BASIC APPLIED FLUID MECHANICS

Hydrostatics, Dynamics and Pumping Systems

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PREFACE

The purpose of this book is to present the basic principles of fluid mechanics and to illustrate them by application to problems in day-to-day life or in different branches of engineering. This is a book for engineers rather than scientists. Hence, the occasional small sacrifice of detailed mathematical analysis is more than justified by the greater ease of visualizing and understanding the physical circumstances. This book will serve as a first course in fluid mechanics.

The topics of study are simply explained and developed, and illustrated through numerous practical examples based on applications with which most students in developed countries will be readily familiar through common everyday experience. Basic physical knowledge and reasoned common sense are used to analyse and solve the problems using fundamental concepts rather than the blind application of formulae. We believe that this approach encourages better appreciation of the concepts and demonstrates the usefulness of the subject to a wide diversity of engineering problems. It also places the emphasis on understanding rather than memorisation.

The topics covered include fluid pressure on surfaces, buoyancy, stability of floating bodies, conservation of mass and energy, flow measurement, flow through pipes and ducts, pumping systems and selection of pumps.

With regards to the structure of the book, each chapter starts with a summary which presents an overview of the chapter contents. Simple English is then used to explain the subject content, and technical terms are introduced only as necessary.

Numerous worked examples are provided to illustrate the analysis of realistic problems. Each problem is designed to further the student's grasp of the subject and is not to be solved simply by inserting figures in a 'standard formula'. The difficulty which many students experience with handling units is overcome through regular unit checks in the worked examples, and conclusions are drawn at the end of many of the examples to reinforce understanding.

Our sincere thanks are due to Mr. L. S. Wong and Ng Hon Chai who pointed out errors and suggested many improvements to the text. We welcome constructive comments and suggestions from readers.

Kannappa Iynkaran and Kolitha Herath
Singapore 1992

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1 INTRODUCTION AND UNITS OF MEASUREMENT

Summary

The chapter begins with the definition of the term *fluid mechanics* and its importance for modern living. The basic and derived units in the S.I. system are discussed. To demonstrate the use of correct units, simple, practical engineering problems are solved.

1.1 WHAT IS FLUID MECHANICS?

A fluid is a substance which can flow, which thus distinguishes it from a solid, which can not. It is further distinguished from a solid in that a given amount of it does not have its own shape, but takes the shape of the vessel containing it. Fluids may be divided into liquids and gases. Fluid mechanics is the study of fluids at rest and in motion, one is concerned with the forces which act on fluids in these states. The study which deals with fluids primarily at rest is called *fluid statics*, and that dealing with fluids in motion is called *fluid dynamics*.

The fundamental principles such as conservation of mass, conservation of energy and Newton's law of motion are needed to analyse problems in fluid mechanics. In fluid statics the forces acting on the fluid are due to pressure and gravity only. Fluid dynamics deals with the velocity, acceleration, inertia forces and other forces associated with fluids in motion.

1.2 WHY SHOULD YOU STUDY FLUID MECHANICS?

The subject of fluid mechanics is of great significance to any civilised society. The storage and distribution of drinking water in cities, the flow of blood through our veins and the cooling of electronic components are some examples of fluid flow. Studying fluid mechanics helps to utilize and control the effects of fluid flow for the benefit of the society by providing a qualitative understanding and quantitative analysis when designing processes and machines.

Engineers need to design systems involving pumps, compressors, pipes, valves, etc. In the field of power generation turbines, engines and windmills involve many complicated flow processes. In air-conditioning systems the circulating air flowing through ducts is cooled by a flowing refrigerant. Ships and airplanes derive their motion from propellers or jet-engines that interact with the fluid medium (water or air). The design of tall buildings must account for the effects of wind loading. A firm grasp of the fundamentals of fluid mechanics is essential for every engineer who may be called upon to solve a wide range of problems during his professional career.

1.3 THE S.I. SYSTEM OF UNITS

If we are going to study Basic Fluid Mechanics, it is obvious that we are going to need to measure such quantities as fluid flow, pressure and energy. To do this we must first establish a system of units for our measurements, since the measurement of any quantity requires a standard unit.

There are several systems of units in common use, but the most important by far is the *Systeme International*, which is abbreviated S.I. As of 1990 nearly every major country in the world, except the United States, is using the S.I. units as their official mode of measurement. The important basic units of the S.I. system are:

Quantity	*Unit*
Mass	kg (kilogram)
Length	m (metre)
Time	s (second)

From these three basic units it is possible to derive several related units which are of great importance in the study of fluid mechanics. Let us look at each unit in more detail.

