ENVE 2061: BASIC FLUID MECHANICS

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Fall 2023

Introduction to Fluid Mechanics

- The movement of clouds in atmosphere
- The flight of birds through the air
- The flow of water in streams
- Breaking of waves at the seashore

Fluid mechanics phenomena are involved in all of these.

Introduction to Fluid Mechanics

Some of the many other aspects of our lives that involve the fluid mechanics;

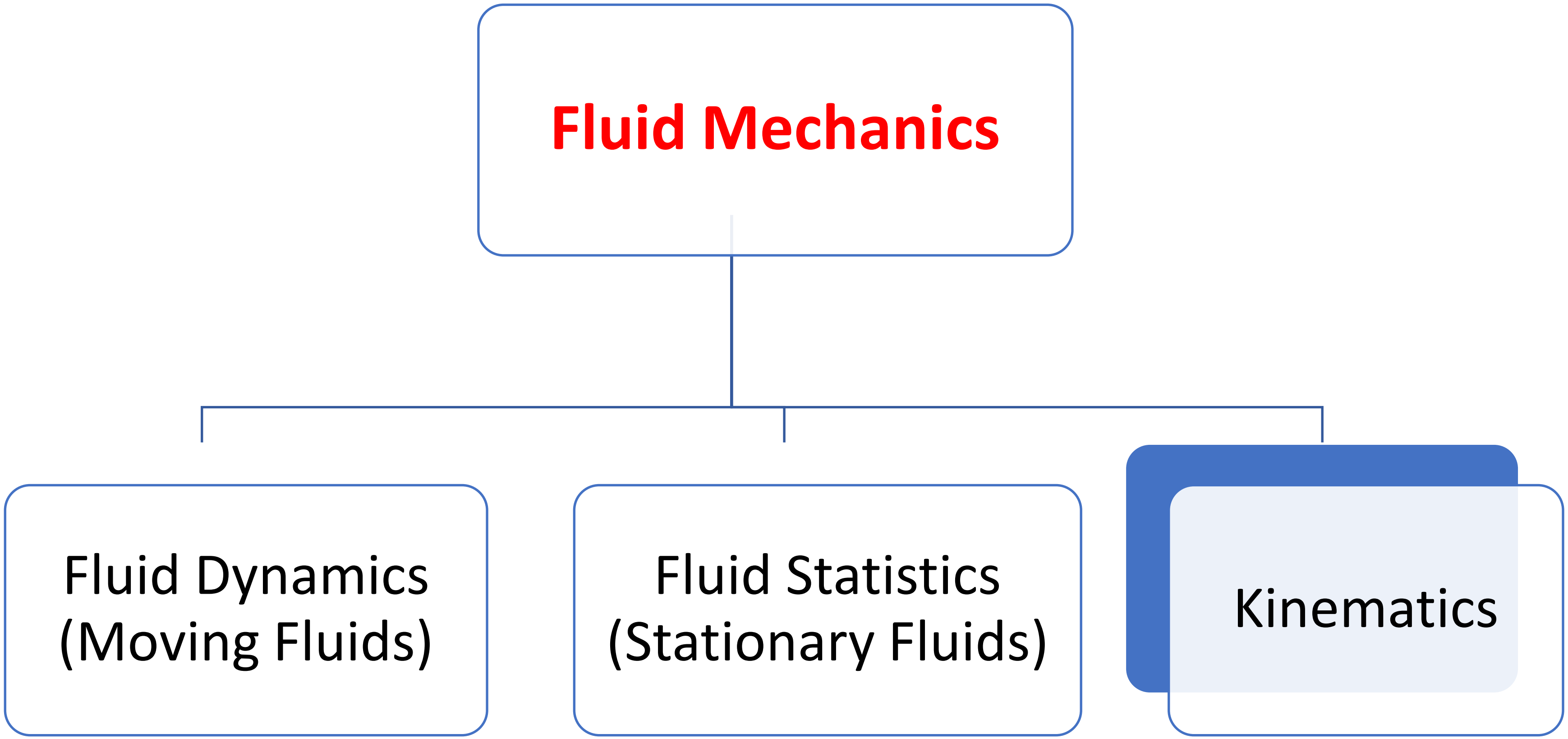
- Flow in pipelines and channels
- Movements of blood in the body
- Wind loading on buildings
- Motion of projectiles
- Combustion
- Irrigation
- Sedimentation
- Meteorology
- Oceanography
- Motion of moisture through soils and oil through geologic formations and other applications

Introduction to Fluid Mechanics

- Fluid Mechanics: It is the study of fluids and forces on them

- Fluids: liquids, gases and plasmas

you will be involved in the analysis and design of systems that require a good understanding of fluid mechanics.


Fluid Mechanics
Fluid Dynamics
(Moving Fluids)
Fluid Statistics
(Stationary Fluids)
Kinematics

PROPERTIES OF FLUID

What is fluid?

- ***a fluid*** is defined as a substance that deforms continuously when acted on by a shearing stress of any magnitude.

- ***a shearing stress*** (*force* per unit area) is created whenever a tangential force acts on a surface.

CHARACTERISTICS OF FLUID

What is fluid?

- When common ***solids*** such as steel or other metals are acted on by a ***shearing stress***, they will initially ***deform*** (usually a very small deformation), but they will not continuously deform (flow).

- However, common ***fluids*** such as water, oil, and air satisfy the definition of a fluid—that is, they will ***flow*** when acted on by a shearing stress.

DISTINCTION BETWEEN A SOLID AND FLUID

Solid	Liquid
• Molecules of solid are usually closer together than those of a fluid. • The attractive forces between the molecules of a solid are so large that a solids tends to retain its shape.	• Attractive forces between the molecules are smaller. • The intermolecular cohesive forces in a fluid are no great enough to hold the various elements of the fluid together.

