CHAPTER 8

Basic properties of fluids

Objectives

On completion of this chapter you should be able to:

- define a fluid and describe the characteristics of the various types of fluids;
- describe the basic properties of fluids and recognise that these properties can be physical or chemical properties;
- define the following physical properties of fluids and quote correct units for them: mass, volume, density, relative density, specific volume, force, weight, pressure, temperature and viscosity; also calculate a property given relevant data, for example density, given mass and dimensions;
- describe how viscosity may be measured and know the difference between kinematic and dynamic viscosity;
- describe saturation vapour pressure and temperature and draw a graph showing the typical relationship between them for a liquid;
- describe the environmental impact considerations necessary when using fluids in engineering applications.

Introduction

Fluid mechanics is the study of fluids. It has several branches. The branch concerned with fluids at rest is known as fluid statics, and the branch concerned with fluids in motion is called fluid dynamics,. The study of pressurised air systems is known as pneumatics and the study of pressurised liquid systems is known as hydraulics.

This chapter is primarily concerned with the fundamental concepts and the basic properties of fluids; later chapters will be devoted to the study of the statics and dynamics of fluids in greater detail.

8.1 TYPES OF FLUID

A **fluid** is a liquid or a gas. At the molecular level, the distinction between fluids and solids is that in fluids the molecules have translational mobility whereas in solids they retain fixed spatial orientation. In solids, the molecules are able to vibrate or rotate only, but cannot change position relative to each other. The observable result of this is that fluids can flow whereas solids cannot.

A **liquid** is a fluid in which the molecules are free to move yet they still have *cohesiveness* because the molecules are close together and are attracted to each other. If a liquid is poured onto a flat surface, the liquid spreads out but remains in pools. A liquid poured into a container will settle with a free surface.

A **gas** is a fluid in which there is usually little or no cohesiveness between the molecules because they are widely spaced. If a gas is released from a vessel into the atmosphere, the molecules tend to disperse in all directions and do not cling together. A gas pumped into a vessel occupies the entire volume available with no free surface.

A **vapour** is a gas. However, the term vapour is usually used to refer to the gaseous state of substances that are usually liquid. For example, mercury is normally a liquid but there is mercury vapour present above the liquid surface in a mercury barometer. Similarly, water that evaporates is also known as water vapour. Solids can also be vaporised; for example, in a welding arc there is metal vapour.

A **slurry** is a liquid mixture containing suspended solid particles. The particles may be very fine as is the case when fine dusts are mixed with resins to make fillers or in the case of muddy water. The particles may also be quite coarse as is the case with blue-metal stones in concrete. Solid particles may also be suspended in gases as is the case with dust in air or the fine particles of carbon that appear as smoke in exhausts. Fine particles may remain in suspension for a long time but coarser particles tend to settle out under the influence of gravity.

Atomised liquids contain liquid particles suspended in a gas as fine droplets. For example, when liquid perfume, paint, fly spray or fuel is atomised, the liquid is converted to numerous fine droplets and mixed with air. The distinction between atomised liquids and vaporised liquids is that atomised liquids have not undergone a phase change and have not absorbed the latent heat necessary for the phase change. For example, steam can be superheated, dry or wet; superheated and dry steam are vapours whereas wet steam is vapour mixed with water droplets that have not yet undergone the phase change.

Foam (or froth) is produced when a liquid is agitated and large numbers of bubbles form. The bubbles are numerous pockets of gas within the liquid. Certain liquids are much more prone to foaming than others; for example, detergents foam very readily but mercury does not. Foaming adds to the difficulties of filling or pumping liquids but sometimes it serves a useful purpose (as with foam fire extinguishers or when clothes are being washed).

8.2 PROPERTIES OF A FLUID

Fluids have many characteristics or properties that are often classified as either physical or chemical properties. Some fluid properties important in engineering are now outlined.

The **solubility** of a substance in a liquid is the extent to which the substance will dissolve in the liquid to form a homogenous mixture. Unlike a slurry, separation cannot be effected by mechanical means (such as centrifuging). For example, when a cup of coffee is made with instant coffee, the coffee particles dissolve in the water, which is also the case if sugar is added. In carbonated beverages (such as soft drinks or soda water), the gas (carbon dioxide) is dissolved in water. Many liquids will also dissolve other liquids; for example, alcohol will readily dissolve in water (the basis of alcoholic drinks), whereas kerosene and oil are insoluble and will quickly separate out if mixed with water.