1.3.1 Mass

Symbol: m Unit: kilogram (kg)

Mass is the quantity of matter in a body (see Figure 1.1). It does not change with position, and is not affected by pressure, temperature or motion. In fact, mass remains constant whatever happens to the body. One of the most fundamental laws of nature is that mass cannot be created or destroyed, and this is known as the Law of Conservation of Mass.

Figure 1.1 Mass of a fluid

1.3.2 Length

Symbol: L Unit: metre (m)

Length is a measure of distance from one point to another (see Figure 1.2). The unit of length in the S.I. system is the metre (m) but this is sometimes too large for convenience. Common subdivisions of the metre are the centimetre (cm) and the millimetre (mm).

$$1 \text{ m} = 100 \text{ cm} = 1000 \text{ mm}$$

Figure 1.2 Length

1.3.3 Time

Symbol: t Unit: second (s)

Time is a measure of duration (see Figure 1.3). It is important in fluid mechanics since it provides a measure of the rate at which something occurs. The S.I. unit of time is the second (s), but this is often too small for convenience and related units such as the minute (min) and the hour (h) are commonly used.

$$1 \text{ min} = 60 \text{ s}$$
$$1 \text{ h} = 60 \text{ min} = 3600 \text{ s}$$

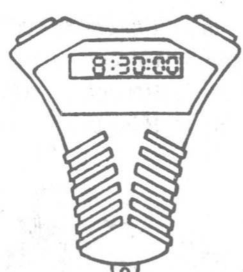

Figure 1.3 Time

1.4 THE DERIVED S.I. UNITS

Units of measurements for many quantities may be derived from the basic units, but we will restrict ourselves to those units which are widely used for the study of fluid mechanics.

In all engineering problems it is particularly important to evaluate the solution with careful attention to the units used for data measurement and the unit required for the answer. We shall be looking at some examples of this in this book.

1.4.1 Area

Symbol: A Unit: square metre (m^2)

Area can mean either the surface area or the cross-sectional area of an object. For example:

$$\text{surface area of a cylinder} = \pi DL$$

$$\text{cross-sectional area of a cylinder} = \frac{\pi D^2}{4}$$

where D = diameter of the cylinder (m)
L = length of the cylinder (m)

1.4.2 Volume

Symbol: V Unit: cubic metre (m^3)

The volume of a body is the amount of space which it occupies. Since the unit of length in the S.I. system is the metre (m), the unit of volume is the cubic metre (m^3) (see Figure 1.4). However, for many practical purposes this unit is too large and inconvenient and so subdivisions such as cubic centimetres (cm^3) or cubic millimetres (mm^3) are sometimes used. Another common unit of volume is the litre (L). Such units are not strictly S.I. units but are nevertheless in common use. The following conversion factors are often useful:

$$1\ m = 100\ cm = 1000\ mm$$
$$1\ m^2 = 10^4\ cm^2 = 10^6\ mm^2$$
$$1\ m^3 = 10^6\ cm^3 = 10^9\ mm^3$$
$$1\ m^3 = 1000\ L$$

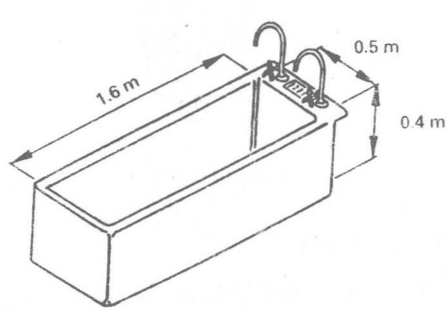

Figure 1.4 A bathtub can hold a certain volume of water

Example 1.1

A bathtub measures 1.6 m × 50 cm × 40 cm. How many litres of water are contained in the tub when it is full?

Solution:

Volume,

$$V = XYZ$$
$$= 1.6 \times 0.5 \times 0.4 \qquad \text{m m m} \equiv \text{m}^3$$
$$= 0.32 \text{ m}^3$$

Since 1 m^3 = 1000 L, the contents of a full tub is

$$0.32 \times 1000 \qquad \text{m}^3 \frac{\text{L}}{\text{m}^3} \equiv \text{L}$$

$$= 320 \text{ L}$$

1.4.3 Velocity

Symbol: v Unit: metre per second (m/s)

Velocity is the rate of change of displacement. It is a measure of how fast an object moves, i.e.

$$\text{Average velocity} = \frac{\text{displacement}}{\text{time taken}}$$

$$v = \frac{L}{t}$$

Example 1.2

The following data were collected from a car cruising on a straight road (see Figure 1.5):

At 10:26 the odometer shows 37 541 km
At 10:42 the odometer shows 37 563 km

Determine the average velocity of the car.