DISTINCTION BETWEEN A GAS AND A LIQUID

Gas	Liquid
• Molecules of a gas are much farther apart than those of a liquid. • Gas is very compressible and when all external pressure is removed it tends to expand indefinitely. • In equilibrium only when it is completely enclosed. •	• A liquid is relatively incompressible • if all pressure, except that its own vapor pressure, is removed, the cohesion between molecules holds them together • Liquid does not expand indefinitely

Dimensions and Units

- it is necessary to develop a system for describing fluid characteristics both ***qualitatively*** *and* ***quantitatively***
- **Qualitative** ➔ identify the nature, or type, of the characteristics (such as length, time, stress, and velocity)
- ***Quantitative*** ➔ numerical measure of the characteristics.

Dimensions and Units

- The quantitative description requires both a **numbe**r and a **standard** by which various quantities (dimensions) can be compared.
  - for length might be a meter or foot
  - for time an hour or second
  - for mass a slug or kilogram.

- Such standards are called units, and several systems of units are in common use

- The qualitative description is conveniently given in terms of certain primary quantities,
  - such as length (L), time (T), mass (M) and temperature (θ)

Dimensions and Units

These primary quantities (dimensions) can then be used to provide a qualitative description of any other secondary quantity (dimension): for example,

$$area \doteq L^2 \qquad velocity \doteq LT^{-1} \qquad density \doteq ML^{-3}$$

$$(\doteq)$$

the symbol is used to indicate the dimensions of the secondary quantity in terms of the primary quantities.

to describe qualitatively a velocity,

$$V \doteq LT^{-1}$$

"the dimensions of a velocity equal length divided by time."

Dimensional Homogeneity

- All theoretically derived equations are dimensionally homogenous ;

- The dimensions of the left side must be the same as those on the right side and all the additive separate terms must have the same dimensions

$$V = Vo + at$$

$$LT^{-1} = LT^{-1} + LT^{-1}$$

$$d = 16.1t^2$$

Systems of Units

- The International Systems of Units (SI)
  - Length = meter (m)
  - Time = second (s)
  - Mass = kilogram (kg) or $N.s^2/m$
  - Force = newton (N) or $kg.m/s^2$

- The U.S. Customary System (English Gravitational Unit System or British Units)
  - Length = foot (ft)
  - Time =second (s)
  - Force = pound (Ib)
  - Mass =slug or $Ib\text{-}s^2/ft$

1 Ibm = 0.45 kg

1 ft =0.3048 m

Primary dimension	SI unit	BG unit	Conversion factor
Mass $\{M\}$	Kilogram (kg)	Slug	1 slug = 14.5939 kg
Length $\{L\}$	Meter (m)	Foot (ft)	1 ft = 0.3048 m
Time $\{T\}$	Second (s)	Second (s)	1 s = 1 s
Temperature $\{\Theta\}$	Kelvin (K)	Rankine (°R)	1 K = 1.8°R

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 $\{ML^2T^{-2}\}$	$J = N \cdot m$	$ft \cdot lbf$	$1\ ft \cdot lbf = 1.3558\ J$
Power $\{ML^2T^{-3}\}$	W = J/s	$ft \cdot lbf/s$	$1\ ft \cdot lbf/s = 1.3558\ W$
Density $\{ML^{-3}\}$	kg/m^3	$slugs/ft^3$	$1\ slug/ft^3 = 515.4\ kg/m^3$
Viscosity $\{ML^{-1}T^{-1}\}$	$kg/(m \cdot s)$	$slugs/(ft \cdot s)$	$1\ slug/(ft \cdot s) = 47.88\ kg/(m \cdot s)$
Specific heat $\{L^2T^{-2}\Theta^{-1}\}$	$m^2/(s^2 \cdot K)$	$ft^2/(s^2 \cdot °R)$	$1\ m^2/(s^2 \cdot K) = 5.980\ ft^2/(s^2 \cdot °R)$

Source:White, Fluid Mechanics, 4th Edition

Force (F)

- Force is usually considered as the primary dimension in English System

Force = (mass) (acceleration)

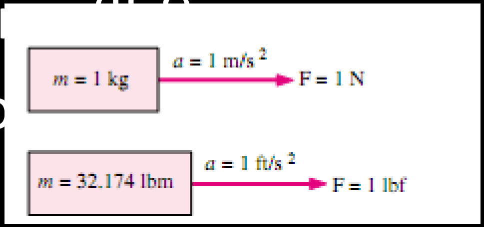
In SI system → Force unit is N

1 N = force required to accelerate a mass of 1 kg at a rates of 1 m/s^2.

In English System → Force unit is pound-for

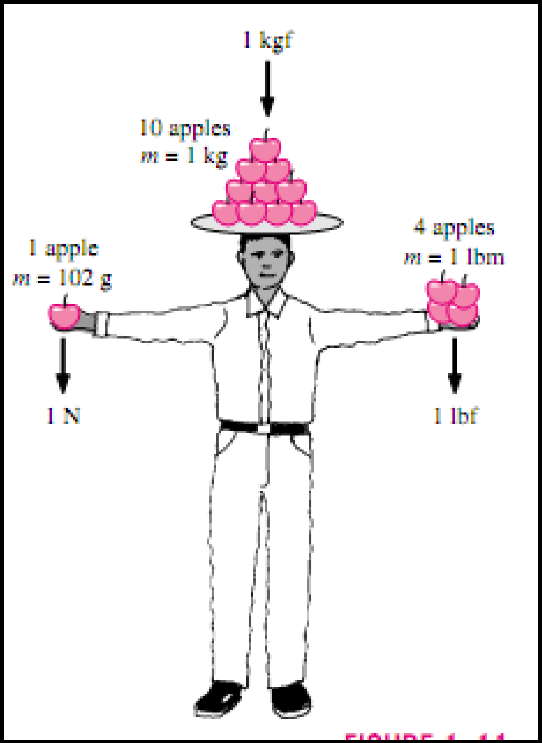
1 lb$_f$ = force required to accelerate a mass o

(1 slug) at a rate of 1 ft/s^2.



