# Introduction

## Chapter 1

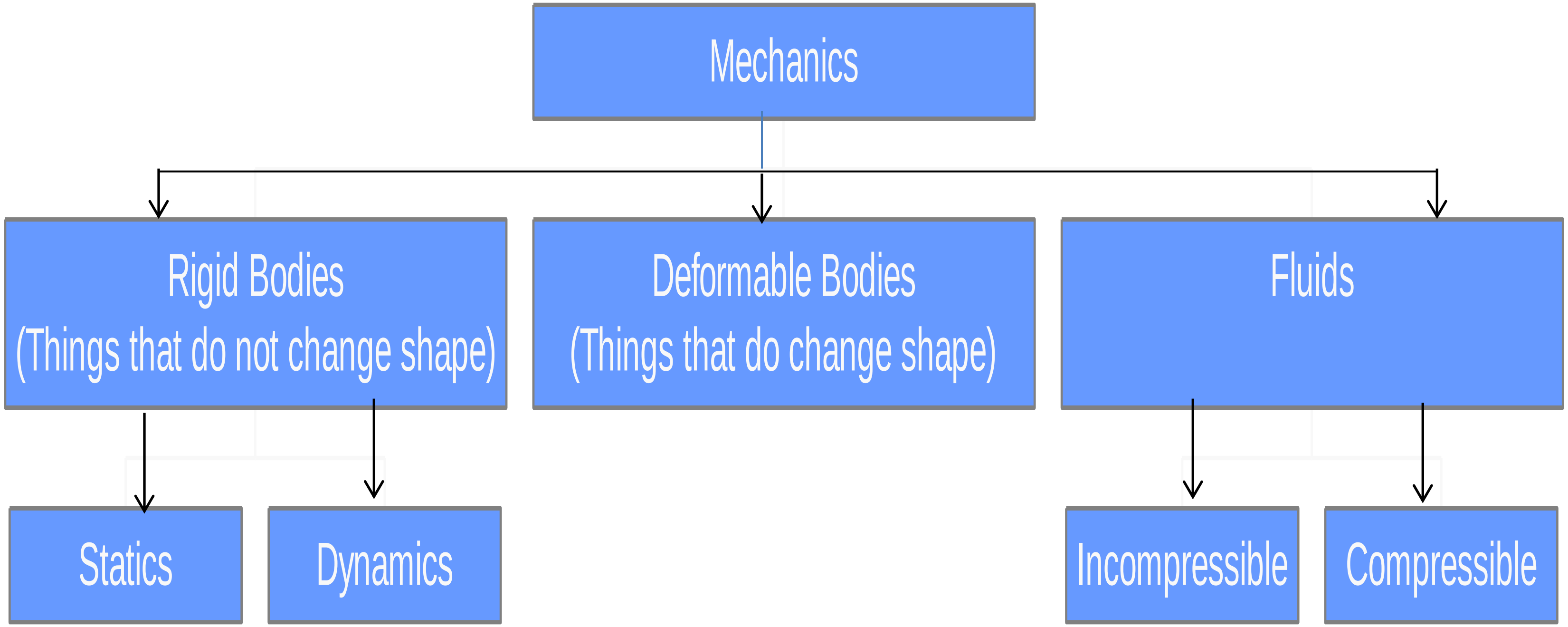
**Fluid Mechanics: Fundamentals and Applications, 4th edition**

Yunus A. Cengel, John M. Cimbala

Lecture slides by Mehmet Kanoglu

# 1. INTRODUCTION

## Branch of Mechanics



# Physical Characteristics of Fluids

- Fluid mechanics is the science that deals with the action of forces on fluids.

. Fluid is a substance

- The particles of which easily move and change position
- That will continuously deform

# Distinction Between Solids, Liquids & Gases

- A fluid can be either gas or liquid.
- Solid molecules are arranged in a specific lattice formation and their movement is restricted.
- Liquid molecules can move with respect to each other when a shearing force is applied.
- The spacing of the molecules of gases is much wider than that of either solids or liquids and it is also variable.

# Flow Classification

The subject of Fluid Mechanics

- Hydrodynamics deal with the flow of fluid with no density change (incompressible fluid), hydraulics, the study of fluid force on bodies immersed in flowing liquids or in low speed gas flows.

- Gas Dynamics deals with the flow of fluids that undergo significant density change (compressible fluid: PV=mRT: equation of states).

  P: pressure (Pa)

  V:volume (m3)

  m: mass (Kg)

  T: temperature (K) (K=C+273.15)

  Rair=287 J/Kg.K

# UNIT SYSTEMS

- We will work with two unit systems in FLUID MECHANICS:
  - International System (SI)
  - U.S. Customary (USCS) (used in the United States)

- SI UNITS

In the SI system, the unit of force, the Newton, is derived unit. The meter, second and kilogram are base units.

- U.S. CUSTOMORY

In the US Customary system, the unit of mass, the slug, is a derived unit. The foot, second and pound are base unit.