Whereas a solvent is any liquid that has dissolved another substance, the word solvent is also used to describe liquids that will dissolve solids readily. For example, many paints contain solvents that dissolve the colour pigments and other ingredients of the paint.

The amount of a substance that may be dissolved in the solvent (at given conditions) is known as the **concentration** and is limited to a maximum amount. Maximum concentration is known as the **saturated** condition. For example, if sugar is added to a cup of coffee until the water is saturated, then additional sugar will not dissolve but will remain in the solid state.

With solids or liquids, solubility depends primarily on the temperature of the solvent, and the higher the temperature the greater the solubility. For example, if salt is added to hot water until the saturation condition is reached, then, as the water cools, salt will come out of solution and form crystals.

With gases, solubility depends on both the temperature and the pressure of the solvent. The lower the temperature, the higher the solubility and the higher the pressure the greater the solubility. For example, if water is heated, dissolved air will be seen to come out of solution long before the water boils. Similarly, when a carbonated drink under pressure is opened, bubbles form as the carbon dioxide comes out of solution with the reduced pressure.

Solubility has significance in many engineering applications. For example, in a steam boiler, dissolved air coming out of the water is a nuisance because it reduces the heat-transfer capability and increases corrosion. Also, with propellers or pumps operating with liquids, gas bubbles in regions of low pressure may severely impede performance.

The **compressibility** of a fluid is the extent to which the fluid volume may be reduced by an increase in pressure. In liquids, the molecules are close together and, like a solid, cannot be made to close up much more even with the application of enormous pressures. Therefore, for most engineering applications in fluid mechanics, liquids may be regarded as *incompressible,* with little error.

However, the molecules of a gas are far apart and they can be brought closer together by compressing the gas and reducing the volume. Similarly a compressed gas can expand and increase in volume. There are many ways (or processes) by which expansion or compression of a gas can occur. These are dealt with in detail in Chapter 5.

The **surface tension** of a liquid is the cohesive force that occurs at the surface of the liquid. That is, the liquid surface appears to have a 'skin' or membrane over it. This can be verified experimentally by carefully placing a steel razor blade or a needle on a water surface, where it can be made to 'float'. However, if placed below the surface it will sink because steel is more dense than water. The apparent flotation is due to surface tension. Surface tension effects are also observable at the edges of a liquid in a container, where there is a 'meniscus'. With water the meniscus has an upward curve, whereas with mercury it has a downward curve.

Surface tension forces are small and can generally be neglected in fluid mechanics calculations. However, surface tension has some important effects; it is responsible for the spherical shape of bubbles and droplets of fluid and for 'capillary' action. When a small-bore tube (capillary) is inserted into a liquid that has an upward curving meniscus, the liquid will rise in the tube because there is an upward component of the surface tension force. This also causes 'wicking' where such a liquid will move of its own accord into a porous substance. This principle is used in the lubrication of bearings, enables ink to flow in ball-point pens and is the reason paper or cotton towels absorb liquids.

The **corrosiveness** of a fluid is the extent to which the fluid will enter into a chemical reaction with the materials it comes in contact with. For example, many acids react with many metals and are best kept in glass or plastic containers. Sea water is also corrosive and will react with many metals such as aluminium, copper and steel. Corrosiveness is very important in fluid mechanics because it dictates the materials suitable for containing or pumping fluids. For example, it would be poor engineering to specify aluminium or mild steel impellers for sea-water pumps because they would soon corrode and malfunction.

The **toxicity** of a fluid is the extent to which the fluid has harmful effects on humans (or other animals) when inhaled or digested. A toxic fluid is also known as a poisonous fluid. Toxicity depends primarily on concentration. For example, low concentrations of carbon monoxide in air cause no apparent health detriment, but as the concentration increases, there comes a point at which death can occur rapidly.