Source:Çengel & Turner, Fundamentals of Thermal-Fluid Sciences

Relative Magnitudes of the Force Units



- 1 N = weight of 102 g
- 1 lbf = weight of 454 g
- 1 kgf= weight of 1 kg = 9.807 N

Source:Çengel & Turner, Fundamentals of Thermal-Fluid Sciences

Weight versus Mass

- Mass : Measure of the amount of material in an object.
- does not change with the body's position, movement or alteration of its shape unless material is added or removed.

- Weight: Gravitational force acting on a body mass

$$W = m.g$$

W ↓ N

m ↓ kg

g → 9.807 m/s2 in SI system
32.174 ft/s2 in US Customary at sea level and 45 latitude

Work

- Work is a form of energy and simply defined as force times distance

$$W = \text{Force (N)} \times \text{Distance (m)}$$

$$1 \text{ Joule} = 1 \text{ N.m}$$

- In SI system ➔ kilojoules (1 kJ=1000 J)
- In English System ➔ Btu (British Thermal Unit)

  - Btu: The energy required to raise the temperature of 1 Ibm of water at 68 ^oF by 1^oF.

- 1 calorie : the energy required to raise the temperature of 1 g of water at 15^oC by 1 ^oC

$$1 \text{ cal} = 4.1868 \text{ J}$$

$$1 \text{ Btu} = 1.055 \text{ kJ}$$

PRESSURE

- Pressure is defined as the amount of force exerted on a unit area of a substance

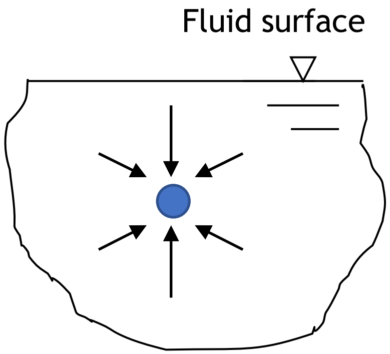
$$\text{Pressure} = \frac{Force}{Area\ of\ which\ the\ force\ is\ applied}$$

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

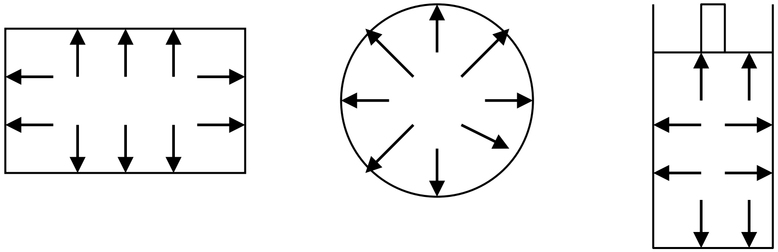
Unit: N / m^2 or Pascal (Pa).

(Also frequently used is bar, where 1 bar = 10^5 Pa).

- *Two important principles about pressure;*
  - Pressure acts uniformly in all directions on a small volume of a fluid.

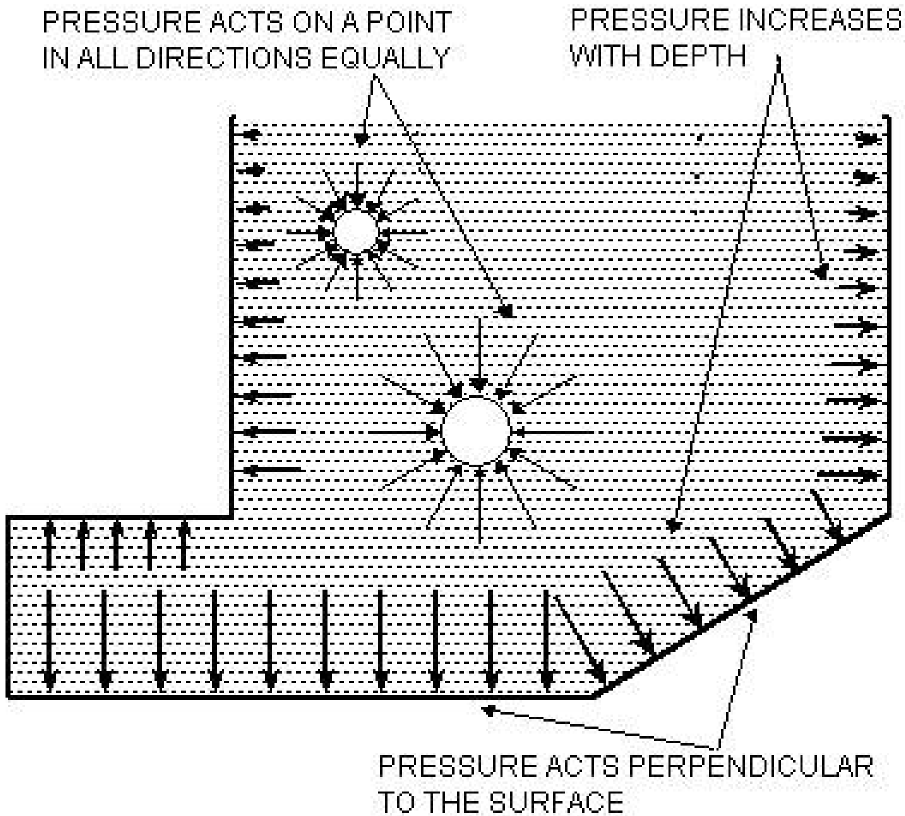


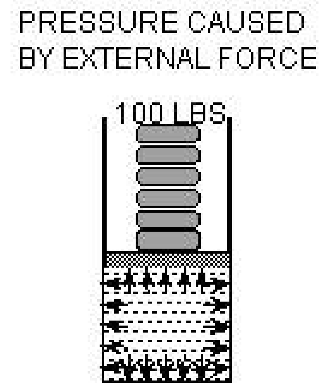
  - In a fluid confined by solid boundaries, pressure acts perpendicular to the boundary.