# Basic Unit System & Units

The SI system consists of **six** **primary** units, from which all quantities may be described but in fluid mechanics **we are generally** only interested in the top four units from this table.

| Quantity | SI Unit | Dimension |
|---|---|---|
| length | metre, m | L |
| mass | kilogram, kg | M |
| time | second, s | T |
| temperature | Kelvin, K | θ |
| current | ampere, *A* | I |
| luminosity | candela | Cd |

## Derived Units

There are many **derived** units all obtained from combination of the above **primary** units. Those most used are shown in the table below:

# Derived Units

| Quantity | SI Unit | | Dimension |
|---|---|---|---|
| velocity | m/s | $ms^{-1}$ | $LT^{-1}$ |
| acceleration | $m/s^2$ | $ms^{-2}$ | $LT^{-2}$ |
| force | N<br>$kg\ m/s^2$ | $kg\ ms^{-2}$ | $M\ LT^{-2}$ |
| energy (or work) | Joule J<br>N m,<br>$kg\ m^2/s^2$ | $kg\ m^2s^{-2}$ | $ML^2T^{-2}$ |
| power | Watt W<br>N m/s<br>$kg\ m^2/s^3$ | $Nms^{-1}$<br>$kg\ m^2s^{-3}$ | $ML^2T^{-3}$ |
| pressure ( or stress) | Pascal P,<br>$N/m^2$,<br>$kg/m/s^2$ | $Nm^{-2}$<br>$kg\ m^{-1}s^{-2}$ | $ML^{-1}T^{-2}$ |
| density | $kg/m^3$ | $kg\ m^{-3}$ | $ML^{-3}$ |
| specific weight | $N/m^3$<br>$kg/m^2/s^2$ | $kg\ m^{-2}s^{-2}$ | $ML^{-2}T^{-2}$ |
| relative density | a ratio<br>no units | | 1<br>no dimension |
| viscosity | $N\ s/m^2$<br>$kg/m\ s$ | $N\ sm^{-2}$<br>$kg\ m^{-1}s^{-1}$ | $M\ L^{-1}T^{-1}$ |
| surface tension | N/m<br>$kg\ /s^2$ | $Nm^{-1}$<br>$kg\ s^{-2}$ | $MT^{-2}$ |

| Secondary dimension | SI unit | BG unit | Conversion factor |
|---|---|---|---|
| Area $\{L^2\}$ | $m^2$ | $ft^2$ | $1\ m^2 = 10.764\ ft^2$ |
| Volume $\{L^3\}$ | $m^3$ | $ft^3$ | $1\ m^3 = 35.315\ ft^3$ |
| Velocity $\{LT^{-1}\}$ | m/s | ft/s | 1 ft/s = 0.3048 m/s |
| Acceleration $\{LT^{-2}\}$ | $m/s^2$ | $ft/s^2$ | $1\ ft/s^2 = 0.3048\ m/s^2$ |
| Pressure or stress $\{ML^{-1}T^{-2}\}$ | $Pa = N/m^2$ | $lbf/ft^2$ | $1\ lbf/ft^2 = 47.88\ Pa$ |
| Angular velocity $\{T^{-1}\}$ | $s^{-1}$ | $s^{-1}$ | $1\ s^{-1} = 1\ s^{-1}$ |
| Energy, heat, work $\{ML^2T^{-2}\}$ | J = N · m | ft · lbf | 1 ft · lbf = 1.3558 J |
| Power $\{ML^2T^{-3}\}$ | W = J/s | ft · lbf/s | 1 ft · lbf/s = 1.3558 W |
| Density $\{ML^{-3}\}$ | $kg/m^3$ | $slugs/ft^3$ | $1\ slug/ft^3 = 515.4\ kg/m^3$ |
| Viscosity $\{ML^{-1}T^{-1}\}$ | kg/(m · s) | slugs/(ft · s) | 1 slug/(ft · s) = 47.88 kg/(m · s) |
| Specific heat $\{L^2T^{-2}\Theta^{-1}\}$ | $m^2/(s^2 \cdot K)$ | $ft^2/(s^2 \cdot °R)$ | $1\ m^2/(s^2 \cdot K) = 5.980\ ft^2/(s^2 \cdot °R)$ |

# SI System of Units

- The corresponding unit of force derived from Newton's second law:

" the force required to accelerate a kilogram at one meter per second is defined as the *Newton* (N)"

The acceleration due to gravity at the earth's surface: 9.81 $m/s^2$.

Thus, the *weight of one kilogram* at the earth's surface:

$$
\begin{aligned}
W &= m\,g \\
&= (1)\,(9.81)\ kg\ m / s^2 \\
&= 9.81\ N
\end{aligned}
$$

# DIMENSIONAL HOMOGENEITY

- **All theoretically derived equations are *dimensionally homogeneous*: dimensions of the left side of the equation must be the same as those on the right side.**

  * ***Some empirical formulas used in engineering practice are not dimensionally homogeneous***

- **All equations must use consistent units: each term must have the same units. Answers will be incorrect if the units in the equation are not consistent. Always chose the system of units prior to solving the problem**

# 4. FLUID PROPERTIES

Every fluid has certain characteristics by which its physical conditions may be described.

