Chapter 1
Properties of Fluids

1.1 Introduction

A **fluid** is a substance which deforms continuously, or flows, when subjected to shear stresses. The term fluid embraces both gases and liquids; a given mass of liquid will occupy a definite volume whereas a gas will fill its container. Gases are readily compressible; the low compressibility, or elastic volumetric deformation, of liquids is generally neglected in computations except those relating to large depths in the oceans and in pressure transients in pipelines.

This text, however, deals exclusively with liquids and more particularly with Newtonian liquids (i.e. those having a linear relationship between shear stress and rate of deformation).

Typical values of different properties are quoted in the text as needed for the various worked examples. For more comprehensive details of physical properties, refer to tables such as Kaye and Laby (1995) or internet versions of such information.

1.2 Engineering units

The **metre–kilogram–second (mks) system** is the agreed version of the international system (SI) of units that is used in this text. The physical quantities in this text can be described by a set of three primary dimensions (units): mass (kg), length (m) and time (s). Further discussion is contained in Chapter 9 regarding dimensional analysis. The present chapter refers to the relevant units that will be used.

The unit of force is called newton (N) and 1 N is the force which accelerates a mass of 1 kg at a rate of 1 m/s^2 (1 N = 1 kg m/s^2).

The unit of work is called joule (J) and it is the energy needed to move a force of 1 N over a distance of 1 m. Power is the energy or work done per unit time and its unit is watt (W) (1 W = 1 J/s = 1 N m/s).

Nalluri & Featherstone's Civil Engineering Hydraulics: Essential Theory with Worked Examples,
Sixth Edition. Martin Marriott.

Companion Website: www.wiley.com/go/Marriott

1.3 Mass density and specific weight

Mass density (ρ) or **density** of a substance is defined as the mass of the substance per unit volume (kg/m^3) and is different from **specific weight** (γ), which is the force exerted by the earth's gravity (g) upon a unit volume of the substance ($\gamma = \rho g$: N/m^3). In a satellite where there is no gravity, an object has no specific weight but possesses the same density that it has on the earth.

1.4 Relative density

Relative density (s) of a substance is the ratio of its mass density to that of water at a standard temperature (4°C) and pressure (atmospheric) and is dimensionless.

For water, $\rho = 10^3$ kg/m^3, $\gamma = 10^3 \times 9.81 \simeq 10^4$ N/m^3 and $s = 1$.

1.5 Viscosity of fluids

Viscosity is that property of a fluid which by virtue of cohesion and interaction between fluid molecules offers resistance to shear deformation. Different fluids deform at different rates under the action of the same shear stress. Fluids with high viscosity such as syrup deform relatively more slowly than fluids with low viscosity such as water.

All fluids are viscous and 'Newtonian fluids' obey the linear relationship

$$\tau = \mu \frac{\mathrm{d}u}{\mathrm{d}y} \quad \text{(Newton's law of viscosity)} \qquad [1.1]$$

where τ is the shear stress (N/m^2), du/dy the velocity gradient or the rate of deformation (rad/s) and μ the coefficient of dynamic (or absolute) viscosity (N s/m^2 or kg/(m s)).

Kinematic viscosity (ν) is the ratio of dynamic viscosity to mass density expressed in metres squared per second.

Water is a Newtonian fluid having a dynamic viscosity of approximately 1.0×10^{-3} N s/m^2 and kinematic viscosity of 1.0×10^{-6} m^2/s at 20°C.

1.6 Compressibility and elasticity of fluids

All fluids are compressible under the application of an external force and when the force is removed they expand back to their original volume, exhibiting the property that stress is proportional to volumetric strain.

$$\text{The bulk modulus of elasticity, } K = \frac{\text{pressure change}}{\text{volumetric strain}}$$
$$= -\frac{\mathrm{d}p}{(\mathrm{d}V/V)} \qquad [1.2]$$

The negative sign indicates that an increase in pressure causes a decrease in volume.

Water with a bulk modulus of 2.1×10^9 N/m^2 at 20°C is 100 times more compressible than steel, but it is ordinarily considered incompressible.

1.7 Vapour pressure of liquids

A liquid in a closed container is subjected to partial vapour pressure due to the escaping molecules from the surface; it reaches a stage of equilibrium when this pressure reaches saturated vapour pressure. Since this depends upon molecular activity, which is a function of temperature, the vapour pressure of a fluid also depends upon its temperature and increases with it. If the pressure above a liquid reaches the vapour pressure of the liquid, boiling occurs; for example, if the pressure is reduced sufficiently, boiling may occur at room temperature.

The saturated vapour pressure for water at 20°C is 2.45×10^3 N/m^2.

1.8 Surface tension and capillarity

Liquids possess the properties of cohesion and adhesion due to molecular attraction. Due to the property of cohesion, liquids can resist small tensile forces at the interface between the liquid and air, known as **surface tension** (σ: N/m). If the liquid molecules have greater adhesion than cohesion, then the liquid sticks to the surface of the container with which it is in contact, resulting in a capillary rise of the liquid surface; a predominating cohesion, in contrast, causes capillary depression. The surface tension of water is 73×10^{-3} N/m at 20°C.

The capillary rise or depression h of a liquid in a tube of diameter d can be written as

$$h = \frac{4\sigma \cos\theta}{\rho g d} \qquad [1.3]$$

where θ is the angle of contact between liquid and solid.

Surface tension increases the pressure within a droplet of liquid. The internal pressure p balancing the surface tensional force of a small spherical droplet of radius r is given by

$$p = \frac{2\sigma}{r} \qquad [1.4]$$

Worked examples

Example 1.1

The density of an oil at 20°C is 850 kg/m^3. Find its relative density and kinematic viscosity if the dynamic viscosity is 5×10^{-3} kg/(m s).