  - These principles called Pascal’s principles

PRESSURE CONCEPTS:





IN A STATIC FLUID PRESSURE IS THE SAME
AT ALL LOCATIONS WITH THE SAME DEPTH

COMPRESSIBILITY

- Compressibility: change of volume (V) of a substance that is subjected to a change in pressure on it.
- Quantity used to measure bulk ***modulus of elasticity*** or, simply, ***bulk modulus***, E.

$$E = \frac{-\Delta P}{(\Delta V)/V}$$

- The units are same as those for the pressure.

COMPRESSIBILITY

- Liquids are very slightly compressible
- It would take a very large change in pressure to produce a small change in volume.

Bulk modulus for selected liquids at atmospheric pressure and 20^0C.

Liquid	Bulk Modulus (psi)	Bulk Modulus (MPa)
Ethyl alcohol	130 000	896
Benzene	154 000	1 062
Machine oil	189 000	1 303
Water	316 000	2 179
Glycerine	654 000	4 509
Mercury	3 590 000	24 750

Liquids will be considered as **incompressible**

Density, specific weight and specific gravity

- **Density:** Amount of mass per unit volume of substance

- Symbol: ρ

$$\rho = \frac{m}{V} = \frac{mass}{volume}$$

- Units: $\frac{kg}{m^3}$ in SI system

  : $\frac{slugs}{ft^3}$ in U.S. customary units.

Density, specific weight and specific gravity

- Specific weight: The amount of weight per unit volume of a substance.

- Symbol: γ

$$\gamma = \frac{w}{V} = \frac{weight}{volume} = \frac{W}{\forall} = \frac{m.g}{\forall} = \rho.g$$

- Units: $\frac{N}{m^3}$ in SI system

  : $\frac{Ib_f}{ft^3}$ in U.S. customary units.

- γ_{water} = 9.80 $\frac{N}{m^3}$ $(15.5^0$ C), 62.4 $\frac{Ib_f}{ft^3}$ $(60^0$ F),

Density, specific weight and specific gravity

- **Specific gravity:** Ratio of the density of a substance to the density of water at 4^0C.

- Ratio of the specific weight of a substance to the specific weight of the water at 4^0C.

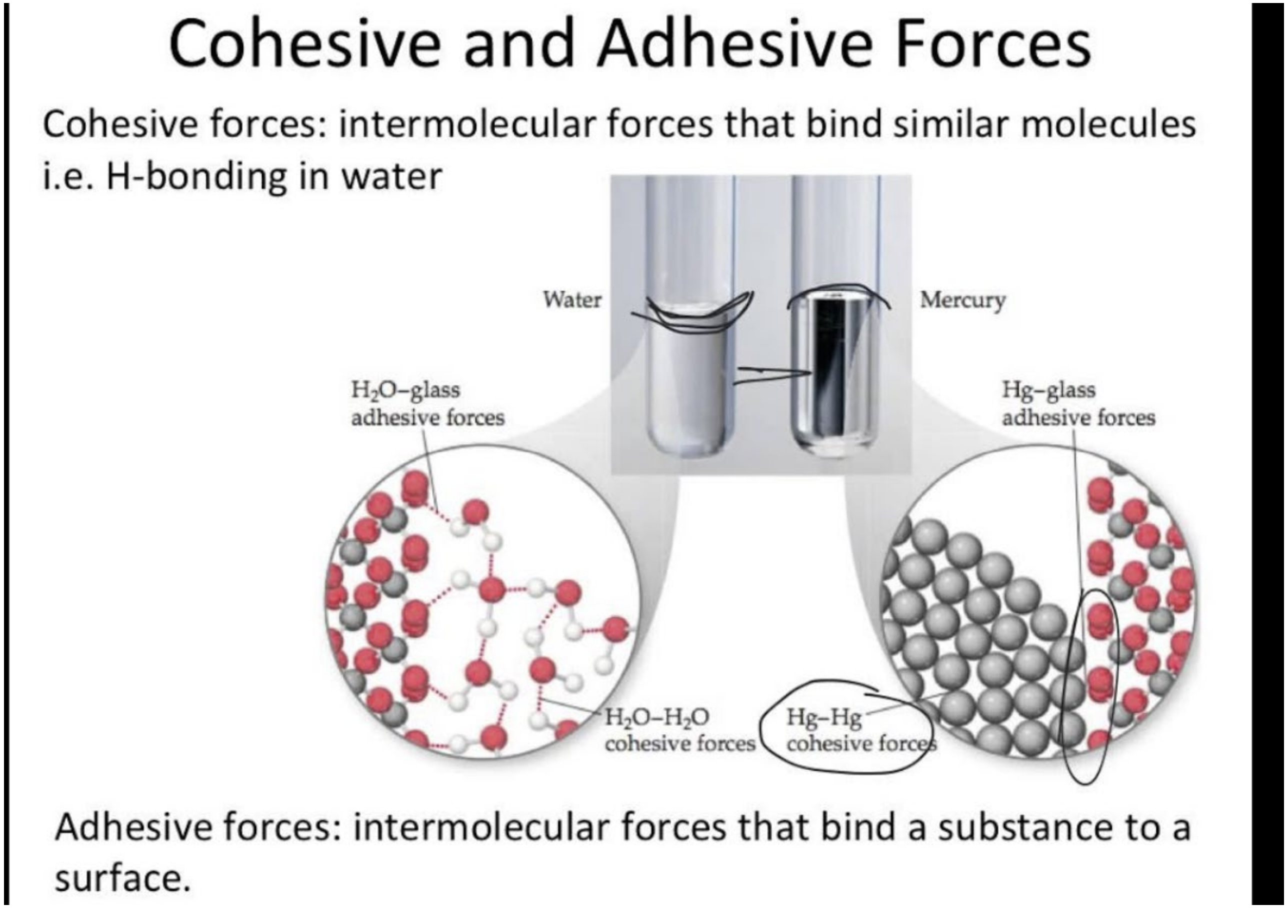
$$sg = \frac{\gamma s}{\gamma w @ 4^o C} = \frac{\rho s}{\rho w @ 4^o C}$$