Toxicity is important to engineers because many fluid applications involve fluids that can be ingested by humans. For example, gases are often stored under pressure and a small leak of a toxic gas could increase the concentration of the gas to a dangerous level over a period of time. Also, fluids can dissolve substances that can accumulate over a period of time to toxic levels; for this reason lead pipes are no longer used for conveying water to be used for drinking or washing.

Other properties of fluids such as mass, volume, density and so on, are important physical properties that have already been treated in this book in Chapter 2. It is suggested that they now be revised under the following sections: 2.3 Mass, 2.4 Volume, 2.5 Density, 2.6 Relative density, 2.7 Specific volume, 2.8 Force, 2.9 Weight, 2.10 Pressure (absolute and gauge), 2.11 Temperature (absolute and Celsius). Two self-test problems now follow to help in this revision process.

Self-test problem 8.1

A cylindrical vessel of internal diameter 560 mm and length 1200 mm contains 520 kg of liquid.

(a) Determine the density and relative density of the liquid.

(b) If the vessel held a gas of specific volume 0.35 kg/m^3 what mass of gas would there be?

Self-test problem 8.2

A pressure gauge calibrator as shown in Figure 8.1 has a 30 mm diameter piston. The combined mass of the piston and carrier is 0.5 kg. Determine the correct pressure gauge reading when a mass of 1.5 kg is placed on the carrier.

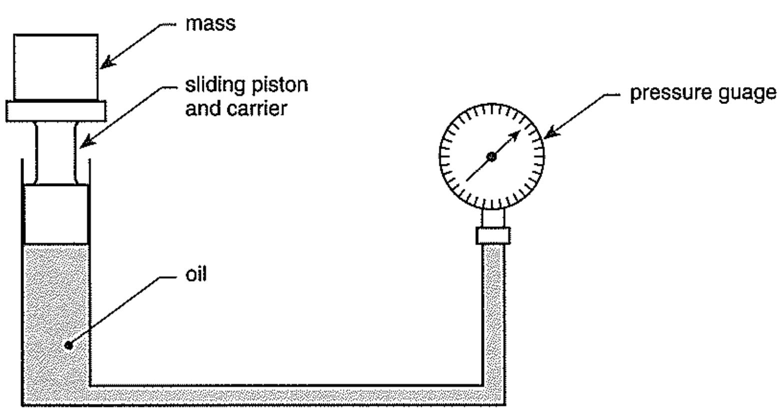

Fig. 8.1

8.3 VISCOSITY

The main distinction between fluids and solids is that fluids can flow whereas solids cannot. When a solid is moved over another solid, there is a friction force opposing the motion. Fluids also exhibit friction when the fluid flows through a pipe or from a hole in a tank. Some fluids flow more readily than others, and the resistance to flow is an important fluid property known as **viscosity**. For example, highly viscous liquids like honey or thick oil do not flow readily whereas low-viscosity liquids like water or alcohol flow far more readily. Gases also exhibit resistance to flow and have viscosity. As would be expected, the viscosity of liquids is far greater than the viscosity of gases.

In liquids, viscosity is due to cohesiveness, because the molecules tend to stick together and resist the shearing action necessary for flow to occur. Consequently, the viscosity of liquids decreases with temperature because cohesive forces reduce with temperature.

In gases, viscosity is due to momentum transfer, that is, collisions between faster and slower moving molecules, which have a component of the velocity in a direction perpendicular to the direction of flow. Because molecular velocity increases with temperature, the viscosity of gases (unlike liquids) increases with temperature.

Viscosity measurement

Viscosity can be measured in many different ways, but devices to measure viscosity (viscometers) can be grouped into one of three classes as outlined below. Theoretical calculation of the viscosity is impractical and viscometers need to be *calibrated* using fluids of known viscosity.

Types of viscometers

Rotational viscometers The fluid is enclosed as a thin film between two concentric cylinders. The outer cylinder is rotated at a given speed and the torque on the inner cylinder is measured. The greater the viscosity of the fluid, the higher the torque.

Falling-sphere viscometers A ball of standard size and weight is dropped a given distance through the fluid and the time measured. The higher the viscosity, the longer the time.

Flow viscometers A known quantity of fluid flows through a small orifice or capillary tube. The time taken is measured. The higher the viscosity, the longer the time.