We call such characteristics as the fluid properties.

- Specific Weight
- Mass Density
- Viscosity
- Vapor Pressure
- Surface tension
- Capillarity
- cp & cv, Specific heats
- *e*, Specific internal energy
- *h*, Specific enthalpy

Properties involving the Mass or Weight of the Fluid

## Mass Density (or density), ρ

The "mass per unit volume" is mass density. Hence it has units of kilograms per cubic meter.

- The mass density of water at 4 °C is 1000 kg/$m^3$ while it is 1.20 kg/$m^3$ for air at 20 °C at standard pressure.

### Specific Gravity, SG

- **The specific gravity is the ratio of density of a given fluid to the density of water at a standard reference temperature (4 °C). It is defined as *specific gravity*, SG.**
- **The specific gravity of mercury at 20 °C is**

$$SG = \frac{\rho}{\rho_{ref}} \quad Where\ \rho_{ref} = 1000\frac{kg}{m^3}; 1\frac{g}{cm^3}; 62.4\frac{lb_m}{ft^3}; 8.33\frac{lb_m}{gal}$$

# Specific Weight, $\gamma$

The gravitational force per unit volume of fluid, or simply "weight per unit volume":

$$\gamma = W/V = mg/V = \rho\, g$$

*where*

$\gamma$ = *specific weight* ($N/m^3$, $lb/ft^3$)

$\rho$ = *density* ($kg/m^3$, $slugs/ft^3$)

$g$ = *acceleration of gravity* ($9.81\ m/s^2$, $32.174\ ft/s^2$)

Specific volume, $v = 1/\rho$ (m3/kg)

## Example - Specific Weight Water

Specific weight for water at 4 $^oC$ is 62.4 $lb/ft^3$ (9.81 $kN/m^3$) in US units.

With a density of water *1000* $kg/m^3$ - specific weight in SI units can be calculated as

$\gamma = (1000\ kg/m^3)\ (9.81\ m/s^2)$

$= \underline{9810}\ (N/m^3)$

$= \underline{9.81}\ (kN/m^3)$

With a density of water *1.940* $slugs/ft^3$ - specific weight in US units can be calculated as

$\gamma = (1.940\ slugs/ft^3)\ (32.174\ ft/s^2)$

$= \underline{62.4}\ (lb/ft^3)$

# NEWTONIAN AND NON-NEWTONIAN FLUIDS

A fluid is defined as a material that can not support a **stress** or as a material that is continuously deformed by the application of a stress.

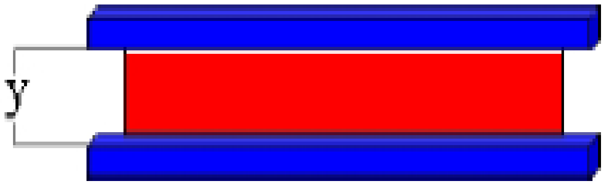



Figure 1.1: A fluid element before deformation.

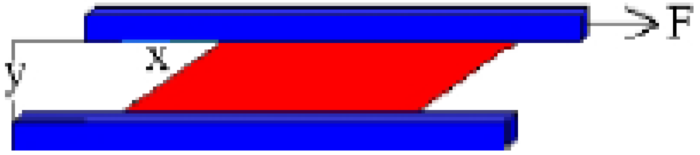



Figure 1.2: Fluid element after the application of a force acting tangentially on the top of the element.

# Viscosity

Newton first proposed that the shear stress could be related to the shear rate by

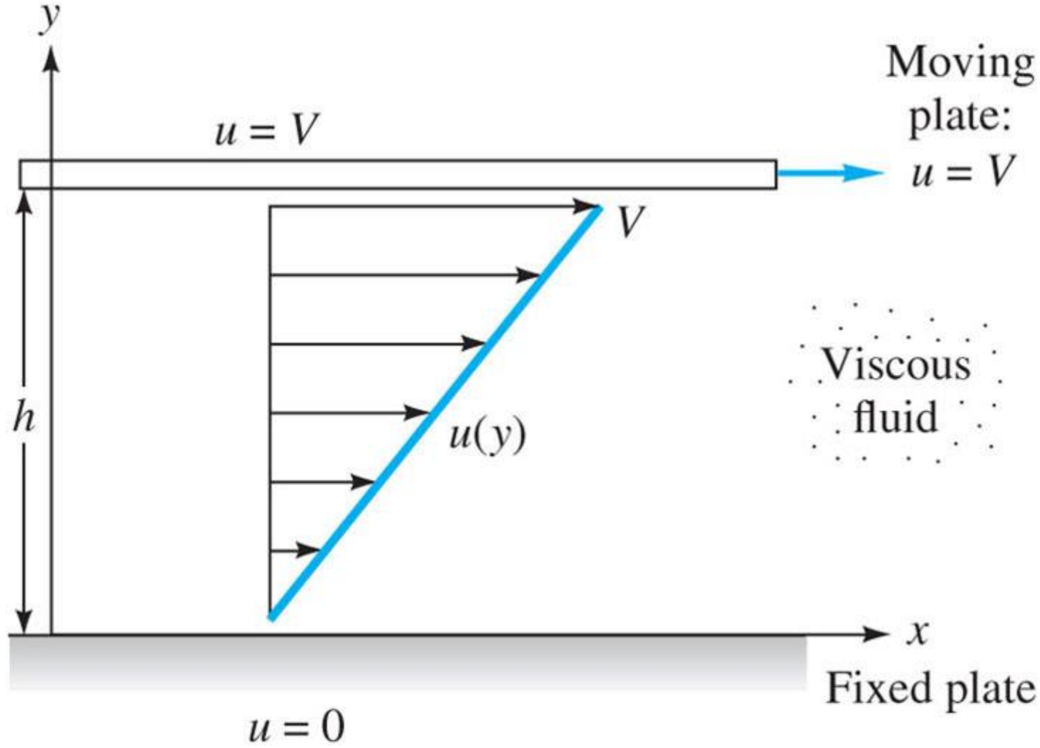
$$\tau = Constant\ \dot{\gamma} \cdot = \mu \frac{du}{dy}$$ **For Newtonian fluids**