$\rho H_2O \ at \ 4^o C = 998 \text{ kg/m}^3 \cong 1000 \text{ kg/m}^3$ is taken for practical purposes

$\rho H_2O \ at \ 4^o C = 1.94 \text{ slugs/ft}^3$

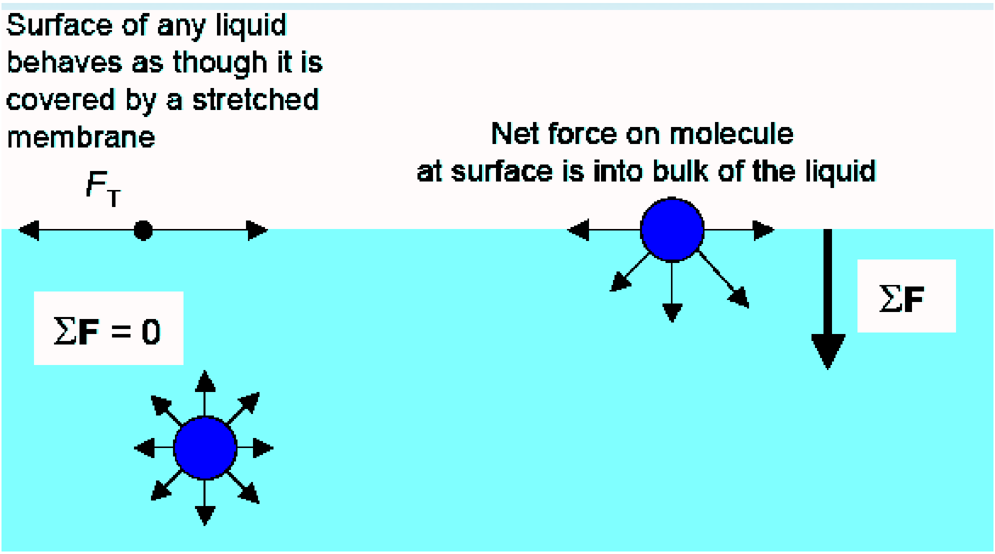
SURFACE TENSION

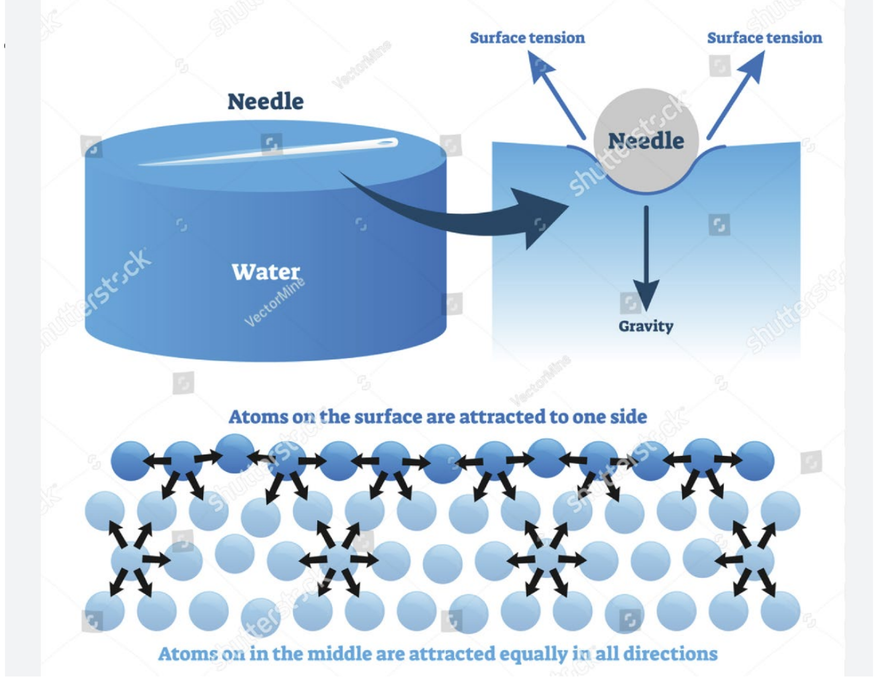
- Liquids have cohesion and adhesion, both of which are forms of molecular attraction. **Cohesion** enables a liquid to resist tensile stress. **Adhesion** enables it to adhere to another body.



SURFACE TENSION

- At the interface between a liquid and a gas, or between two immiscible liquids, forces develop in the liquid surface.
- This force cause the surface to behave as if it were a «skin» or «membrane» stretched over the fluid mass.
- Molecules along the surface may experience a net force toward the interior. The physical consequence of this unbalanced force along the surface is to create the hypothetical skin or membrane.





Even at a small distance below the surface of a liquid body, liquid molecules are attracted to each other by equal forces in all directions

The molecules on the surface, however, are not able to bond in all directions and therefore form stronger bonds with adjacent liquid molecules.