Units of viscosity

There are two types of viscosity, namely kinematic viscosity and dynamic viscosity and each has different units.

Dynamic viscosity In the SI system, dynamic viscosity has units kg/ms, which is more often written as Pas (pascal seconds). In this book the Greek letter μ (pronounced mu) will be used for dynamic viscosity. The imperial unit of dynamic viscosity, the centipoise, is still in use. To convert from centipoise to Pas, multiply by 10^{-3}.

Note The SAE rating used with motor oils is the dynamic viscosity in centipoises at rated engine-oil temperature of 68°C. For example, SAE 30 oil has a viscosity of 30 centipoises at the rated temperature.

Kinematic viscosity In the SI system, kinematic viscosity has units m^2/s. In this book the Greek letter ν (pronounced nu) will be used for kinematic viscosity. In imperial units, kinematic viscosity is measured in centistokes. To convert from centistokes to m^2/s, multiply by 10^{-6}. Kinematic viscosity can be calculated from dynamic viscosity by dividing by the density of the fluid as given by Equation 8.1 below:

$$\nu = \frac{\mu}{\rho} \qquad \text{kinematic viscosity (8.1)}$$

Note It is very important not to confuse kinematic and dynamic viscosity. Sometimes viscosity will be stated without qualifying whether it is dynamic or kinematic viscosity. In such cases, look at the units, which will define clearly which viscosity is being used.

Self-test problem 8.3

An SAE 60 motor oil has a relative density of 0.92. Determine the dynamic and kinematic viscosity in SI units.

8.4 SATURATION VAPOUR TEMPERATURE AND PRESSURE OF A LIQUID

If water is placed in a container at atmospheric pressure and heat is supplied so as to raise the temperature, the water will boil at 100°C. This temperature is known as the *saturation vapour temperature*, because at this temperature the liquid water has absorbed all the energy it can without changing phase. That is to say, further energy input causes no change in temperature but rather a change in phase. If the pressure is reduced, and the experiment repeated, it will be found that the water boils at a lower temperature. If the pressure is increased, the water boils at a higher temperature (a fact used in pressurised-cooling systems and in pressure cookers). The relationship between saturation vapour temperature and pressure for water is shown graphically in Figure 8.2 (opposite).

A similarly *shaped* curve is obtained for most liquids but the *position* of the curve relative to the axes may be quite different from that of water. Liquids that boil more readily than water at lower temperatures (for the same pressure) are known as **volatile** liquids and include ether, alcohol and refrigerants. Indeed, the lower temperature of boiling of these liquids is the principle behind mechanical refrigerators. A typical curve for a volatile liquid (in this case a refrigerant, R12) is also shown in Figure 8.2.

8.5 ENVIRONMENTAL IMPACT

Fluids can escape into the atmosphere or into a waterway far more readily than solids and therefore their environmental impact is an important consideration for engineers. For example, when a car is hosed after being washed, detergents and oils in the wash water may flow into gutters and drains and eventually end up in a river or sea, where they will have deleterious environmental effects. Even non-toxic gases such as carbon dioxide or refrigerants have adverse ecological effects if released into the atmosphere in sufficient quantities (greenhouse effect).