The constant is termed the viscosity ($\mu$). It is a constant of proportionality between shear stress and shear rate. Viscosity is analogous to a modulus.

$$\tau = \mu\ \dot{\gamma} \implies \mu = \frac{\tau}{\dot{\gamma}} \quad Units: \frac{F \cdot t}{area}; \frac{dyne \cdot s}{cm^2}; \frac{N \cdot s}{m^2}\ or\ Pa \cdot s \qquad (1.7)$$

The unit ($\frac{dyne \cdot s}{cm^2}$) is called a $Poise$. It is more common to use $centipoise$ ($cp$) or $0.01 Poise$. Water has a viscosity of 1 $cp$ while honey has a viscosity of about 400 $cp$. It is easy to confuse $Poise$ and $centipoise$ when making calculations. Remember, a Poise is equal to $1, \frac{dyne \cdot s}{1 cm^2}$. A $Pa \cdot s$ is equal to 0.1 Poise. Viscosity can also be expressed in $\frac{lb_f \cdot s}{ft^2}$. The viscosity of water in the AES system of units is $2.1x10^{-5}\ \frac{lb_f \cdot s}{ft^2}$. Converting from $Poise$ to $\frac{lb_f \cdot s}{ft^2}$ is accomplished by multiplying $Poise$ by $1\ \frac{lb_f \cdot s}{ft^2} / 478.8\ Poise$. The equivalents for viscosity are

$$1\ \frac{lb_f \cdot s}{ft^2} = 47.88\ \frac{N \cdot s}{m^2} = 478.8\ Poise = 47880\ centipoise$$



y
u = V
Moving plate: u = V
V
h
u(y)
Viscous fluid
x
Fixed plate
u = 0

## EXAMPLE 1.7

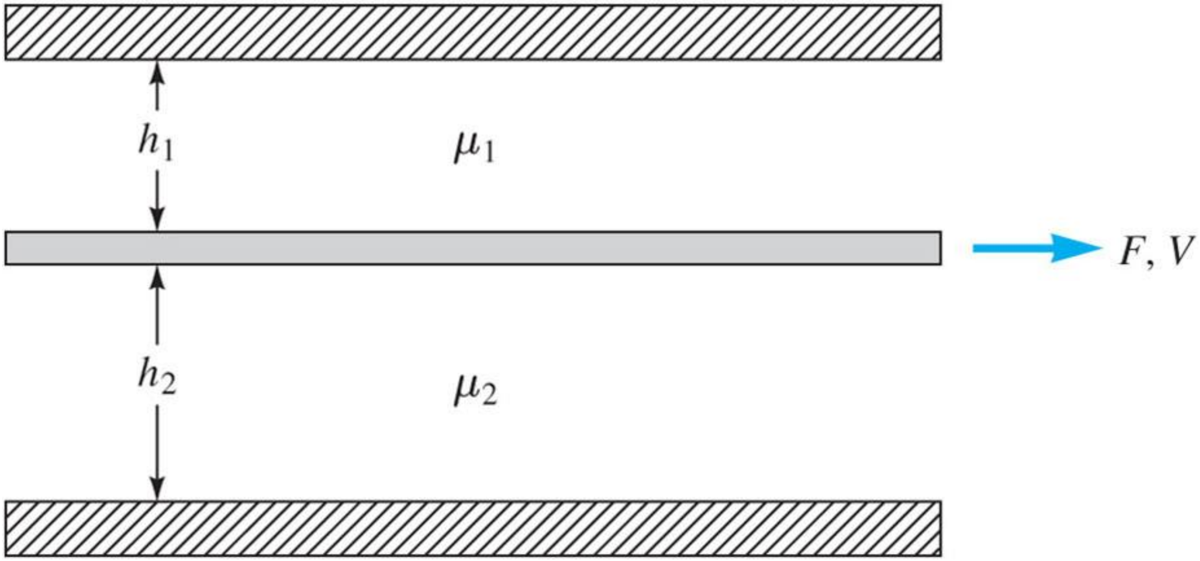
Suppose that the fluid being sheared in Fig. 1.7 is SAE 30 oil at 20°C. Compute the shear stress in the oil if $V = 3$ m/s and $h = 2$ cm.