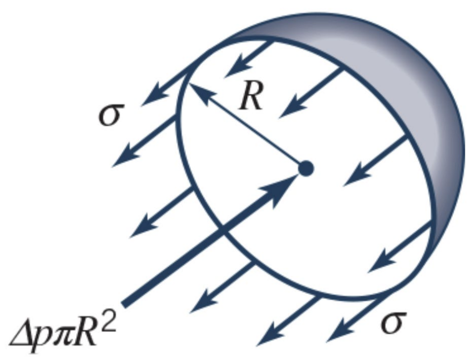
SURFACE TENSION

- Tensile force may be considered to be acting on the plane of the surface along any line in the surface.

$$\text{Tensile Force}= \frac{Intensity\ of\ molecular\ attraction}{Length}$$

$$\text{Tensile Force}= \frac{Force}{Length}\ \ \frac{N}{m}\, in\ SI\ units\, \frac{Ib}{ft}\, in\ BG\ units$$

Symbol =σ (sigma)



Force develop around the edge= Perimeter x σ = 2πR σ

Force developed with the internal and external pressure difference, DP, over the circular area, πR^2

$$2\pi R\sigma = \Delta p\ \pi R^2$$

$$\Delta p = p_i - p_e = \frac{2\sigma}{R}$$

Forces acting on one-half of a liquid drop.

Capillarity

- Common phenomena associated with surface tension is the rise (or fall) of a liquid in a capillary tube
- It is the property of exerting forces on fluids by fine tubes or porous media
- It is due to both cohesion and adhesion
- Cohesion < Adhesion ➔ The liquid will wet a solid surface with which it is in contact and rise at the point of contact
- Cohesion>Adhesion ➔ The liquid surface will be depressed at the point of contact.

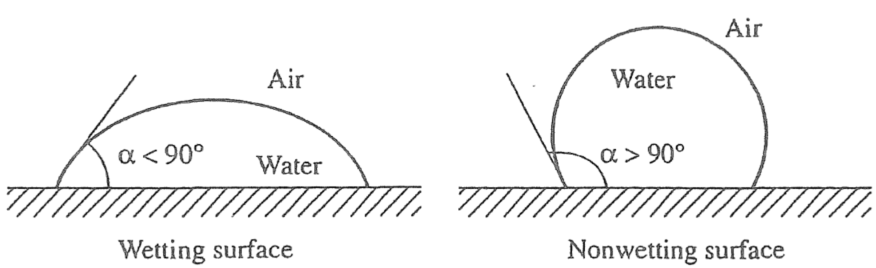
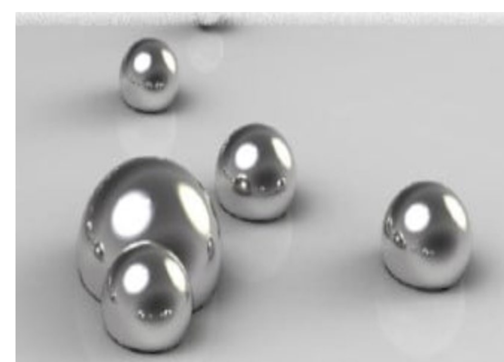


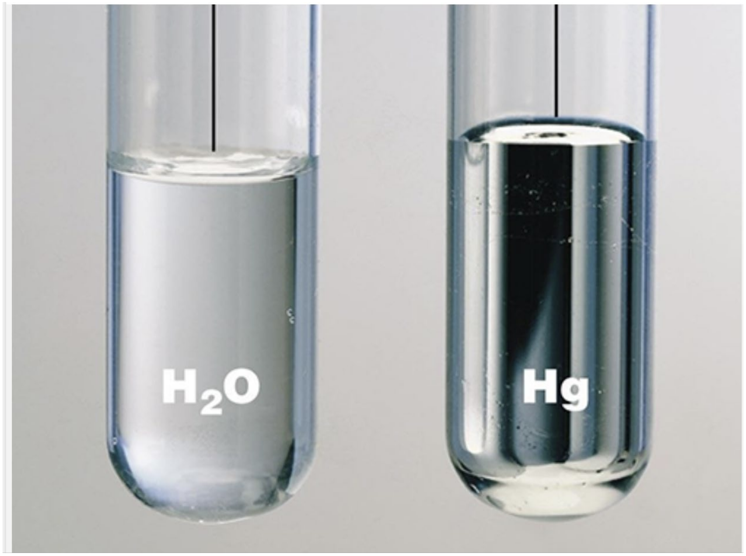
Figure 1.2 Wetting and nonwetting surfaces

If the cohesion is greater, then a **small drop forms**

If the adhesive force between the liquid and the solid surface is greater than the cohesion in the liquid molecules, then the liquid tends to spread over and wet the surface



Capillarity



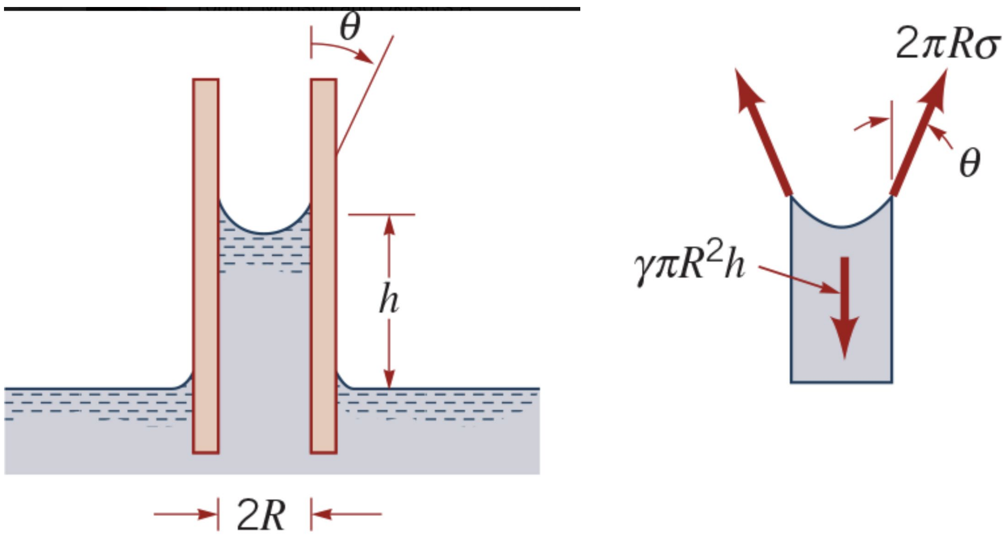
- Water wets the surface of glass, but mercury does not.
- If we place a small-bore vertical glass tube into the free surface of water, the water surface in the tube rises.
- The same experiment performed with mercury will show that the mercury falls.

