Chapter 1
Introduction

Fluid mechanics is concerned with the behavior of liquids and gases, at rest and in motion.

Some Characteristics of Fluids

A fluid, such as water or air, deforms continuously when acted on by shearing stresses of any magnitude. Brief comparison between a solid and a fluid is given in the following table.

Solid	Fluid
• It is hard • It is not easily deformed • It is densely spaced molecules. • The intermolecular forces are large cohesive ones that allow the solid to maintain its shape.	• It is soft • It is easily deformed. • Its molecules are spaced farther apart. • The intermolecular force is smaller than that for solids. The molecules have more freedom to move. For gases and liquids at normal pressures and temperatures, the intermolecular spacing is of order $10^{-6}\ mm$. The average number of molecules $\approx 10^{18}/mm^3$ for gases. $\approx 10^{21}/mm^3$ for liquids.
• When common solids (steel or other metals) are acted on by a shearing stress, they will initially deform, with a very small deformation. They will not continuously deform (flow).	• It is a substance that deforms continuously when acted on by a shearing stress of any magnitude.

Systems of Units

Quantity	International System (SI)	British Gravitational System (BG)
Length	**M**	foot (**ft**) (1 ft= 0.3048 m)
Mass	**kg**	**slug** (1 slug=14.5939 kg)
force	Newton (**N**) According to Newton's second law, $\vec{F} = m\ \vec{a}$ 1 N = (1 kg)(1 m/s^2)	pound (**lb**) 1 lb= (1 slug) (1ft/s^2)
The acceleration due to gravity	9.8 **m/s^2**	32.2 **ft/s^2**

The temperature unit	Celsius (°**C**)	Fahrenheit **(°F)**
The absolute temperature unit	Kelvin $K = °C + 273.15$	Rankine (1°**R** = 0.556 **K**) $°R = °F + 459.67$

Measures of Fluid Mass and Weight:

Density (ρ): It is the mass per unit volume

The ***specific volume*** (v): It is the volume per unit mass. It is the reciprocal of the density.

$$v = 1/\rho$$

This property is commonly used in thermodynamics.

The ***specific weight*** (γ): It is the weight per unit volume.

$$\gamma = \frac{W}{V} = \frac{mg}{V} = \rho g$$

The ***specific gravity*** of a fluid (*SG*): It defined as the ratio of the density of the fluid to the density of water, at some specified temperature.

Ideal Gas Law: Gases are highly compressible in comparison to liquids. The change in the gas density is directly related to changes in its pressure and temperature through the equation

$$P = \rho RT$$

Here, *P* is the absolute pressure and ρ is the density. *T* defines the absolute temperature. *R* is a gas constant. In the ideal gas law, absolute pressures and temperatures must be used.

Viscosity:

Two fluids such as water and oil can have approximately the same value of density but flow in different ways. In such case, viscosity is used as additional property to measure the "fluidity" of the fluid.
Consider a fluid such as water, oil, or gasoline is placed between two plates (Fig. 1).

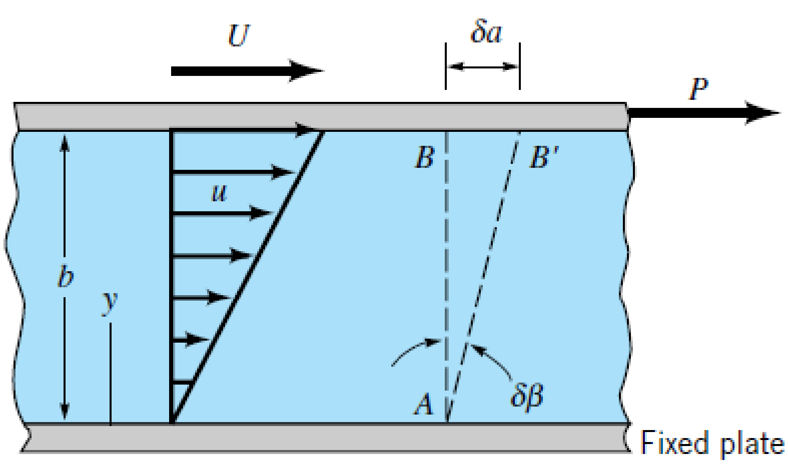


Fig. 1

Dynamic viscosity (μ) is the fluid property that relates shearing stress ($\tau = P/A$) and the fluid motion. For common fluids, the acting shearing stress varies linearly with the rate of the produced shearing strain (Fig. 2). The shearing stress (τ) and rate of shearing strain (velocity gradient) $\frac{du}{dy}$ can be related by the relationship,