## Solution

- *System sketch:* This is shown earlier in Fig. 1.7.
- *Assumptions:* Linear velocity profile, laminar newtonian fluid, no slip at either plate surface.
- *Approach:* The analysis of Fig. 1.7 leads to Eq. (1.26) for laminar flow.
- *Property values:* From Table 1.4 for SAE 30 oil, the oil viscosity $\mu = 0.29$ kg/(m-s).
- *Solution steps:* In Eq. (1.26), the only unknown is the fluid shear stress:

$$\tau = \mu \frac{V}{h} = \left(0.29 \frac{\text{kg}}{\text{m} \cdot \text{s}}\right) \frac{(3 \text{ m/s})}{(0.02 \text{ m})} = 43.5 \frac{\text{kg} \cdot \text{m/s}^2}{\text{m}^2} = 43.5 \frac{\text{N}}{\text{m}^2} \approx 44\text{Pa} \qquad \textit{Ans.}$$

- *Comments:* Note the unit identities, 1 kg-m/s$^2$ ≡ 1 N and 1 N/m$^2$ ≡ 1 Pa. Although oil is very viscous, this shear stress is modest, about 2400 times less than atmospheric pressure. Viscous stresses in gases and thin (watery) liquids are even smaller.


h1
μ1
F, V
h2
μ2

# Non-Newtonian Fluids

Fluids that exhibit a nonlinear relationship between stress and strain rate are termed non-Newtonian fluids. Many common fluids that we see everyday are non-Newtonian. Paint, peanut butter, and toothpaste are good examples. High viscosity does not always imply non-Newton behavior. Honey is viscous and Newtonian while a 5W30 motor oil is not very viscous, but it is non-Newtonian. There are several types of non-Newtonian fluids. Figure 1.3 shows several of the more common types.

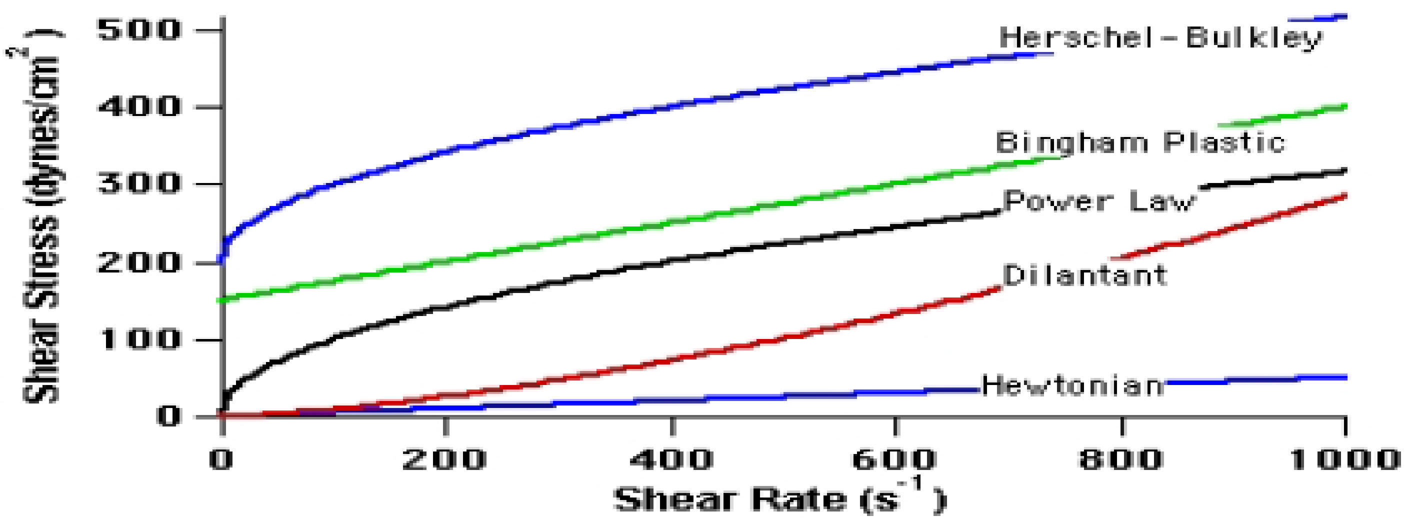



Figure 1.3: Types of non-Newtonian fluids.

