in nature of review

Class Operation

- Tuesday: lecture on new material
 - Review text and notes before class
- Thursday: group problem solving
- Tuesday: 30-minute quiz at start of class followed by new material lecture
- Starts next week
 - Introduction during first week
- First quiz is on Tuesday, February 5

Quizzes

- Twelve during the semester
- Based on group work and homework
 - Homework assigned, but not collected or graded
 - Solutions available on line
- Count ten highest quiz grades for final
 - No makeup quizzes; final quiz grade based only on quizzes taken if fewer than ten
- First few quizzes closed book; remainder will be open book and equation sheet

Grading

- Quiz grades 45%
- Midterm (March 13) 22%
- Final (May 13) 33%
- Plus/minus grading will be used
- Grading criteria in course outline
- No make-up quizzes or exams

See the Course Outline

- Download from course web site
 - <http://www.csun.edu/~lcaretto/me390>
- Contains lecture schedule and homework assignments (homework also on web)
- Also read information on the following items
 - Class participation and courtesy
 - Collaboration versus plagiarism: students found cheating receive F grade in course
- Students are responsible for changes to outline announced in class



Galileo Galilei
(1564-1642)

You cannot
teach people
anything; you
can only help
them find it within
themselves.

<http://space.about.com/od/astronomyhistory/a/galileoquotes.htm>

Goals for this Course

- My goal is to help all students find within themselves sufficient knowledge of fluid mechanics so that they will all get an A grade in the course
- What is your goal for this course?
- What will you do to achieve that goal?

How to get your A

- Spend six to ten hours per week outside class studying for the course
- Prepare for lecture and be ready to ask questions
 - Read the assigned reading before class
 - Download, print, and review the lecture presentations before class
 - Use these as notes so that you can follow the lecture; write additional notes on these presentations

How to Get your A, Part II

- Study with fellow students and try to answer each other's questions
- Do the homework as well as you can before reviewing the on-line solutions
- Contact me by email, telephone or office visits to ask questions
- Develop a good working relation with other members of your self-study group

What I will do to help

- Arrive at class a few minutes early to answer any questions you may have
- Give lectures that stress application of basics to problem solving
- Return quizzes and exams promptly so that you can learn from your errors
- Be available for questions by email, office visits or phone calls
 - Send entire class emails as appropriate

Preliminary Assessment

- Designed to help instruction
- One set of questions on student background
- Second set of questions is ungraded quiz
- Take about 10 minutes for this assessment
- Hand yours in when finished
 - Will call time when most students are done

Dimensions and Units

- Any physical quantity has a unique dimension: e.g., mass, length, time, ...
- Several units may be available for any dimension
 - Length is measured in meters, feet, miles, fathoms, furlongs, yards, light-years, etc.
 - You cannot measure length in units with the dimension of mass

Systems of Units

- Arbitrary units for fundamental dimensions, e.g. mass (M), length (L), time (T), and temperature (Θ).
- Units for other physical quantities from the physical relations to quantities with fundamental units
 - Velocity dimensions are length/time, L/T
 - Acceleration dimensions are length/time²
 - Force dimension of (mass)(length)/(time)²

More Dimensions

- Pressure = force per unit area
 - = [force] / [length]²
 - = [(mass) (length) / (time)²] / (length)²
 - = (mass) / [(time)²(length)] or MT⁻²L⁻¹
- Common dimensions for energy terms are (mass)(length)²/(time)² or ML²T⁻²
 - Work = force times distance
 - = (force)(length)
 - = (mass)(length)²/(time)² or ML²T⁻²
 - Kinetic energy = mV²/2
 - = (mass)(velocity)²
 - = (mass)(length)²/(time)² or ML²T⁻²

Still More Dimensions

- Another energy term
 - Potential energy = mgh = (mass)(acceleration)(length) = (mass)(length)²/(time)²
- Power = (energy)/(time) = (mass) (length)² / (time)³ or ML²T⁻³
- Thermodynamic work is PdV
 - This is like Fdx where P = F/A and dV = Adx (A is area)
 - PdV dimensions are (length)³(force)/(area) which also is (mass)(length)²/(time)²