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

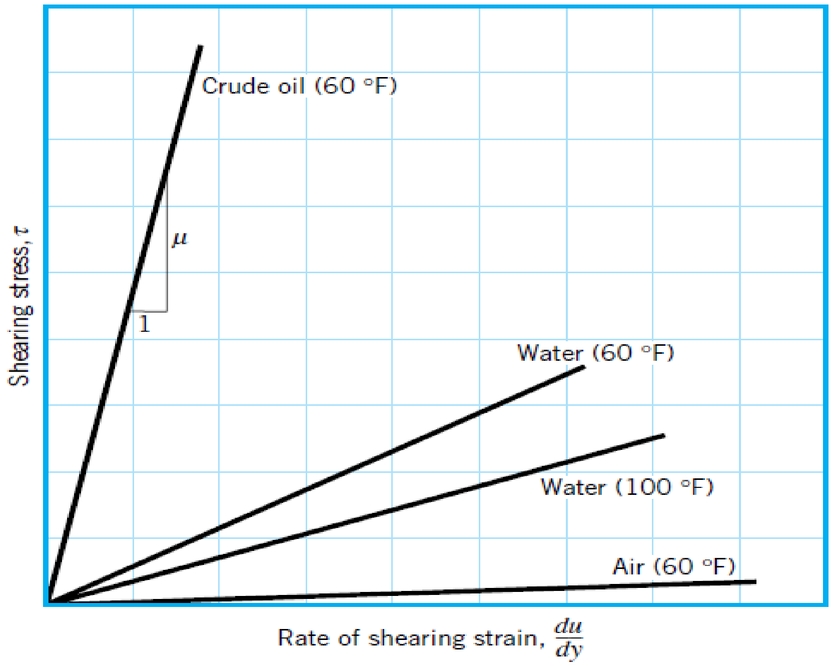


Fig. 2.

The effect of temperature on viscosity can be closely approximated using two empirical formulas. For gases,

$$\boldsymbol{\mu = \mu \frac{CT^{3/2}}{T + S}}.$$

Here, C and S are empirical constants. T is absolute temperature. This equation is called *Sutherland equation*. Thus, if the viscosity is known at two temperatures, C and S can be determined.

For liquids,

$$\mu = De^{B/T}$$

where D and B are constants. This equation is called *Andrade's equation*.

Quite often, viscosity appears in fluid flow problems combined with the density in the form

$$\nu = \frac{\mu}{\rho}$$

ν is called the *Kinematic viscosity*.
Dynamic viscosity has units of $poise \equiv dyne \cdot s/cm^2$.
Kinematic viscosity has units of $stoke \equiv cm^2/s$.

Example 1:

A dimensionless combination of variables that is important in the study of viscous flow through pipes is called the *Reynolds number* (Re). It is defined as $Re = \rho VD/\mu$ where ρ is the fluid density. V is the mean fluid velocity. D is the pipe diameter. μ is the fluid viscosity. A Newtonian fluid having a viscosity of $0.38\ \mathrm{N \cdot s/m^2}$ and a specific gravity of 0.91 flows through a 25 mm-diameter pipe with a velocity of 2.6 m/s. Determine the value of the Reynolds number using (a) SI units, and (b) BG units.