## Power Law Fluids

Power law fluids are fluids that follow the power law (Equation 1.8) over part or all of the shear rate range. These fluids are also known as pseudoplastic fluids. Where $m$ is the consistency index ($K$ is also used in the literature) with units of $\frac{F \cdot s^n}{area}$ and $n$ is the power law or flow behavior index. For power law fluids, $n$ ranges from 0 to 1. While it is greater than one for dilatant fluids. The value of $m$ or $K$ depends upon the system of units. Viscosity of a power law fluid is obviously a function of shear rate and not constant as it is for Newtonian fluids. There are two different ways to describe the viscosity: the slope of the tangent line at any point on the curve and the slope of the line drawn from the origin to the shear rate of interest (Figure 1.4). The latter is the preferred method and is termed the apparent viscosity and given the symbol ($\eta_a$). This is short for the apparent Newtonian viscosity because it is the viscosity that a Newton fluid would have if the line is based on a single point measurement. Because the viscosity is a function of shear rate it is necessary to specify the shear rate at which the viscosity is reported ($\eta_a(\dot{\gamma})$).

$$\tau = m\dot{\gamma}^n \tag{1.8}$$

$$\eta_a(\dot{\gamma}) = \frac{\tau}{\dot{\gamma}} = \frac{m\,\dot{\gamma}^n}{\dot{\gamma}} = \frac{m}{\dot{\gamma}^{1-n}} \tag{1.9}$$

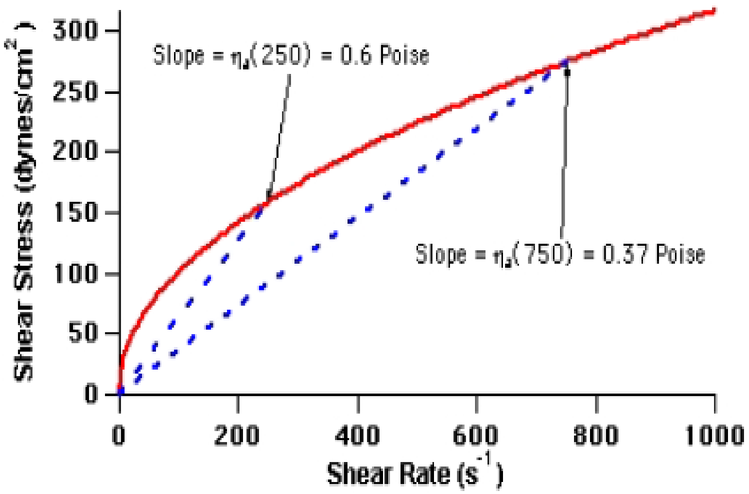



Figure 1.4: Apparent Newtonian viscosity.

## Bingham Plastic

Bingham plastic fluids are fluids that exhibit a yield stress (Figure 1.3. This means that the fluid will support a stress up to a point before flow begins. Good paints are Bingham plastics. The flow behavior of Bingham plastic fluids is described by

$$\tau = \tau_0 + \mu_p \, \dot{\gamma} \tag{1.10}$$

Where $\tau_0$ is the yield stress (the stress that must be exceeded before flow begins) and $\mu_p$ is the plastic viscosity.

## Herschel-Bulkley Fluids

The Herschel-Bulkley formulation is a generalization of the Bingham plastic equation. In the Bingham plastic model, the viscosity is constant after the yield stress is exceeded while the Herschel-Bulkley model allows for power law behavior.

$$\tau = \tau_0 + m\,\dot{\gamma}^n \qquad (1.11)$$

Looking at the various parameters in the Herschel-Bulkley equation, we can make the following observations for

$$\tau = \tau_0 + m\,\dot{\gamma}^n$$

when

$$\begin{aligned} \tau_0 = 0 &\implies \tau = m\dot{\gamma}^n && PowerLaw \\ \tau_0 = 0 \; and \; n = 1 &\implies \tau = \mu\,\dot{\gamma} && Newtonian \\ n = 1 &\implies \tau = \tau_0 + \mu_p\dot{\gamma} && BinghamPlastic \end{aligned}$$

The Herschel-Bulkley fluid model can be reduced to the three other models and is therefore the most general of the simple fluid models.

## Dilatant Fluids

Dilatant fluids are shear thickening fluids. This means that the viscosity increases with shear. There are few examples of dilatant fluids. Most dilatant fluids are concentrated slurries. The power law can be used to describe dilatant fluid behavior ($n > 1$).

# Kinematic Viscosity

m2/s

The kinematic viscosity, ($\nu$), is derived from gravity driven flow measurements. Usually a glass capillary viscomer is used. Kinematic viscosity can be derived from the shear viscosity ($\mu$) by dividing $\mu$ by the fluid density.

