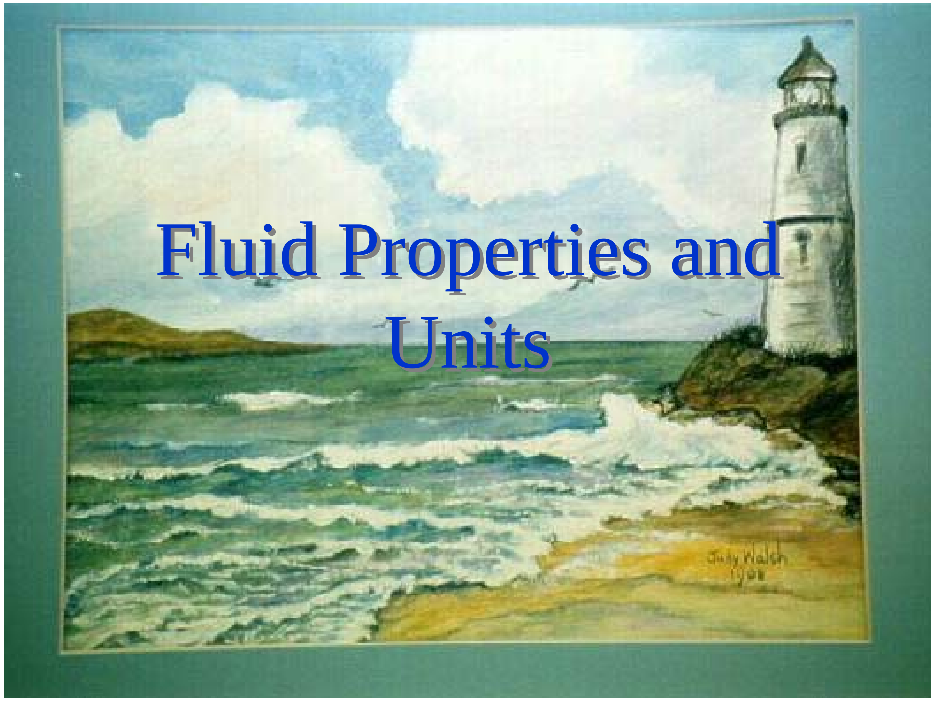
Fluid Properties and Units

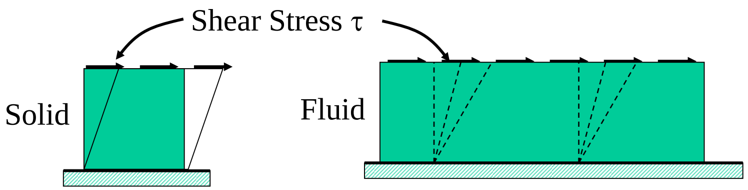


Fluid Mechanics

- Definition
  - The study of liquids and gasses at rest (statics) and in motion (dynamics)
- Engineering applications
  - Blood in capillaries
  - Oil in pipelines
  - Groundwater movement
  - Runoff in parking lots
  - Pumps, filters, rivers, etc.

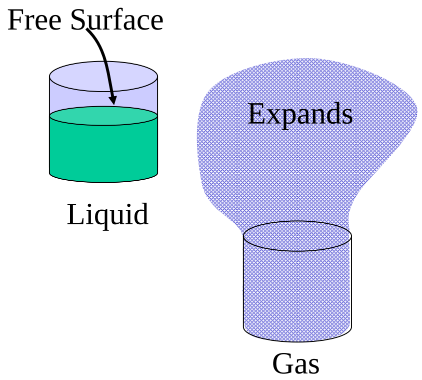
States of Matter

- Fluids (gasses and liquids) and solids
- What's the difference?
  - Fluid particles are free to move among themselves and give way (flow) under the slightest tangential (shear) force



Classes of Fluids

- Liquids and gasses – What's the difference?
  - **Liquids:** Close packed, strong cohesive forces, retains volume, has free surface
  - **Gasses:** Widely spaced, weak cohesive forces, free to expand



Common Fluids

- Liquids:
  - water, oil, mercury, gasoline, alcohol
- Gasses:
  - air, helium, hydrogen, steam
- Borderline:
  - jelly, asphalt, lead, toothpaste, paint, pitch