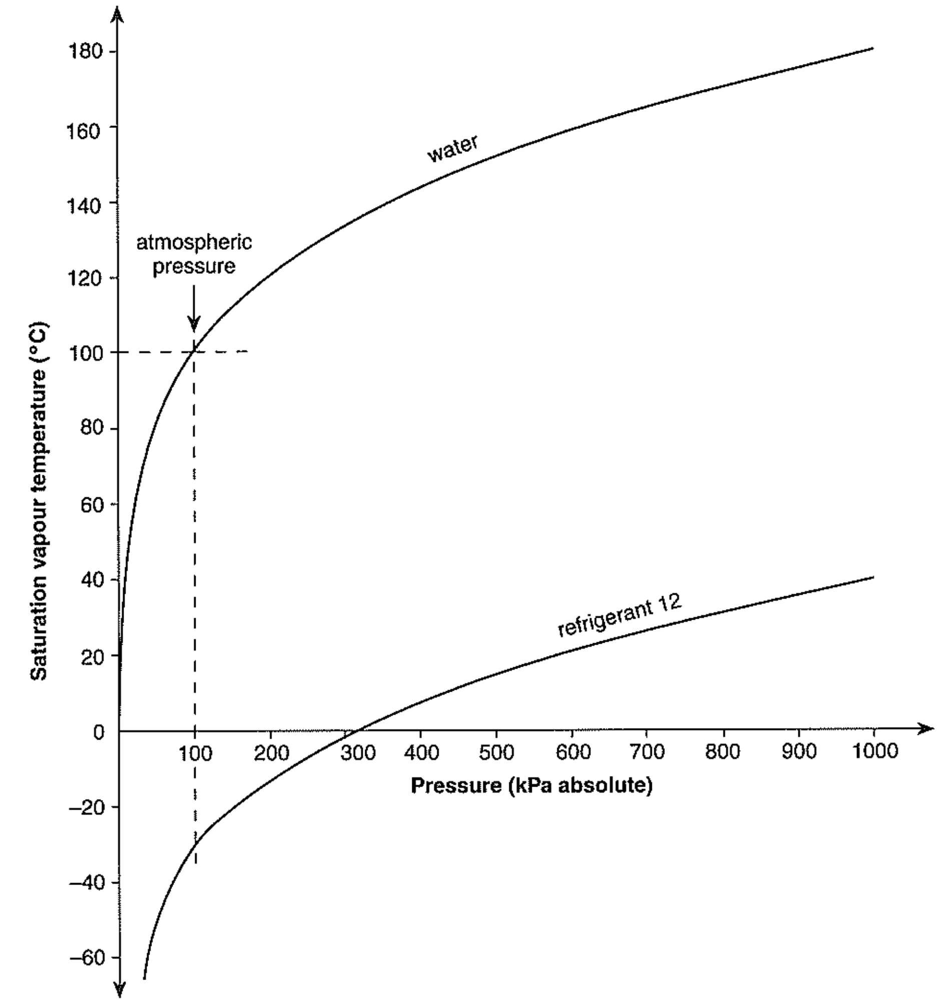

Fig. 8.2 *Relationship between saturation vapour temperature and pressure*

Disposal of liquids through sewage systems does not eliminate the environmental problems and is usually not allowed by governmental authorities. These systems are an essentially biological treatment of effluent and cannot eliminate heavy metals and other toxic substances. Therefore nowadays, most industrial plants are obliged to install and operate pollution-control equipment that reduces pollutant levels to an acceptable limit. Alternatively, liquids are often held in sludge tanks, then pumped out at periodic intervals and taken away to be dumped at a site where the ecological impact will be minimal.

Summary

A fluid is a liquid or a gas. Fluids can flow but exhibit resistance to flow in the same way that friction resists the movement of one solid over another. The resistance to flow of a fluid is known as its viscosity; high-viscosity liquids like honey do not flow readily whereas low-viscosity fluids like water flow readily. The viscosity of liquids is much higher than the viscosity of gases because of the cohesiveness of the molecules of a liquid. There are two types of viscosity, namely dynamic viscosity and kinematic viscosity and each has different units. Care should be taken to apply the correct viscosity and units when substituting in equations.

Often, fluids exist as a mixture of liquids, gases and solid particles. A liquid containing solid particles is known as a slurry whereas foams are a mixture of gases and liquids. Liquids may also be atomised and exist as numerous fine droplets.

Many solids, liquids or gases dissolve to some extent in a different type of liquid to form a homogeneous solution. The amount dissolved is known as the concentration (usually expressed as a percentage) and is limited to a certain maximum amount that occurs at the saturated condition. The concentration of a solid or liquid in another liquid increases with the temperature of the liquid. The concentration of a gas in a liquid decreases with the temperature of the liquid and increases with the pressure of the gas.

Liquids exhibit surface tension at the liquid surface. Surface tension forces are only small but are of importance in the operation of many devices. Surface tension causes capillary action, which enables liquids to 'wick' through porous substances and enables cotton or paper towels to absorb liquids.