Pa.s

$$\nu = \frac{\mu}{\rho}$$ m2/s

Kg/m3

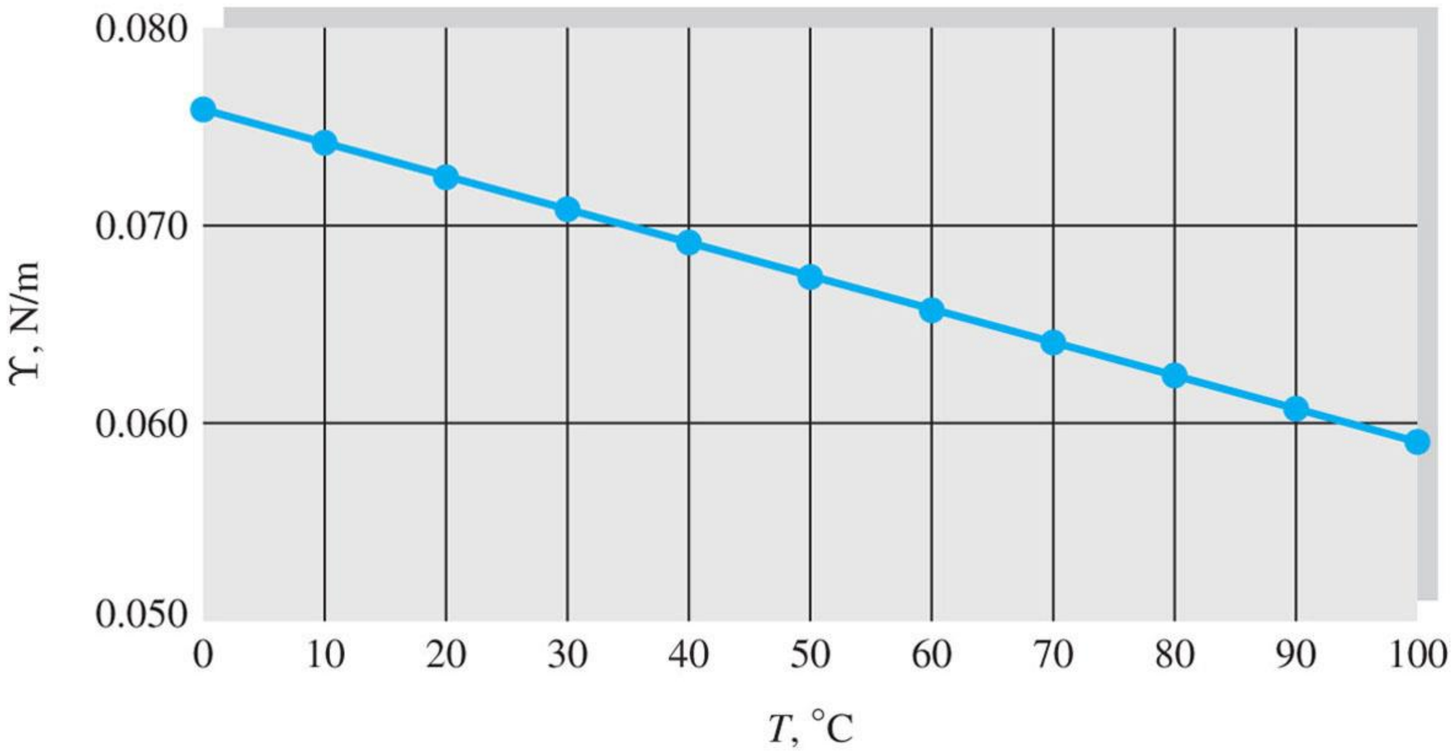
Units are $\frac{area}{time}(\frac{ft^2}{s}, \frac{cm^2}{s}, etc)$.