SI Units

- Basic definitions for fundamental units
 - Mass: kilogram (kg) = international prototype
 - Time: second (s) = time for 9 192 631 770 periods of radiation from Cs¹³³
 - Length: meter (m) = length light travels in 1/299 792 458 of a second
 - Temperature: kelvin (K) = 1/273.16 of the triple point of water
 - Current: ampere (A) defined in terms of electrostatic force

Other Units

- Light intensity and molar units
- Units for velocity and acceleration are m/s and m/s²
- Units for force are kg·m/s²
 - 1 newton (N) = 1 kg·m/s²
- Units for energy are kg(m/s)² = N·m
 - 1 joule (J) = 1 N·m = 1 kg·m²/s²

Still More Units

- Power: (energy)/(time) = joules/second
 - 1 watt (W) = 1 J/s = 1 N·m/s = 1 kg·m²/s³
- Pressure: (force)/(area) = newtons per square meter (1 atm = 101,325 Pa)
 - 1 pascal (Pa) = 1 N/m² = 1 kg/(m·s²)
- Note that Sir Isaac Newton has a capital N; 1 newton of force does not, unless it is abbreviated as 1 N (true for all units named after individuals)

Some Prefixes

pico, p	nano, n	micro, μ	milli, m
10 ⁻¹²	10 ⁻⁹	10 ⁻⁶	10 ⁻³
tera, t	giga, g	mega, M	kilo, k
10 ¹²	10 ⁹	10 ⁶	10 ³

Engineering Units

- Second is the basic unit of time
- The foot = 0.3048 m (exactly) is the basic unit of length
- Pound is confusing because it can be used to represent two dimensions
 - Mass: pound-mass (lb_m = 0.453592 kg)
 - Force: pound force (lb_f = 32.174 lb_m·ft/s²)
 - What is SI equivalent for pound force?

$$1 \text{ lb}_f = 4.4482 \text{ N}$$

Why Use a Pound Force?

- From the definition of a pound force, the weight, $W = mg$, of a pound mass in a standard gravitational field is 1 lb_f

$$W = mg = (m \text{ lb}_m) \frac{32.174 \text{ ft}}{\text{s}^2} \frac{\text{lb}_f \cdot \text{s}^2}{32.174 \text{ lb}_m \cdot \text{ft}} = m \text{ lb}_f$$

- This is convenient, but the same name for two dimensions is confusing and the conversion factor is awkward

Two Engineering Unit Systems

- English engineering units use mass as pound mass and force as pound force
 - $1 \text{ lb}_f = 32.174 \text{ lb}_m \cdot \text{ft}/\text{s}^2$
- British gravitational (BG) system uses slug as the mass unit
 - $1 \text{ lb}_f = 1 \text{ slug} \cdot \text{ft}/\text{s}^2$
- Which mass is larger, slug or lb_m ?
What is their conversion factor?
 $- 1 \text{ lb}_f \cdot \text{s}^2/\text{ft} = 32.174 \text{ lb}_m = 1 \text{ slug}$

More Engineering Units

- foot-pound is work (energy unit)
- British thermal unit ($\text{Btu} = 778.16 \text{ ft} \cdot \text{lb}_f$)
- Pressure in lb_f/in^2 (psi) – $1 \text{ atm} = 14.696 \text{ psi} = (144)(14.696) \text{ lb}_f/\text{ft}^2$ (psf)
- Horsepower as power unit
 - $1 \text{ hp} \cdot \text{hr} = 2,545 \text{ Btu} = 1.98 \times 10^6 \text{ ft} \cdot \text{lb}_f$
 - $1 \text{ kW} \cdot \text{hr} = 3,412 \text{ Btu}$
- The metric unit, calorie = $1/252 \text{ Btu}$
- The food Calorie is a kilocalorie