The phenomenon is commonly known as **capillary action.**

The magnitude of the **capillary rise (or depression), *h***, is determined by the balance of adhesive force between the liquid and solid surface and **the weight of the liquid column above (or below) the liquid-free surface**

Vertical force due to surface tension: $2\pi R\sigma cos\theta$
Weight: (specific weight) x (volume): $\gamma\pi R2h$

Capillarity



(a) (b)

Attraction (adhesion)between the wall of the tube and liquid molecules which is strong enough to overcome the mutual attraction (cohesion) of the molecules and pull them up the wall.

The liquid is said to ***wet*** the solid surface.

Vertical force due to surface tension: $2\pi R\sigma cos\theta$

Weight: (specific weight) x (volume): $\gamma\pi R2h$

$$\gamma\pi R2h=2\pi R\sigma cos\theta \qquad \boxed{h=\frac{2\sigma cos\theta}{\gamma R}}$$

The angle of contact is a function of both the liquid and the surface. For water in contact with clean glass $\theta = 0^o$

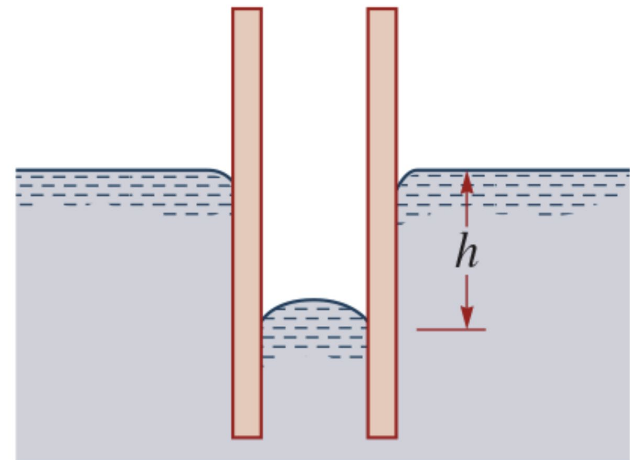
$$\boxed{h=\frac{2\sigma}{\gamma R}}$$

Capillarity

If adhesion of molecules to the solid surface is weak compared to the cohesion between molecules, the liquid will not wet the surface and the level in a tube placed in a nonwetting liquid will actually be depressed.

Mercury is a good example of a nonwetting liquid when it is in contact with a glass tube.

For nonwetting liquids, the angle of contact is greater than 90°, and for mercury in contact with clean glass ≈ 130°.



(c)

TABLE B.1

Physical Properties of Water (BG Units)[a]

Temperature (°F)	Density, ρ (slugs/ft^3)	Specific Weight[b], γ (lb/ft^3)	Dynamic Viscosity, μ (lb·s/ft^2)	Kinematic Viscosity, ν (ft^2/s)	Surface Tension[c], σ (lb/ft)	Vapor Pressure, p_v [lb/in.^{2}(abs)]	Speed of Sound[d], c (ft/s)
32	1.940	62.42	3.732 E − 5	1.924 E − 5	5.18 E − 3	8.854 E − 2	4603
40	1.940	62.43	3.228 E − 5	1.664 E − 5	5.13 E − 3	1.217 E − 1	4672
50	1.940	62.41	2.730 E − 5	1.407 E − 5	5.09 E − 3	1.781 E − 1	4748
60	1.938	62.37	2.344 E − 5	1.210 E − 5	5.03 E − 3	2.563 E − 1	4814
70	1.936	62.30	2.037 E − 5	1.052 E − 5	4.97 E − 3	3.631 E − 1	4871
80	1.934	62.22	1.791 E − 5	9.262 E − 6	4.91 E − 3	5.069 E − 1	4819
90	1.931	62.11	1.500 E − 5	8.233 E − 6	4.86 E − 3	6.979 E − 1	4960
100	1.927	62.00	1.423 E − 5	7.383 E − 6	4.79 E − 3	9.493 E − 1	4995
120	1.918	61.71	1.164 E − 5	6.067 E − 6	4.67 E − 3	1.692 E + 0	5049
140	1.908	61.38	9.743 E − 6	5.106 E − 6	4.53 E − 3	2.888 E + 0	5091
160	1.896	61.00	8.315 E − 6	4.385 E − 6	4.40 E − 3	4.736 E + 0	5101
180	1.883	60.58	7.207 E − 6	3.827 E − 6	4.26 E − 3	7.507 E + 0	5195
200	1.869	60.12	6.342 E − 6	3.393 E − 6	4.12 E − 3	1.152 E + 1	5089
212	1.860	59.83	5.886 E − 6	3.165 E − 6	4.04 E − 3	1.469 E + 1	5062

[a]Based on data from *Handbook of Chemistry and Physics*, 69th Ed., CRC Press, 1988. Where necessary, values obtained by interpolation.

[b]Density and specific weight are related through the equation $\gamma = \rho g$. For this table, $g = 32.174$ ft/s^2.

[c]In contact with air.

[d]From R. D. Blevins, *Applied Fluid Dynamics Handbook*, Van Nostrand Reinhold Co., Inc., New York, 1984.