(a) The fluid density is calculated from the specific gravity as

$$\rho = SG\, \rho_{H_2O@4°C} = 0.91\ (1000\ \mathrm{kg/m^3}) = 910\ \mathrm{kg/m^3}$$

and from the definition of the Reynolds number

$$\mathrm{Re} = \frac{\rho VD}{\mu} = \frac{(910\ \mathrm{kg/m^3})(2.6\ \mathrm{m/s})(25\ \mathrm{mm})(10^{-3}\ \mathrm{m/mm})}{0.38\ \mathrm{N \cdot s/m^2}}$$
$$= 156\ (\mathrm{kg \cdot m/s^2})/\mathrm{N}$$

However, since $1\ \mathrm{N} = 1\ \mathrm{kg \cdot m/s^2}$ it follows that the Reynolds number is unitless—that is,

$$\mathrm{Re} = 156$$ **(Ans)**

The value of any dimensionless quantity does not depend on the system of units used if all variables that make up the quantity are expressed in a consistent set of units. To check this we will calculate the Reynolds number using BG units.

(b) We first convert all the SI values of the variables appearing in the Reynolds number to BG values by using the conversion factors from Table 1.4. Thus,

$$\rho = (910\ \mathrm{kg/m^3})(1.940 \times 10^{-3}) = 1.77\ \mathrm{slugs/ft^3}$$

$$V = (2.6\ \mathrm{m/s})(3.281) = 8.53\ \mathrm{ft/s}$$

$$D = (0.025\ \mathrm{m})(3.281) = 8.20 \times 10^{-2}\ \mathrm{ft}$$

$$\mu = (0.38\ \mathrm{N \cdot s/m^2})(2.089 \times 10^{-2}) = 7.94 \times 10^{-3}\ \mathrm{lb \cdot s/ft^2}$$

and the value of the Reynolds number is

$$\mathrm{Re} = \frac{(1.77\ \mathrm{slugs/ft^3})(8.53\ \mathrm{ft/s})(8.20 \times 10^{-2}\ \mathrm{ft})}{7.94 \times 10^{-3}\ \mathrm{lb \cdot s/ft^2}}$$
$$= 156\ (\mathrm{slug \cdot ft/s^2})/\mathrm{lb} = 156$$

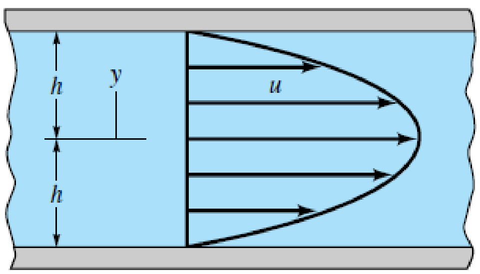
since $1\ \mathrm{lb} = 1\ \mathrm{slug \cdot ft/s^2}$. The values from part (a) and part (b) are the same,

Example 2:

The velocity distribution for the flow of a Newtonian fluid between two wide, parallel plates (see Fig. E1.5) is given by the equation

$$u = \frac{3V}{2}\left[1 - \left(\frac{y}{h}\right)^2\right]$$

where V is the mean velocity. The fluid has a viscosity of 0.04 $\text{lb} \cdot \text{s/ft}^2$. When $V = 2$ ft/s and $h = 0.2$ in. determine: (a) the shearing stress acting on the bottom wall, and (b) the shearing stress acting on a plane parallel to the walls and passing through the centerline (midplane).



■ FIGURE E1.5

S: For this parallel flow, the shearing stress is given as

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

For the given flow, we have

$$\frac{du}{dy} = -\frac{3Vy}{h^2}.$$

(a) Along the bottom wall, $y = -h$. Then, we have

$$\frac{du}{dy} = \frac{3V}{h}$$

and therefore the shearing stress is

$$\tau_{\substack{\text{bottom}\\\text{wall}}} = \mu\left(\frac{3V}{h}\right) = \frac{(0.04 \text{ lb} \cdot \text{s/ft}^2)(3)(2 \text{ ft/s})}{(0.2 \text{ in.})(1 \text{ ft/12 in.})}$$

$$= 14.4 \text{ lb/ft}^2 \text{ (in direction of flow)} \qquad \textbf{(Ans)}$$

This stress creates a drag on the wall. Since the velocity distribution is symmetrical, the shearing stress along the upper wall would have the same magnitude and direction.