Primary Dimensions & Units

- **<u>Dimension:</u>** Generalization of "unit" telling us what kind of units are involved in a quantitative statement
  - Mass [M], length [L], time [T], temperature [θ]
- **<u>Unit:</u>** Particular dimension
  - **kg, m, s, ^oK (Systeme International)**
  - slug, ft, s, ^oR (British Gravitational)
  - lbm, ft, s, ^oR (English Engineering)

Secondary Units

$$\vec{F} = m\vec{a}$$

$$\left[\frac{ML}{T^2}\right] = [M]\left[\frac{L}{T^2}\right]$$

- Force

N	= kg-m/s^2	(Newton)
lbf	= slug-ft/s^2	(pound force)
	= 32.2 lbm-ft/s^2	

- Work/Energy (Force through a distance)

J	= N-m	(Joule)
ft-lbf		(foot pound)

- Power (Work per time)

W	= J/s	(Watt)
ft-lbf/s		(foot pound per sec)
hp	550 ft-lb/s	(horsepower)

Dimensions and Units

Quantity	Symbol	Dimensions
Velocity	V	LT^{-1}
Acceleration	a	LT^{-2}
Area	A	L^2
Volume	$\forall$	L^3
Discharge	Q	L^3T^{-1}
Pressure	p	$ML^{-1}T^{-2}$
Gravity	g	LT^{-2}
Temperature	T'	Θ
Mass concentration	C	ML^{-3}

Fluid as a Continuum

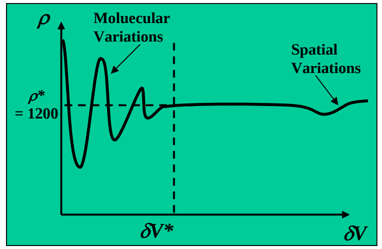
- Fluids are aggregates of molecules
  - Widely spaced: gasses
  - Closely spaced: liquids

- Intermolecular distance is large compared to molecular diameter
- Molecules move freely
- Air at STP (standard temperature and pressure):
  $\delta V^*=10^{-9}$ mm^3 and
  contains 3×10^7 molecules
- Continuum hypothesis

Fluid Properties

- Density: Mass per unit volume
  - How large is the volume?
    - Too small: # molecules changes continuously
    - Large: # molecules remains almost constant
  - At these scales, fluid properties (e.g., density) can be thought of as varying continuously in space.

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



Density

- Mass per unit volume (e.g., @ 20 ^{o}C, 1 atm)
  - Water ρ_{water} = 1000 kg/m^3
  - Mercury ρ_{Hg} = 13,500 kg/m^3
  - Air ρ_{air} = 1.22 kg/m^3
- Densities of gasses increase with pressure
- Densities of liquids are nearly constant (incompressible) for constant temperature
- Specific volume = 1/density

Specific Weight

$$\gamma = \rho g \qquad [N/m^3] \text{ or } [lbf/ft^3]$$

- Weight per unit volume (e.g., @ 20 ^{o}C, 1 atm)

γ_{water} = (998 kg/m^3)(9.807 m^2/s)
= 9790 N/m^3
[= 62.4 lbf/ft^3]

γ_{air} = (1.205 kg/m^3)(9.807 m^2/s)
= 11.8 N/m^3
[= 0.0752 lbf/ft^3]

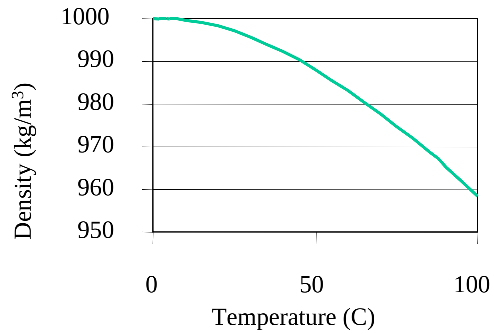
Specific Gravity

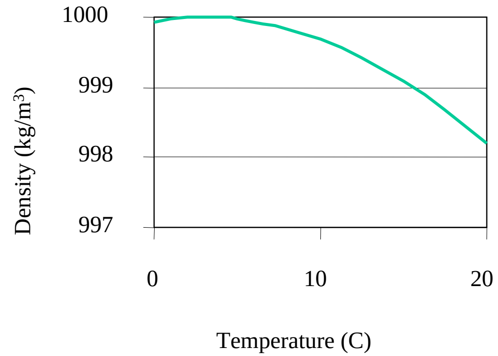
- Ratio of fluid density to density at STP
  (e.g., @ 20 °C, 1 atm)