Calculating Units

- What is kinetic energy of a 100 lb_m mass moving at $10 \text{ ft}/\text{s}$
- $mV^2/2 = (100 \text{ lb}_m)(10 \text{ ft}/\text{s})^2 / 2 = 5000 \text{ lb}_m \cdot \text{ft}^2 \cdot \text{s}^{-2}$
- Unit conversion

$$KE = \frac{(100 \text{ lb}_m)}{2} \left(\frac{10 \text{ ft}}{\text{s}} \right)^2 \frac{\text{lb}_f \cdot \text{s}^2}{32.174 \text{ lb}_m \cdot \text{ft}} = 165.4 \text{ ft} \cdot \text{lb}_f$$
- Note algebraic cancellation of units

Calculating Units II

- What is kinetic energy of a 3 slug mass moving at $10 \text{ ft}/\text{s}$
- $mV^2/2 = (3 \text{ slugs})(10 \text{ ft}/\text{s})^2 / 2 = 15 \text{ slug} \cdot \text{ft}^2 \cdot \text{s}^{-2}$
- Unit conversion

$$KE = \frac{(3 \text{ slugs})}{2} \left(\frac{10 \text{ ft}}{\text{s}} \right)^2 \frac{\text{lb}_f \cdot \text{s}^2}{1 \text{ slug} \cdot \text{ft}} = 150 \text{ ft} \cdot \text{lb}_f$$
- Note algebraic cancellation of units
 - Especially simple if numeric value is one!

Units quiz

- What is the change in potential energy when a mass of 20 slugs is raised a distance of 15 ft ?
- Do you need more data to answer this question?
- What is g ? Use $5 \text{ ft}/\text{s}^2$ for this problem

$$PE = mgh = (20 \text{ slug}) \frac{5 \text{ ft}}{\text{s}^2} (15 \text{ ft}) \frac{\text{lb}_f \cdot \text{s}^2}{1 \text{ slug} \cdot \text{ft}} = 1500 \text{ ft} \cdot \text{lb}_f$$

Another Quiz

- Some European engineering calculations use the kilogram-force, defined in the same way as the pound force and measure pressure in kg_f/cm^2
- What exactly is the definition of a kg_f ?
- How many newtons are in a kg_f ?
- How many pascals are in a kg_f/cm^2 ?

Solutions to Another Quiz

- One kg_f is the force required to accelerate 1 kg at an acceleration of standard gravity, $g = 9.80665 \text{ m/s}^2$

$$1 \text{ kg}_f = 1 \text{ kg} \frac{9.80665 \text{ m} \cdot \text{s}^{-2}}{\text{s}^2} \frac{1 \text{ N} \cdot \text{s}^2}{\text{kg} \cdot \text{m}} = 9.80665 \text{ N}$$

$$1 \frac{\text{kg}_f}{\text{cm}^2} = 1 \frac{\text{kg}_f}{\text{cm}^2} \frac{9.80665 \text{ N}}{\text{kg}_f} \left(\frac{100 \text{ cm}}{\text{m}} \right)^2 \frac{\text{Pa} \cdot \text{m}^2}{1 \text{ N}} = 98066.5 \text{ Pa}$$

$$1 \frac{\text{kg}_f}{\text{cm}^2} \approx 10^5 \text{ Pa} \approx 1 \text{ atm}$$

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37

A Few Other Units

- Volume is sometimes measured in liters (or litres), L, where $1 \text{ L} = 1000 \text{ cm}^3 = 0.001 \text{ m}^3$
- Gallons, gal, is another volume measure; $7.4805 \text{ gal} = 1 \text{ ft}^3$
- Speed is sometimes measured in miles per hour, mph; $30 \text{ mph} = 44 \text{ ft/s}$ and $1 \text{ mph} = 0.44704 \text{ m/s}$
- 1 hogshead = 63 gallons