(b) Along the midplane where $y = 0$ it follows from Eq. 2 that

$$\frac{du}{dy} = 0$$

and thus the shearing stress is

$$\tau_{\text{midplane}} = 0 \qquad \textbf{(Ans)}$$

From Eq. 2 we see that the velocity gradient (and therefore the shearing stress) varies linearly with y and in this particular example varies from 0 at the center of the channel to 14.4 lb/ft^2 at the walls. For the more general case the actual variation will, of course, depend on the nature of the velocity distribution.

Problems: (1.40, 1.49, 1.50, 1.52,1.53)

References: "***Fundamentals of Fluid Mechanics***" by Munson, Young and Okishi, Ch. 1
Fluid Mechanics, R. K. Rajput.

TABLE 1.3

Conversion Factors from BG and EE Units to SI Units[a]

	To Convert from	to	Multiply by
Acceleration	ft/s^2	m/s^2	3.048 E − 1
Area	ft^2	m^2	9.290 E − 2
Density	lbm/ft^3	kg/m^3	1.602 E + 1
	$slugs/ft^3$	kg/m^3	5.154 E + 2
Energy	Btu	J	1.055 E + 3
	ft · lb	J	1.356
Force	lb	N	4.448
Length	ft	m	3.048 E − 1
	in.	m	2.540 E − 2
	mile	m	1.609 E + 3
Mass	lbm	kg	4.536 E − 1
	slug	kg	1.459 E + 1
Power	ft · lb/s	W	1.356
	hp	W	7.457 E + 2
Pressure	in. Hg (60 °F)	N/m^2	3.377 E + 3
	lb/ft^2 (psf)	N/m^2	4.788 E + 1
	$lb/in.^2$ (psi)	N/m^2	6.895 E + 3
Specific weight	lb/ft^3	N/m^3	1.571 E + 2
Temperature	°F	°C	$T_C = (5/9)(T_F - 32°)$
	°R	K	5.556 E − 1
Velocity	ft/s	m/s	3.048 E − 1
	mi/hr (mph)	m/s	4.470 E − 1
Viscosity (dynamic)	$lb \cdot s/ft^2$	$N \cdot s/m^2$	4.788 E + 1
Viscosity (kinematic)	ft^2/s	m^2/s	9.290 E − 2
Volume flowrate	ft^3/s	m^3/s	2.832 E − 2
	gal/min (gpm)	m^3/s	6.309 E − 5

[a]If more than four-place accuracy is desired, refer to Appendix A.

TABLE 1.4

Conversion Factors from SI Units to BG and EE Units[a]

	To Convert from	to	Multiply by
Acceleration	m/s^2	ft/s^2	3.281
Area	m^2	ft^2	1.076 E + 1
Density	kg/m^3	lbm/ft^3	6.243 E − 2
	kg/m^3	$slugs/ft^3$	1.940 E − 3
Energy	J	Btu	9.478 E − 4
	J	ft · lb	7.376 E − 1
Force	N	lb	2.248 E − 1
Length	m	ft	3.281
	m	in.	3.937 E + 1
	m	mile	6.214 E − 4
Mass	kg	lbm	2.205
	kg	slug	6.852 E − 2
Power	W	ft · lb/s	7.376 E − 1
	W	hp	1.341 E − 3
Pressure	N/m^2	in. Hg (60 °F)	2.961 E − 4
	N/m^2	lb/ft^2 (psf)	2.089 E − 2
	N/m^2	$lb/in.^2$ (psi)	1.450 E − 4
Specific weight	N/m^3	lb/ft^3	6.366 E − 3
Temperature	°C	°F	$T_F = 1.8\, T_C + 32°$
	K	°R	1.800
Velocity	m/s	ft/s	3.281
	m/s	mi/hr (mph)	2.237
Viscosity (dynamic)	$N \cdot s/m^2$	$lb \cdot s/ft^2$	2.089 E − 2
Viscosity (kinematic)	m^2/s	ft^2/s	1.076 E + 1
Volume flowrate	m^3/s	ft^3/s	3.531 E + 1
	m^3/s	gal/min (gpm)	1.585 E + 4

[a]If more than four-place accuracy is desired, refer to Appendix A.