TABLE B.2

Physical Properties of Water (SI Units)[a]

Temperature (°C)	Density, ρ (kg/m^3)	Specific Weight[b], γ (kN/m^3)	Dynamic Viscosity, μ (N·s/m^2)	Kinematic Viscosity, ν (m^2/s)	Surface Tension[c], σ (N/m)	Vapor Pressure, p_v [N/m^2(abs)]	Speed of Sound[d], c (m/s)
0	999.9	9.806	1.787 E − 3	1.787 E − 6	7.56 E − 2	6.105 E + 2	1403
5	1000.0	9.807	1.519 E − 3	1.519 E − 6	7.49 E − 2	8.722 E + 2	1427
10	999.7	9.804	1.307 E − 3	1.307 E − 6	7.42 E − 2	1.228 E + 3	1447
20	998.2	9.789	1.002 E − 3	1.004 E − 6	7.28 E − 2	2.338 E + 3	1481
30	995.7	9.765	7.975 E − 4	8.009 E − 7	7.12 E − 2	4.243 E + 3	1507
40	992.2	9.731	6.529 E − 4	6.580 E − 7	6.96 E − 2	7.376 E + 3	1526
50	988.1	9.690	5.468 E − 4	5.534 E − 7	6.79 E − 2	1.233 E + 4	1541
60	983.2	9.642	4.665 E − 4	4.745 E − 7	6.62 E − 2	1.992 E + 4	1552
70	977.8	9.589	4.042 E − 4	4.134 E − 7	6.44 E − 2	3.116 E + 4	1555
80	971.8	9.530	3.547 E − 4	3.650 E − 7	6.26 E − 2	4.734 E + 4	1555
90	965.3	9.467	3.147 E − 4	3.260 E − 7	6.08 E − 2	7.010 E + 4	1550
100	958.4	9.399	2.818 E − 4	2.940 E − 7	5.89 E − 2	1.013 E + 5	1543

[a]Based on data from *Handbook of Chemistry and Physics*, 69th Ed., CRC Press, 1988.

[b]Density and specific weight are related through the equation $\gamma = \rho g$. For this table, $g = 9.807\ \text{m/s}^2$.

[c]In contact with air.

[d]From R. D. Blevins, *Applied Fluid Dynamics Handbook*, Van Nostrand Reinhold Co., Inc., New York, 1984.

EXAMPLE 1.8 | Capillary Rise in a Tube

Given

Pressures are sometimes determined by measuring the height of a column of liquid in a vertical tube.

Find

What diameter of clean glass tubing is required so that the rise of water at $20\ ^{\circ}\mathrm{C}$ in a tube due to capillary action (as opposed to pressure in the tube) is less than $h = 1.5\ \mathrm{mm}$?

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

TABLE B.2

Physical Properties of Water (SI Units)[a]

Temperature (°C)	Density, ρ (kg/m^3)	Specific Weight[b], γ (kN/m^3)	Dynamic Viscosity, μ (N·s/m^2)	Kinematic Viscosity, ν (m^2/s)	Surface Tension[c], σ (N/m)	Vapor Pressure, p_v [N/m^2(abs)]	Speed of Sound[d], c (m/s)
0	999.9	9.806	1.787 E − 3	1.787 E − 6	7.56 E − 2	6.105 E + 2	1403
5	1000.0	9.807	1.519 E − 3	1.519 E − 6	7.49 E − 2	8.722 E + 2	1427
10	999.7	9.804	1.307 E − 3	1.307 E − 6	7.42 E − 2	1.228 E + 3	1447
20	998.2	9.789	1.002 E − 3	1.004 E − 6	7.28 E − 2	2.338 E + 3	1481
30	995.7	9.765	7.975 E − 4	8.009 E − 7	7.12 E − 2	4.243 E + 3	1507
40	992.2	9.731	6.529 E − 4	6.580 E − 7	6.96 E − 2	7.376 E + 3	1526
50	988.1	9.690	5.468 E − 4	5.534 E − 7	6.79 E − 2	1.233 E + 4	1541
60	983.2	9.642	4.665 E − 4	4.745 E − 7	6.62 E − 2	1.992 E + 4	1552
70	977.8	9.589	4.042 E − 4	4.134 E − 7	6.44 E − 2	3.116 E + 4	1555
80	971.8	9.530	3.547 E − 4	3.650 E − 7	6.26 E − 2	4.734 E + 4	1555
90	965.3	9.467	3.147 E − 4	3.260 E − 7	6.08 E − 2	7.010 E + 4	1550
100	958.4	9.399	2.818 E − 4	2.940 E − 7	5.89 E − 2	1.013 E + 5	1543

[a]Based on data from *Handbook of Chemistry and Physics*, 69th Ed., CRC Press, 1988.

[b]Density and specific weight are related through the equation $\gamma = \rho g$. For this table, $g = 9.807$ m/s^2.

[c]In contact with air.

[d]From R. D. Blevins, *Applied Fluid Dynamics Handbook*, Van Nostrand Reinhold Co., Inc., New York, 1984.

EXAMPLE 1.8 | Capillary Rise in a Tube

Given

Pressures are sometimes determined by measuring the height of a column of liquid in a vertical tube.

Find

What diameter of clean glass tubing is required so that the rise of water at $20\ ^{\circ}\mathrm{C}$ in a tube due to capillary action (as opposed to pressure in the tube) is less than $h = 1.5\ \mathrm{mm}$?

$$R = \frac{2\,(0.0728\ \mathrm{N/m})\,(1)}{(9.789 \times 10^3\ \mathrm{N/m^3})(1.5\ \mathrm{mm})(10^{-3}\ \mathrm{m/\,mm})} = 0.00991\ \mathrm{m}$$

$$D = 2R = 0.0198\ \mathrm{m} = 19.8\ \mathrm{mm}$$

By repeating the calculations for various values of the capillary rise, h, the results shown in Figure, are obtained. Note that as the allowable capillary rise is decreased, the diameter of the tube must be significantly increased. There is always some capillarity effect, but it can be minimized by using a large enough diameter tube.