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38

Working With Units

- Carrying units in the calculation is a good approach for correct results
- If you do not want to do that, here are some hints for correct unit results
 - In the BG system convert all lengths to feet time to seconds, and pressures to lb_f/ft^2 (psf); $1 \text{ lb}_f = 1 \text{ slug} \cdot \text{ft}/\text{s}^2$
 - In the SI system always use m, Pa and N (instead of mm, cm, kPa, kN, etc.; $1 \text{ N} = 1 \text{ kg} \cdot \text{m}/\text{s}^2$)

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39

Temperature Units

- SI unit: absolute temperature in K
- Degrees Celsius, $^{\circ}\text{C} = \text{K} - 273.15$
- Degrees Fahrenheit, $^{\circ}\text{F} = 1.8(^{\circ}\text{C}) + 32$
- Rankine, $\text{R} = ^{\circ}\text{F} + 459.67$ is absolute temperature for Fahrenheit scale
- $\text{T}(\text{R}) = 1.8 \text{ T}(\text{K})$
 - What is a ΔT of 25°F in Rankine? **25 R**
 - What is 15°C in Rankine?
 - $15^{\circ}\text{C} = 288.15 \text{ K} = 59^{\circ}\text{F} = 518.67 \text{ R}$**

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40

Density and Related Properties

- Density**, ρ , is mass per unit volume ($\rho = 1/v$, where v is specific volume used more commonly in thermodynamics)
 - Units for density are (SI) kg/m^3 , (EE) lb_m/ft^3 , and (BG) slug/ft^3
- Specific weight**, $\gamma = \rho g$, typically tabulated at standard gravity, $g = 9.80665 \text{ m/s}^2 = 32.174 \text{ ft/s}^2$, in N/m^3 for SI and lb_f/ft^3 for both EE and BG

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41

Density and Related Properties II

- Specific gravity**, SG, of a substance:
 - ratio of the substance density to the density of a reference substance at a specified temperature
 - Reference substance is usually water for liquids and air for gases
 - Water reference temperature: 4°C (39.4°F) where $\rho_{\text{water}} = 1000 \text{ kg}/\text{m}^3 = 1.94 \text{ slugs}/\text{ft}^3$
- The specific gravity of mercury at 68°F is 13.56 (relative to water at 39.4°F). What is its density at this temperature?

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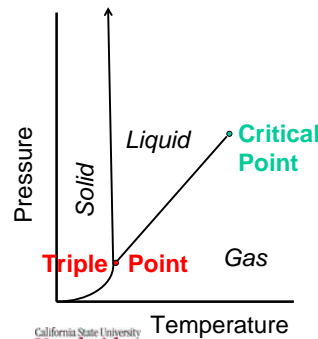
$\rho_{\text{Hg}} = 1.356 \times 10^4 \text{ kg}/\text{m}^3 = 26.3 \text{ slugs}/\text{ft}^3$

42

Density and Related Summary

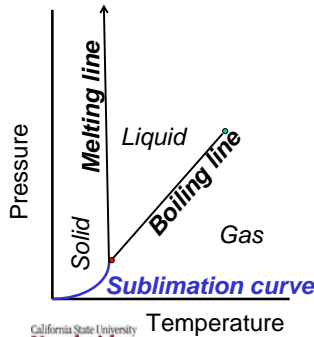
- **Density:** ρ = mass per unit volume with units of kg/m^3 or slugs/ft^3
- **Specific weight:** $\gamma = \rho g$ with units of N/m^3 or lb_f/ft^3 (varies with local g)
- **Specific gravity:** $\text{SG} = \rho/\rho_{\text{ref}} = \gamma/\gamma_{\text{ref}}$
 - Liquid ρ_{ref} : water at 4°C with $\rho = 1000 \text{ kg/m}^3$ and $\gamma = 9806.65 \text{ N/m}^3$ or water at 60°F with $\rho = 1.94 \text{ slugs/ft}^3$ and $\gamma = 62.4 \text{ lb}_f/\text{ft}^3$
 - Gas ρ_{ref} : air at 15°C (59°F) with $\rho = 1.23 \text{ kg/m}^3 = 0.00238 \text{ slugs/ft}^3$ and $\gamma = 62.4 \text{ lb}_f/\text{ft}^3$