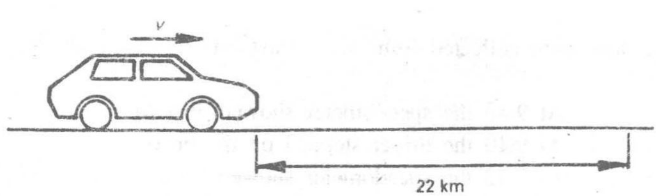

Figure 1.5 Velocity of a car

Solution:

The displacement is

$$37\,563 - 37\,541 = 22 \text{ km}$$
$$= 22\,000 \text{ m}$$

The time taken is

$$10{:}42 - 10{:}26 = 16 \text{ min}$$
$$= 16 \times 60 = 960 \text{ s}$$

Average velocity,

$$v = \frac{\text{displacement}}{\text{time taken}}$$
$$= \frac{22\,000}{960} \qquad \text{m}\,\frac{1}{\text{s}}$$
$$= 22.91 \text{ m/s}$$

1.4.4 Acceleration

Symbol: a Unit: metre per square second (m/s^2)

Acceleration is the rate of increase in velocity.

$$\text{Average acceleration} = \frac{\text{increase in velocity}}{\text{time taken}}$$

If the velocity is constant then there is no acceleration, i.e. the acceleration is zero. If the velocity is decreasing with time it is known as *deceleration*.

Example 1.3

The following data were collected from a car travelling on a straight road:

At 9:10 the speedometer showed 70 km/h
At 9:10 the driver stepped on the brake
At 9:12 the speedometer showed 25 km/h

Determine the average deceleration.

Solution:

Initial velocity of the car,

$$v_1 = 70 \text{ km/h}$$
$$= \frac{70 \times 1000}{3600}$$
$$= 19.44 \text{ m/s}$$

Final velocity of the car,

$$v_2 = 25 \text{ km/h}$$
$$= \frac{25 \times 1000}{3600}$$
$$= 6.94 \text{ m/s}$$

Time taken for this decrease,

$$t = 9{:}12 - 9{:}10 = 2 \text{ min}$$
$$= 120 \text{ s}$$

$$\text{Deceleration} = \frac{\text{decrease in velocity}}{\text{time taken}}$$
$$= \frac{v_1 - v_2}{t}$$
$$= \frac{19.44 - 6.94}{120} \qquad \frac{\text{m}}{\text{s}}\frac{1}{\text{s}} \equiv \frac{\text{m}}{\text{s}^2}$$
$$= 0.104 \text{ m/s}^2$$

1.4.5 Force

Symbol: F Unit: Newton (N)

Force is a measure of the 'push' or 'pull' which is often exerted on a body. When exerted on a mass (m), a force (F) will produce an acceleration (a) (see Figure 1.6). The magnitude of this force is given by Newton's equation:

$$F = m \times a \tag{1.1}$$

Force is not a basic unit since it clearly depends on the units for mass and acceleration. Hence, in the S.I. system, the unit of force is the unit of mass (kg) multiplied by the unit of acceleration (m/s^2), or the kilogram metres per second squared. This is not very convenient and is, therefore, replaced by a unit called the Newton (N).

$$1\ \text{N} \equiv 1\ \text{kg}\ \frac{\text{m}}{\text{s}^2}$$

1 N is too small a force for many practical problems and so the kilonewton is commonly used instead:

$$1\ \text{kN} = 1000\ \text{N}$$

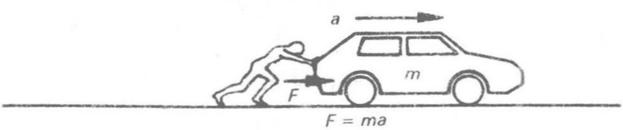

Figure 1.6 A force produces an acceleration

1.4.6 Weight

Symbol: w Unit: Newton (N)

This is the gravitational attractive force which the Earth exerts on a mass (see Figure 1.7). Weight depends on the acceleration due to gravity (g) and this varies with height and location on the earth. However, an average value of $g = 9.81\ m/s^2$ is commonly used, and this is assumed throughout this book. Since weight is a force, weight and mass are related by the equation:

$$w = m \times g \qquad \text{kg}\ \frac{\text{m}}{\text{s}^2} \equiv \text{N} \qquad (1.2)$$

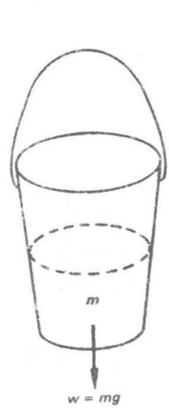

Figure 1.7 The weight of a fluid

1.4.7 Density

Symbol: ρ (Greek letter rho) Unit: kilogram per cubic metre (kg/m^3)

The density of a substance is the mass packed into unit volume. Density is therefore determined by dividing mass by volume:

$$\rho = \frac{\text{mass}}{\text{volume}} = \frac{m}{V} \tag{1.3}$$

Substances have different densities and a dense substance will sink in a fluid (i.e. gas or liquid) which is less dense. In fluid mechanics, the density of a substance is often very important, and some approximate values for common substances are given in Table 1.1.