# Surface Tension

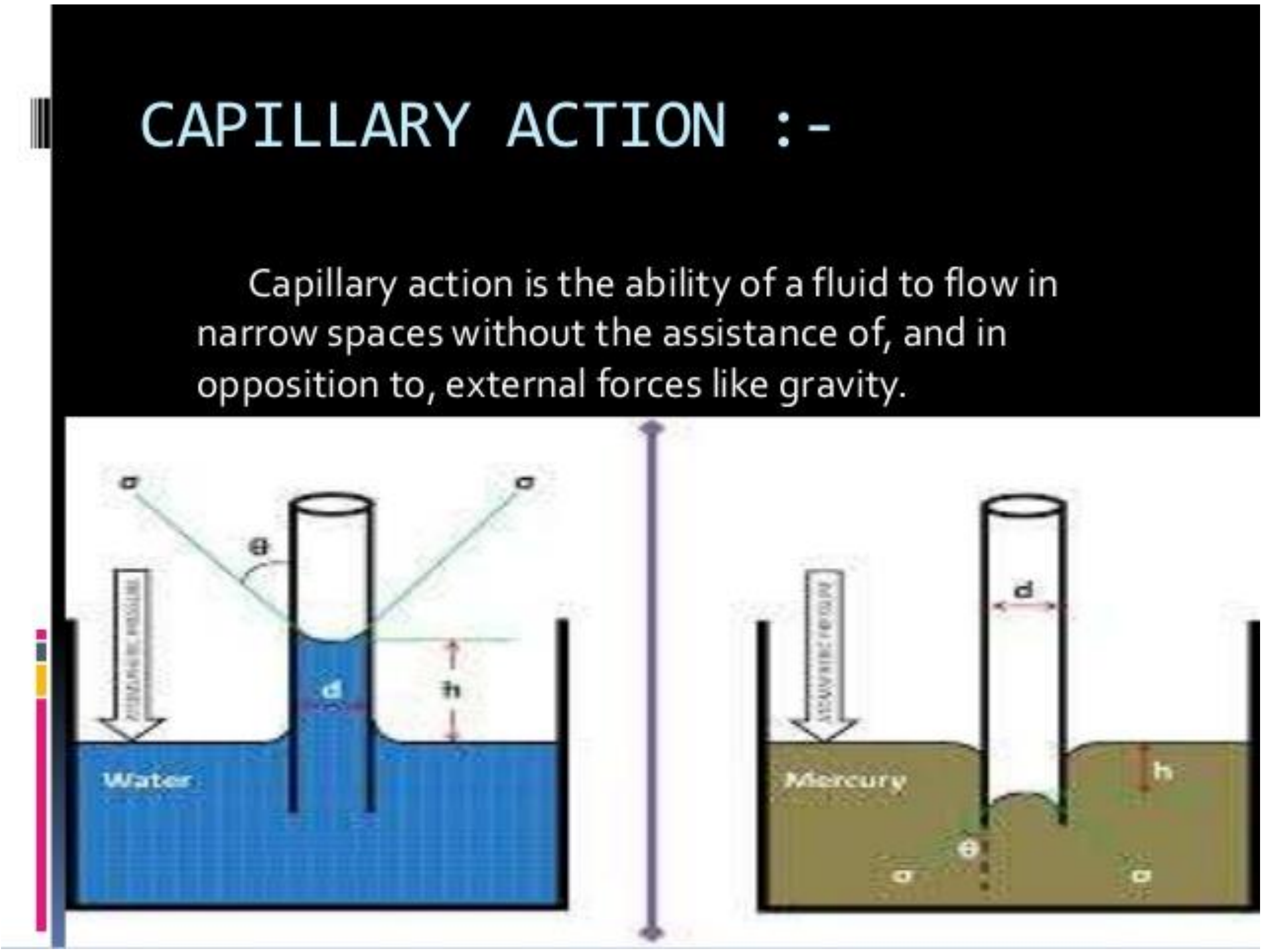
Surface tension, ($\sigma$), is a property of a liquid surface. It describes the strength of the surface interactions. The units on surface tension are $\frac{Force}{length}$. Surface tension is the driving force for water beading on a waxy surface and free droplets of liquid assuming a spherical shape. Lowering of surface tension can be accomplished by adding species that tend collect at the surface. This breaks up the interactions between the molecules of the liquid and reduces the strength of the surface. Pure water has a surface tension that approaches $72\frac{dyne}{cm}$. Surface tension can be reduced by adding surface active agents (surfactants) to the liquid.

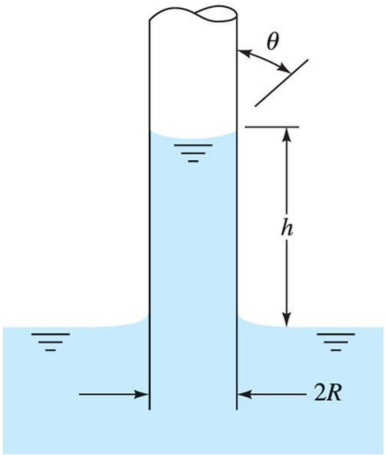
# SURFACE TENSION





# Capillary Action






**E1.8**

## EXAMPLE 1.8

Derive an expression for the change in height $h$ in a circular tube of a liquid with surface tension $\Upsilon$ and contact angle $\theta$, as in Fig. E1.8.

## Solution

The vertical component of the ring surface-tension force at the interface in the tube must balance the weight of the column of fluid of height $h$:

$$2\pi R\Upsilon \cos\theta = \gamma\pi R^2 h$$

Solving for $h$, we have the desired result:

$$h = \frac{2\Upsilon\cos\theta}{\gamma R} \qquad \textit{Ans.}$$

Thus the capillary height increases inversely with tube radius $R$ and is positive if $\theta < 90°$ (wetting liquid) and negative (capillary depression) if $\theta > 90°$.

Suppose that $R = 1$ mm. Then the capillary rise for a water–air–glass interface, $\theta \approx 0°$, $\Upsilon = 0.073$ N/m, and $\rho = 1000$ kg/m$^3$ is

$$h = \frac{2(0.073\ \text{N/m})(\cos 0°)}{(1000\ \text{kg/m}^3)(9.81\ \text{m/s}^2)(0.001\ \text{m})} = 0.015\ (\text{N}\cdot\text{s}^2)/\text{kg} = 0.015\ \text{m} = 1.5\ \text{cm}$$

For a mercury–air–glass interface, with $\theta = 130°$, $\Upsilon = 0.48$ N/m, and $\rho = 13{,}600$ kg/m$^3$, the capillary rise is

$$h = \frac{2(0.48)(\cos 130°)}{13{,}600(9.81)(0.001)} = -0.0046\ \text{m} = -0.46\ \text{cm}$$

When a small-diameter tube is used to make pressure measurements (Chap. 2), these capillary effects must be corrected for.

# VAPOR PRESSURE