States of Matter (Phases)



- **Triple point:** unique point for each substance where solid, liquid and vapor coexist
- No liquid-gas transition above critical point

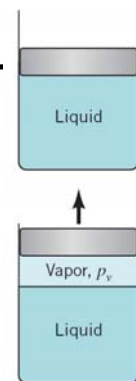
Transitions Between Phases



- For **phase transitions** pressure and temperature are related
- **Vapor pressure** is the pressure at which liquid-vapor transition occurs

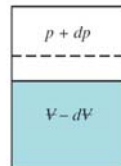
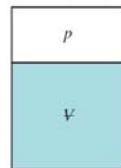
Vapor Pressure

- Pressure exerted by a liquid in equilibrium with a vapor
- Value depends on the nature of the liquid and temperature
- For water the vapor pressure at 100°C is 101.325 kPa
- Vapor pressure is pressure at which liquids change to gas at constant temperature



Volume Change

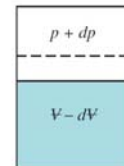
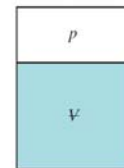
- Changing the pressure on a fluid can change its volume
 - The volume change can be done in different ways
 - In an isothermal process the temperature is constant
 - An isentropic (constant entropy) process is one in which no heat is added to the fluid and there is no friction; this ideal process is approached for short times



Compressibility

- Isothermal bulk modulus

$$E_T = -V \left(\frac{\partial P}{\partial V} \right)_T = \rho \left(\frac{\partial P}{\partial \rho} \right)_T$$
- Isentropic bulk modulus
 - No heat added to fluid
$$E_s = -V \left(\frac{\partial P}{\partial V} \right)_s = \rho \left(\frac{\partial P}{\partial \rho} \right)_s$$
- $E_T \approx E_s$ for liquids



Ideal Gases

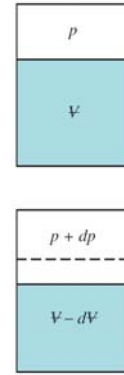
- From chemistry: $PV = nRT$ (V is volume)
 - $n = m / M$ is the number of moles
 - for mass in kg n is in kilogram moles (kmol); for mass in lb_m , n is in pound moles (lbmol)
 - $R = 8.31447 \text{ kJ/kmol}\cdot\text{K} = 10.7316 \text{ psia}\cdot\text{ft}^3 / \text{lbmol}\cdot\text{R}$ is universal gas constant
 - $R = R/M$ is engineering gas constant that is different for each gas
 - Real gases like ideal gases at low pressures
 - $P = nRT / V = (m/M)RT / V = (m/V)(R/M)T$
- $P = \rho RT$

Ideal Gases II

- Isothermal: $P = \rho RT$

$$E_T = \rho \left(\frac{\partial P}{\partial \rho} \right)_T = \rho \frac{1}{RT} = \rho \frac{P}{\rho} = P$$
- Isentropic: $P/\rho^k = C$

$$E_s = \rho \left(\frac{\partial P}{\partial \rho} \right)_s = \rho C k \rho^{k-1} = k C \rho^k = k P$$
- k is heat capacity ratio, a gas property, = 1.4 for air



Introduction to Viscosity

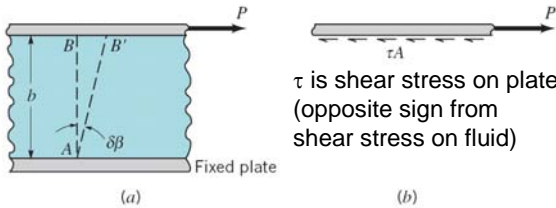


Figure 1.2 (p. 13)
 (a) Deformation of material placed between two parallel plates. (b) Forces acting on upper plate.