TABLE 1.5

Approximate Physical Properties of Some Common Liquids (BG Units)

Liquid	Temperature (°F)	Density, ρ (slugs/ft^3)	Specific Weight, γ (lb/ft^3)	Dynamic Viscosity, μ (lb · s/ft^2)	Kinematic Viscosity, ν (ft^2/s)	Surface Tension,[a] σ (lb/ft)	Vapor Pressure, p_v [lb/in.^{2} (abs)]	Bulk Modulus,[b] E_v (lb/in.^{2})
Carbon tetrachloride	68	3.09	99.5	2.00 E − 5	6.47 E − 6	1.84 E − 3	1.9 E + 0	1.91 E + 5
Ethyl alcohol	68	1.53	49.3	2.49 E − 5	1.63 E − 5	1.56 E − 3	8.5 E − 1	1.54 E + 5
Gasoline[c]	60	1.32	42.5	6.5 E − 6	4.9 E − 6	1.5 E − 3	8.0 E + 0	1.9 E + 5
Glycerin	68	2.44	78.6	3.13 E − 2	1.28 E − 2	4.34 E − 3	2.0 E − 6	6.56 E + 5
Mercury	68	26.3	847	3.28 E − 5	1.25 E − 6	3.19 E − 2	2.3 E − 5	4.14 E + 6
SAE 30 oil[c]	60	1.77	57.0	8.0 E − 3	4.5 E − 3	2.5 E − 3	—	2.2 E + 5
Seawater	60	1.99	64.0	2.51 E − 5	1.26 E − 5	5.03 E − 3	2.26 E − 1	3.39 E + 5
Water	60	1.94	62.4	2.34 E − 5	1.21 E − 5	5.03 E − 3	2.26 E − 1	3.12 E + 5

[a]In contact with air.

[b]Isentropic bulk modulus calculated from speed of sound.

[c]Typical values. Properties of petroleum products vary.

TABLE 1.6

Approximate Physical Properties of Some Common Liquids (SI Units)

Liquid	Temperature (°C)	Density, ρ (kg/m^3)	Specific Weight, γ (kN/m^3)	Dynamic Viscosity, μ (N · s/m^2)	Kinematic Viscosity, ν (m^2/s)	Surface Tension,[a] σ (N/m)	Vapor Pressure, p_v [N/m^2 (abs)]	Bulk Modulus,[b] E_v (N/m^2)
Carbon tetrachloride	20	1,590	15.6	9.58 E − 4	6.03 E − 7	2.69 E − 2	1.3 E + 4	1.31 E + 9
Ethyl alcohol	20	789	7.74	1.19 E − 3	1.51 E − 6	2.28 E − 2	5.9 E + 3	1.06 E + 9
Gasoline[c]	15.6	680	6.67	3.1 E − 4	4.6 E − 7	2.2 E − 2	5.5 E + 4	1.3 E + 9
Glycerin	20	1,260	12.4	1.50 E + 0	1.19 E − 3	6.33 E − 2	1.4 E − 2	4.52 E + 9
Mercury	20	13,600	133	1.57 E − 3	1.15 E − 7	4.66 E − 1	1.6 E − 1	2.85 E + 10
SAE 30 oil[c]	15.6	912	8.95	3.8 E − 1	4.2 E − 4	3.6 E − 2	—	1.5 E + 9
Seawater	15.6	1,030	10.1	1.20 E − 3	1.17 E − 6	7.34 E − 2	1.77 E + 3	2.34 E + 9
Water	15.6	999	9.80	1.12 E − 3	1.12 E − 6	7.34 E − 2	1.77 E + 3	2.15 E + 9

[a]In contact with air.

[b]Isentropic bulk modulus calculated from speed of sound.

[c]Typical values. Properties of petroleum products vary.