Solution:

$$\begin{aligned} \text{Relative density, } s &= \frac{\rho \text{ of oil}}{\rho \text{ of water}} \\ &= \frac{850}{10^3} \\ &= 0.85 \end{aligned}$$

$$\begin{aligned} \text{Kinematic viscosity, } \nu &= \frac{\mu}{\rho} \\ &= \frac{5 \times 10^{-3}}{850} \\ &= 5.88 \times 10^{-6}\ \text{m}^2/\text{s} \end{aligned}$$

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Example 1.2

If the velocity distribution of a viscous liquid ($\mu = 0.9$ N s/m^2) over a fixed boundary is given by $u = 0.68y - y^2$, in which u is the velocity (in metres per second) at a distance y (in metres) above the boundary surface, determine the shear stress at the surface and at $y = 0.34$ m.

Solution:

$$u = 0.68y - y^2$$
$$\Rightarrow \frac{du}{dy} = 0.68 - 2y$$

Hence, $(du/dy)_{y=0} = 0.68\ \text{s}^{-1}$ and $(du/dy)_{y=0.34\text{m}} = 0$.

$$\text{Dynamic viscosity of the fluid, } \mu = 0.9\ \text{N s/m}^2$$

From Equation 1.1,

$$\begin{aligned}\text{shear stress } (\tau)_{y=0} &= 0.9 \times 0.68 \\ &= 0.612\ \text{N/m}^2\end{aligned}$$

and at $y = 0.34$ m, $\tau = 0$.

Example 1.3

At a depth of 8.5 km in the ocean the pressure is 90 MN/m^2. The specific weight of the sea water at the surface is 10.2 kN/m^3 and its average bulk modulus is 2.4×10^6 kN/m^2. Determine (a) the change in specific volume, (b) the specific volume and (c) the specific weight of sea water at 8.5 km depth.

Solution:

$$\begin{aligned}\text{Change in pressure at a depth of 8.5 km, d}p &= 90\ \text{MN/m}^2 \\ &= 9 \times 10^4\ \text{kN/m}^2\end{aligned}$$

$$\text{Bulk modulus, } K = 2.4 \times 10^6\ \text{kN/m}^2$$
$$\text{From } K = -\frac{dp}{(dV/V)}$$
$$\frac{dV}{V} = \frac{-9 \times 10^4}{2.4 \times 10^6} = -3.75 \times 10^{-2}$$

Defining specific volume as $1/\gamma$ (m^3/kN), the specific volume of sea water at the surface = $1/10.2 = 9.8 \times 10^{-2}$ m^3/kN.

$$\begin{aligned}&\text{Change in specific volume between that} \\ &\text{at the surface and at 8.5 km depth, d}V \\ &= -3.75 \times 10^{-2} \times 9.8 \times 10^{-2} \\ &= -36.75 \times 10^{-4}\ \text{m}^3/\text{kN}\end{aligned}$$

$$\text{The specific volume of sea water at 8.5 km depth} = 9.8 \times 10^{-2} - 36.75 \times 10^{-4}$$
$$= 9.44 \times 10^{-2}\,\text{m}^3/\text{kN}$$

$$\text{The specific weight of sea water at 8.5 km depth} = \frac{1}{\text{specific volume}}$$
$$= \frac{1}{9.44 \times 10^{-2}}$$
$$= 10.6\,\text{kN/m}^3$$

References and recommended reading

Kaye, G. W. C. and Laby, T. H. (1995) *Tables of Physical and Chemical Constants*, 16th edn, Longman, London. http://www.kayelaby.npl.co.uk

Massey, B. S. and Ward-Smith, J. (2012) *Mechanics of Fluids*, 9th edn, Taylor & Francis, Abingdon, UK.

Problems

1. **(a)** Explain why the viscosity of a liquid decreases while that of a gas increases with an increase of temperature.
   (b) The following data refer to a liquid under shearing action at a constant temperature. Determine its dynamic viscosity.

du/dy (s^{-1})	0	0.2	0.4	0.6	0.8
τ (N/m^2)	0	0	1.9	3.1	4.0

2. A 300 mm wide shaft sleeve moves along a 100 mm diameter shaft at a speed of 0.5 m/s under the application of a force of 250 N in the direction of its motion. If 1000 N of force is applied, what speed will the sleeve attain? Assume the temperature of the sleeve to be constant and determine the viscosity of the Newtonian fluid in the clearance between the shaft and its sleeve if the radial clearance is estimated to be 0.075 mm.

3. A shaft of 100 mm diameter rotates at 120 rad/s in a bearing 150 mm long. If the radial clearance is 0.2 mm and the absolute viscosity of the lubricant is 0.20 kg/(m s), find the power loss in the bearing.

4. A block of dimensions 300 mm × 300 mm × 300 mm and mass 30 kg slides down a plane inclined at 30° to the horizontal, on which there is a thin film of oil of viscosity 2.3×10^{-3} N s/m^2. Determine the speed of the block if the film thickness is estimated to be 0.03 mm.

5. Calculate the capillary effect (in millimetres) in a glass tube of 6 mm diameter when immersed in (i) water and (ii) mercury, both liquids being at 20°C. Assume σ to be 73×10^{-3} N/m for water and 0.5 N/m for mercury. The contact angles for water and mercury are 0 and 130°, respectively.

6. Calculate the internal pressure of a 25 mm diameter soap bubble if the tension in the soap film is 0.5 N/m.

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