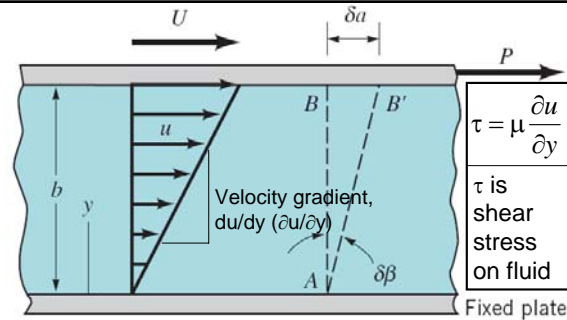
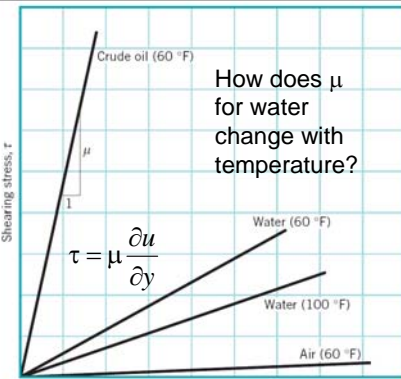


Figure 1.3 (p. 14)
 Behavior of a fluid placed between two parallel plates (top one moving, bottom stationary.)

Viscosity

Newtonian Fluids have a linear variation of shearing stress with rate of shearing strain – slope is viscosity

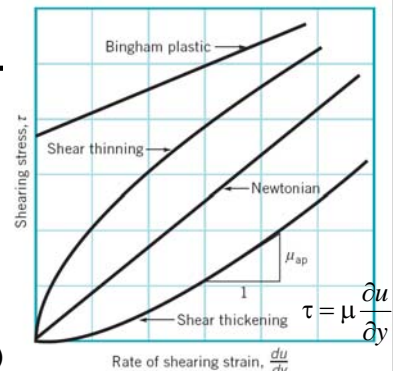
Figure 1.4 (p. 15)



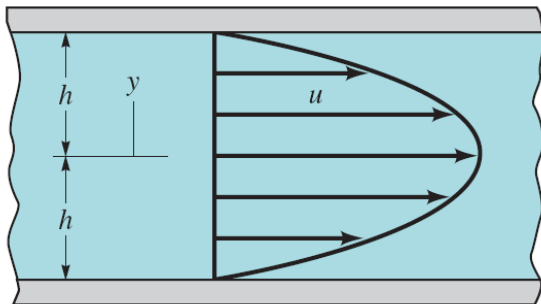
Viscosity II

Newtonian and non-Newtonian Variation of shear stress with rate of shearing strain for several types of fluids, including common non-Newtonian fluids.

Figure 1.5 (p. 16)



What is τ for Velocity Profile?



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Viscosity Dimensions

- What are viscosity dimensions? ($\tau = \mu \partial u / \partial y$)
- What are dimensions of other variables?
 - τ has dimensions of $FL^{-2} = (MLT^{-2})L^{-2} = ML^{-1}T^{-2}$
 - $\partial u / \partial y$ has dimensions of $(L/T) / L = T^{-1}$
 - μ has dimensions of $\tau / (\partial u / \partial y) = FL^{-2} / T^{-1}$
 - What are μ dimensions in terms of mass?
- Dimensions of μ are $FTL^{-2} = ML^{-1}T^{-1}$
 - SI units: $N \cdot s / m^2 = kg / m \cdot s$; BG units: $lb_f \cdot s / ft^2 = slug / ft \cdot s$

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Viscosity III

- Viscosity of gases increases with temperature
- Viscosity of liquids decreases with temperature

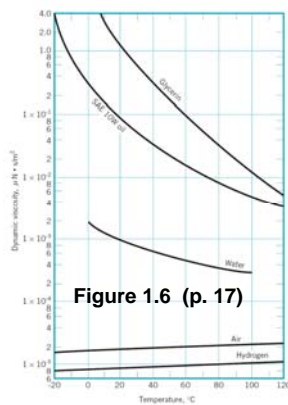


Figure 1.6 (p. 17)

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Surface Tension

- Forces generated at liquid-gas or liquid-liquid interfaces
- Surface tension, σ , a fluid property, with dimensions F/L

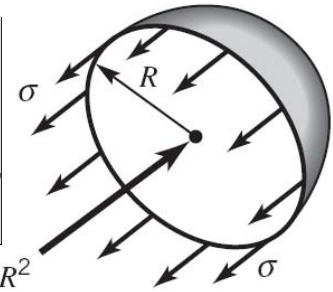


Figure 1.7
 Forces acting on one-half of a liquid drop.