Table 1.1 Density of common substances

Substance	Density kg/m^3
Gold	19 300
Mercury	13 600
Steel	7800
Water	1000
Oil	800
Air	1.22
Helium	0.18

1.4.8 Specific volume

Symbol: None Unit: cubic metre per kilogram (m^3/kg)

The specific volume of a substance is the volume occupied by unit mass. Specific volume is, therefore, the reciprocal of density.

$$\begin{aligned}\text{Specific volume} &= \frac{\text{volume}}{\text{mass}} \\ &= \frac{V}{m} \\ &= \frac{1}{\rho} \qquad (1.4)\end{aligned}$$

$$\text{Specific volume of water} = \frac{1}{\rho} = \frac{1}{1000} = 0.001\ m^3/kg$$

$$\text{Specific volume of atmospheric air} = \frac{1}{\rho} = \frac{1}{1.22} = 0.82\ m^3/kg$$

Example 1.4

A temporary overhead water tank is to be installed on a steel structure as shown in Figure 1.8. The tank size is 1.5 m × 1.5 m × 1 m. Estimate the maximum downward force acting on the structure.

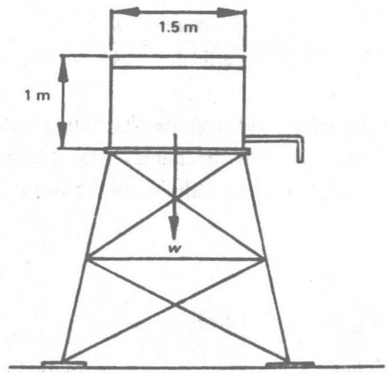

Figure 1.8 An overhead water tank

Solution:

Volume of the tank,

$$= X \times Y \times Z$$
$$= 1.5 \times 1.5 \times 1 \qquad \text{m m m} \equiv \text{m}^3$$
$$= 2.25 \text{ m}^3$$

Mass of water when the tank is full:

$$m = \text{volume} \times \text{density}.$$

$$m = 2.25 \times 1000 \qquad \text{m}^3 \frac{\text{kg}}{\text{m}^3} \equiv \text{kg}$$

$$= 2250 \text{ kg}$$

Weight of water,

$$w = mg$$

$$= 2250 \times 9.81 \qquad \text{kg} \frac{\text{m}}{\text{s}^2} \equiv \text{N}$$

$$= 22\,072 \text{ N} = 22.07 \text{ kN}$$

The maximum force on the structure is about 22 kN.

1.4.9 Relative density

Symbol: s Unit: None

In fluid mechanics it is sometimes useful to say how many times a substance is denser than water. This can be determined by dividing the density of the substance by the density of water:

$$s = \frac{\text{density of substance}}{\text{density of water}} \tag{1.5}$$

Also

$$s = \frac{\text{weight of substance}}{\text{weight of same volume of water}}$$

Since relative density is a ratio, it has no units. The relative density of a substance is also called its specific gravity, often abbreviated to s.g. Specific gravity of some common fluids are given in Table 1.2.

Table 1.2 Relative density of some fluids

Fluids	s
Gasoline	0.68
Alcohol	0.79
Sea water	1.025
Blood	1.05
Mercury	13.6

Example 1.5

A hot-air balloon is 5 m in diameter (as shown in Figure 1.9). A small blower and a gas burner are used to inflate the balloon. If the specific volume of hot air is 0.9 m^3/kg, what is the weight of air in the balloon? Explain briefly why the balloon rises in the atmosphere.

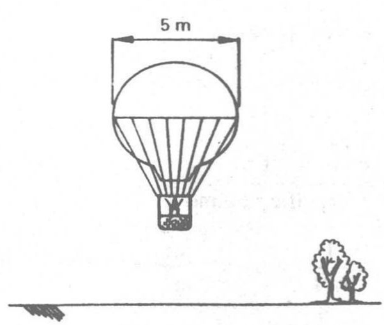

Figure 1.9 A hot-air balloon