$$SG_{liquid} = \frac{\rho_{liquid}}{\rho_{water}} = \frac{\rho_{liquid}}{9790\,kg/m^3}$$

$$SG_{gas} = \frac{\rho_{gas}}{\rho_{air}} = \frac{\rho_{gas}}{1.205\,kg/m^3}$$

  – Water $SG_{water} = 1$
  – Mercury $SG_{Hg} = 13.6$
  – Air $SG_{air} = 1$





APPROXIMATE PHYSICAL PROPERTIES OF COMMON LIQUIDS AT ATMOSPHERIC PRESSURE

Liquid and temperature	Density kg/m³ (slugs/ft³)	Specific gravity (S) water at 4°C is ref.	Specific weight, N/m³ (lbf/ft³)	Dynamic viscosity, N·s/m² (lbf-s/ft²)	Kinematic viscosity, m²/s (ft²/s)	Surface tension, N/m* (lbf/ft)
Ethyl alcohol[3][1]	799	0.79	7,850	1.2×10^{-3}	1.5×10^{-6}	2.2×10^{-2}
20°C (68°F)	(1.55)		(50.0)	(2.5×10^{-5})	(1.6×10^{-5})	(1.5×10^{-3})
Carbon tetrachloride[3]	1,590	1.59	15,600	9.6×10^{-4}	6.0×10^{-7}	2.6×10^{-2}
20°C (68°F)	(3.09)		(99.5)	(2.0×10^{-5})	(6.5×10^{-6})	(1.8×10^{-3})
Glycerine[3]	1,260	1.26	12,300	6.2×10^{-1}	5.1×10^{-4}	6.3×10^{-2}
20°C (68°F)	(2.45)		(78.5)	(1.3×10^{-2})	(5.3×10^{-3})	(4.3×10^{-3})
Kerosene[2][1]	814	0.81	8,010	1.9×10^{-3}	2.37×10^{-6}	2.9×10^{-2}
20°C (68°F)	(1.58)		(51)	(4×10^{-5})	(2.55×10^{-5})	(2.0×10^{-3})
Mercury[3][1]	13,550	13.55	133,000	1.5×10^{-3}	1.2×10^{-7}	4.8×10^{-1}
20°C (68°F)	(26.3)		(847)	(3.2×10^{-5})	(1.3×10^{-6})	(3.3×10^{-2})
Sea water 10°C	1,026	1.03	10,070	1.4×10^{-3}	1.4×10^{-6}	
at 3.3% salinity	(1.99)		(64.1)	(3×10^{-5})	(1.5×10^{-5})	
Oils—38°C (100°F)						
SAE 10W[4]	870	0.87	8,530	3.6×10^{-2}	4.1×10^{-5}	
	(1.69)		(54.4)	(7.4×10^{-4})	(4.4×10^{-4})	
SAE 10W-30[4]	880	0.88	8,630	6.7×10^{-2}	7.6×10^{-5}	
	(1.71)		(55.1)	(1.4×10^{-3})	(8.2×10^{-4})	
SAE 30[4]	880	0.88	8,630	1.0×10^{-1}	1.1×10^{-4}	
	(1.71)		(55.1)	(2.0×10^{-3})	(1.2×10^{-3})	

*Liquid–air surface tension values.

SOURCES: (1) V.L. Streeter, *Handbook of Fluid Dynamics*, McGraw-Hill Book Company, New York, 1961; (2) V.L. Streeter, *Fluid Mechanics*, 4th ed., McGraw-Hill Book Company, New York, 1966; (3) J. Vennard, *Elementary Fluid Mechanics*, 4th ed., John Wiley & Sons, Inc., New York, 1961; (4) R. E. Bolz and G. L. Tuve, *Handbook of Tables for Applied Engineering Sciences*, CRC Press, Inc., Cleveland, 1973.