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Surface Tension Effects

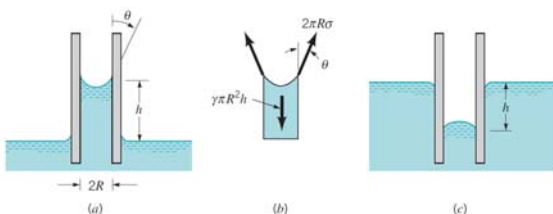
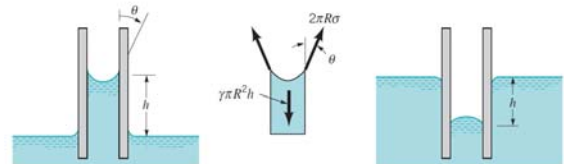


Figure 1.8 Capillary action in small tubes. (a) Rise of column for a liquid that wets the tube. (b) Free-body diagram for calculating column height. (c) Depression of column for a nonwetting liquid.

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Surface Tension Effects II



- Vertical force balance: $\gamma \pi R^2 h = 2 \pi R \sigma \cos \theta$
 - Surface tension depends on fluid and temperature, wetting angle, θ , depends on fluid and surface

$$h = \frac{2 \sigma \cos \theta}{\gamma R}$$

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Surface Tension Problem

- Find the capillary rise for water at 60°F ($\gamma = 62.4 \text{ lb}_f/\text{ft}^3$, $\sigma = 0.00503 \text{ lb}_f/\text{ft}$) in a circular tube with a diameter of 0.5 in?
 - For water in clean glass, $\theta = 0^\circ$

$$h = \frac{2\sigma \cos \theta}{\gamma R} = \frac{2 \frac{0.00503 \text{ lb}_f}{\text{ft}} (\cos 0) \frac{144 \text{ in}^2}{\text{ft}^2}}{\frac{62.4 \text{ lb}_f}{\text{ft}^3} \frac{0.5 \text{ in}}{2}} = 0.093 \text{ in}$$

Tube Diameter vs. Capillary Rise

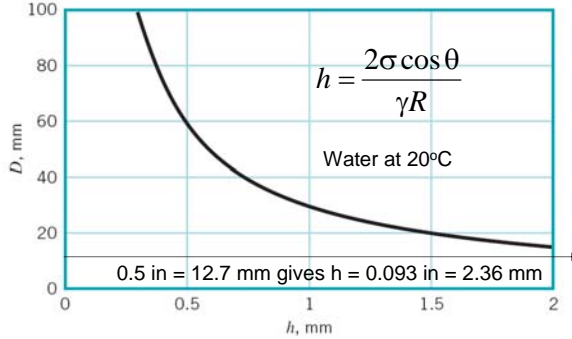


Figure E1.8, Fundamentals of Fluid Mechanics, 5/E by Bruce Munson, Donald Young, and Theodore Okishi, Copyright © 2005 by John Wiley & Sons, Inc. All rights reserved.

Typical Units

Quantity	SI units	EE units	BG units
Density	kg/m ³	lb _m /ft ³	slug/ft ³
Pressure & shear stress	kPa = kN/m ²	1 psi = 1 lb _f /in ² = 144 psf = 144 lb _f /ft ²	
Velocity	m/s	ft/s	
Viscosity	N·s/m ² = kg/m·s	lb _f ·s/ft ² = 32.2 lb _m /ft·s	lb _f ·s/ft ² = slug/ft·s
Specific weight = ρg	N/m ³	lb _f /ft ³	
	Tabulated values at standard gravity		