FLUID MECHANICS

1. Introduction

Fluids play a vital role in many aspects of everyday life. We drink them, breathe them, and swim in them. They circulate through our bodies and control our weather. Airplanes fly through them; ships float in them. A fluid is any substance that can flow; we use the term for both liquids and gases. We usually think of a gas as easily compressed and a liquid as nearly incompressible, although there are exceptional cases.

We begin our study with **fluid statics,** the study of fluids at rest in equilibrium situations. Like other equilibrium situations, it is based on Newton’s first and third laws. We will explore the key concepts of density, pressure, and buoyancy.

Fluid dynamics, the study of fluids in motion, is much more complex; indeed, it is one of the most complex branches of mechanics. Fortunately, we can analyze many important situations using simple idealized models and familiar principles such as Newton’s laws and conservation of energy.

2. Density

An important property of any material is its **density,** *defined as its mass per unit volume*. A homogeneous material such as ice or iron has the same density throughout. We use ρ (the Greek letter rho) for density. If a mass m of homogeneous material has volume V, the density is

$$\rho = \frac{m}{V} \qquad \text{(definition of density)}$$

Two objects made of the same material have the same density even though they may have different masses and different volumes. That’s

because the ratio of mass to volume is the same for both objects (Fig. 1.1).

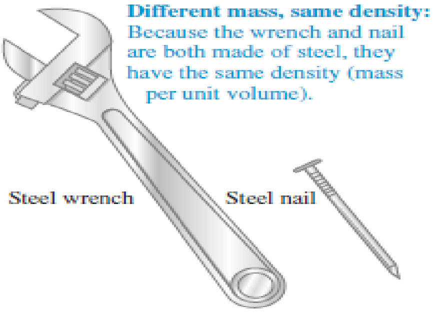

Fig. (1.1): Two objects with different masses and different volumes but the same density.

The SI unit of density is the kilogram per cubic meter (1 kg/m^3). The cgs, unit, the gram per cubic centimeter (1g/cm^3) is also widely used:

$$1\ g/cm^3 = 1000\ kg/m^3$$

The densities of some common substances at ordinary temperatures are given in Table (1.1). Note the wide range of magnitudes. The densest material found on earth is the metal (ρ=22.500 kg/m^3), but its density pales by comparison to the densities of exotic astronomical objects such as white dwarf stars and neutron stars.

Table (1.1): Densities of Some Common Substances

Material	Density (kg/m^3)*	Material	Density (kg/m^3)*
Air (1 atm, 20°C)	1.20	Iron, steel	7.8×10^3
Ethanol	0.81×10^3	Brass	8.6×10^3
Benzene	0.90×10^3	Copper	8.9×10^3
Ice	0.92×10^3	Silver	10.5×10^3
Water	1.00×10^3	Lead	11.3×10^3
Seawater	1.03×10^3	Mercury	13.6×10^3
Blood	1.06×10^3	Gold	19.3×10^3
Glycerine	1.26×10^3	Platinum	21.4×10^3
Concrete	2×10^3	White dwarf star	10^{10}
Aluminum	2.7×10^3	Neutron star	10^{18}

*To obtain the densities in grams per cubic centimeter, simply divide by 10^3.

The ***specific gravity*** of a material is the ratio of its density to the density of water at (4.0^{o}C, 1000 kg/m^3) ,it is a pure number without units. For example, the specific gravity of aluminum is 2.7. “Specific gravity” is a poor term, since it has nothing to do with gravity; “relative density” would have been better.

The density of some materials varies from point to point within the material. One example is the material of the human body, which includes low-density fat (about 940 kg/m^3) and high-density bone (from 1700 to 2500 kg/m^3) .Two others are the earth’s atmosphere (which is less dense at high altitudes) and oceans (which are denser at greater depths). For these materials, Eq. (1.1) describes the **average density**. In general, the density of a material depends on environmental factors such as temperature and pressure.

Measuring density is an important analytical technique. For example, we can determine the charge condition of a storage battery by measuring the density of its electrolyte, a sulfuric acid solution. As the battery discharges, the sulfuric acid (H_2SO_4) combines with lead in the battery plates to form insoluble lead sulfate ($PbSO_4$),decreasing the concentration of the solution. The density decreases from about (1.30*10^3 kg/m^3) for a fully charged battery to (1.15*10^3 kg/m^3) for a discharged battery.

Another automotive example is permanent-type antifreeze, which is usually a solution of ethylene glycol (ρ= 1.12*10^3 kg/m^3) and water. The freezing point of the solution depends on the glycol concentration, which can be determined by measuring the specific gravity. Such measurements can be performed by using a device called a hydrometer.

Example (1.1): *Find the mass and weight of the air at 20°C in a living room with a 4.0 m * 5.0 m floor and a ceiling 3.0 m high, and the mass and weight of an equal volume of water.*

SOLUTION:

IDENTIFY and SET UP: We assume that the air density is the same throughout the room. (Air is less dense at high elevations than near sea level, We use Eq. (1.1) to relate the mass m_{air} to the room's volume V (which we'll calculate) and the air density ρ_{air} (given in Table 1.1).

EXECUTE:

We have $V = (4.0\text{ m}) * (5.0\text{ m}) * (3.0\text{ m}) = 60\text{ m}^3$,

so from Eq. (1.1),

$m_{\text{air}} = \rho_{air} V = (1.20\text{ kg/m}^3)(60\text{ m}^3) = 72\text{ kg}$

$w_{\text{air}} = m_{\text{air}} g = (72\text{ kg})(9.8\text{ m/s}^2) = 705.6\text{ N}$

The mass and weight of an equal volume of water are

$m_{\text{water}} = \rho_{\text{water}} V = (1000\text{ kg/m}^3)(60\text{ m}^3) = 6.0 * 10^4\text{ kg}$

$w_{\text{water}} = m_{\text{water}} g = (6.0 * 10^4\text{ kg})(9.8\text{ m/s}^2)$

$= 5.9 * 10^5\text{ N}$

EVALUATE: A roomful of air weighs about the same as an average. Water is nearly a thousand times denser than air, so its mass and weight are larger by the same factor. The weight of a roomful of water would collapse the floor of an ordinary house.

H.W1 *: Rank the following objects in order from highest to lowest average density: (i) mass 4.00 kg, volume $1.60 * 10^{-3}\text{ m}^3$; (ii) mass 8.00 kg, volume $1.60 * 10^{-3}\text{ m}^3$, (iii) mass 8.00 kg, volume $3.20 * 10^{-3}\text{ m}^3$; (iv) mass 2560 kg, volume 0.640 m^3, (v) mass 2560 kg, volume 1.28 m^3.*