Ideal Gas Law

- Equation of state

$$pV = nR_nT \qquad p = \rho RT, \quad R = R_n / M$$

R_n = universal gas constant= 8.314472 J/(mol•K)
n = number of moles of gas (m/M)
M = molecular weight of the gas

PHYSICAL PROPERTIES OF GASES AT STANDARD ATMOSPHERIC PRESSURE AND 15ºC (59ºF)

Gas	Density, kg/m^3 (slugs/ft^3)	Kinematic viscosity, m^2/s (ft^2/s)	R Gas constant, J/kg K (ft-lbf/slug-°R)	c_p $\frac{J}{kg\,K}$ $\left(\frac{Btu}{lbm\text{-}°R}\right)$	$k = \frac{c_p}{c_v}$	S Sutherland's Constant K (°R)
Air	1.22 (0.00237)	1.46×10^{-5} (1.58×10^{-4})	287 (1716)	1004 (0.240)	1.40	111 (199)
Carbon dioxide	1.85 (0.0036)	7.84×10^{-6} (8.48×10^{-5})	189 (1130)	841 (0.201)	1.30	222 (400)
Helium	0.169 (0.00033)	1.14×10^{-4} (1.22×10^{-3})	2077 (12,419)	5187 (1.24)	1.66	79.4 (143)
Hydrogen	0.0851 (0.00017)	1.01×10^{-4} (1.09×10^{-3})	4127 (24,677)	14,223 (3.40)	1.41	96.7 (174)
Methane (natural gas)	0.678 (0.0013)	1.59×10^{-5} (1.72×10^{-4})	518 (3098)	2208 (0.528)	1.31	198 (356)
Nitrogen	1.18 (0.0023)	1.45×10^{-5} (1.56×10^{-4})	297 (1776)	1041 (0.249)	1.40	107 (192)
Oxygen	1.35 (0.0026)	1.50×10^{-5} (1.61×10^{-4})	260 (1555)	916 (0.219)	1.40	

SOURCE: V. L. Streeter (ed.), *Handbook of Fluid Dynamics*, McGraw-Hill Book Company, New York, 1961; also R. E. Bolz and G. L. Tuve, *Handbook of Tables for Applied Engineering Science*, CRC Press, Inc. Cleveland, 1973; and *Handbook of Chemistry and Physics*, Chemical Rubber Company, 1951.

Example

- Given: Natural gas
  - Time 1: T_1=10ºC, p_1=100 kPa
  - Time 2: T_2=10ºC, p_2=200 kPa
- Find: Ratio of mass at time 2 to that at time 1
  - Ideal gas law (p is absolute pressure)

$$M = \rho V = \frac{p}{RT}V \qquad \frac{M_1}{M_2} = \frac{\frac{p_1}{RT}V}{\frac{p_2}{RT}V} = \frac{p_1}{p_2}$$

$$\boxed{\frac{M_2}{M_1} = \frac{300\,kPa}{200\,kPa} = 1.5}$$

Definition of a Fluid

- "a fluid, such as water or air, deforms continuously when acted on by shearing stresses of any magnitude."
  - *Munson, Young, Okiishi*

Fluid Deformation between Parallel Plates

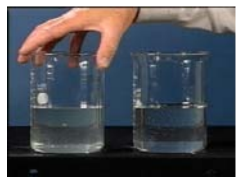
Side view

Force F causes the top plate to have velocity U. What other parameters control how much force is required to get a desired velocity?

Distance between plates (b)

Area of plates (A)

Viscosity!



Shear Stress

$F = \mu \frac{AU}{b}$

$\mu = \frac{Fb}{AU}$ dimension of $\left[\frac{\mathrm{N \cdot s}}{\mathrm{m^2}}\right]$

$\tau = \frac{F}{A}$

Tangential force per unit area $\left[\frac{\mathrm{N}}{\mathrm{m^2}}\right]$

$\tau = \mu \frac{U}{b}$

$\frac{U}{b}$ Rate of angular deformation $\left[\frac{1}{\mathrm{s}}\right]$

$\tau = \mu \frac{du}{dy}$

change in velocity with respect to distance

rate of shear