Two important chemical properties of fluids are corrosiveness and toxicity. Corrosiveness needs to be taken into account when designing fluid-pumping or fluid-holding systems and toxicity is important whenever a fluid may be ingested or inhaled by people. Also care is needed to ensure that fluids do not escape into the atmosphere or waterways where they can have a deleterious environmental impact (particularly if they are toxic).

Many physical properties may be used to describe the state of fluids, such as mass, volume, density, and so on. Temperature and pressure are also important properties and care is needed to distinguish between absolute and Celsius temperatures and absolute and gauge pressures.

The temperature at which a liquid will boil (at a given pressure) is known as the saturation vapour temperature. A graph of saturation vapour temperature plotted against pressure shows that, as pressure rises, saturation vapour temperature also increases (but not linearly). Volatile liquids boil at lower temperatures than do other liquids.

Problems

8.1 Describe briefly what is meant by the following:
(a) liquid
(b) gas
(c) slurry
(d) atomised liquid
(e) foam

8.2 Describe briefly what is meant by the following:
(a) solubility
(b) concentration
(c) saturated solution

8.3 **(a)** Explain what is meant by the compressibility of a fluid; name the group of fluids that can be considered almost incompressible and explain why this is so.
(b) Explain briefly what is meant by surface tension and describe an experiment to demonstrate the existence of surface tension.
(c) Explain briefly what is meant by capilliary action and why it is of significance.

8.4 **(a)** Explain briefly the meaning of corrosiveness and toxicity of a fluid.
(b) Explain briefly why engineers need to be concerned about environmental pollution when dealing with fluids and describe *two* types of environmental pollution that can occur with both gases and liquids.

8.5 **(a)** Explain briefly what is meant by viscosity of a fluid and how temperature affects the viscosity of both liquids and gases.
(b) An SAE 30 oil has a relative density of 0.897 and a dynamic viscosity of 380 centipoise at 16°C. At this temperature determine:
(i) the dynamic viscosity in SI units;
(ii) the kinematic viscosity in SI units.
(i) 0.38 Pas (ii) 424×10^{-6} m²/s

8.6 Define the meaning of and state SI units for:
(a) mass
(b) volume
(c) density
(d) relative density
(e) specific volume

8.7 **(a)** What is meant by the saturation vapour temperature of a liquid?
(b) Draw a neat graph showing the saturation vapour temperature of water against absolute pressure, clearly marking the point of normal atmospheric pressure. Also show how the graph would look for a liquid more volatile than water.

8.8 A liquid half fills a cylindrical container with a diameter of 200 mm and a length of 1500 mm. If the weight of liquid is 223 N, determine the density and relative density of the liquid.
965 kg/m^3; 0.965

8.9 Gas of specific volume 0.6 m^3/kg is in a cylindrical vessel of diameter 400 mm and length 1600 mm. Determine the mass of gas in the vessel.
If a further 0.5 kg of the same gas is added to the vessel what will now be the specific volume and density?
0.335 kg; 0.241 m^3/kg; 4.15 kg/m^3

8.10 Sea water of relative density 1.03 is at a depth of 2.5 m above a horizontal circular plate of diameter 400 mm. Determine the force on the plate and, hence, the pressure exerted by the sea water on it.
3.17 kN; 25.3 kPa

8.11 A steel piston of diameter 50 mm and length 300 mm is placed in a vertical cylinder closed at the bottom end. Determine the pressure of the enclosed air when the piston

comes to rest. Assume no friction or leakage loss and take the relative density of steel to be 7.8.
23 kPa (gauge)

8.12 Some of the trapped air is released from the piston- and cylinder-arrangement given in Problem 8.11 and the arrangement inverted. Determine the gauge and absolute pressure of the trapped air when the piston comes to rest once more.
–23 kPa (vacuum); 78.3 kPa

8.13 A steel tank of weight 4 kN has base dimensions of 1.2 m × 3.5 m and contains kerosene (*RD* 0.8) to a depth of 2.5 m. The tank is supported by four pads such that the load is equally distributed. Determine:
(a) the force on each pad;
(b) the fluid pressure on the base of the tank.
(a) 21.6 kN (b) 19.6 kPa (gauge)

8.14 If 2100 L of kerosene is drawn out of the tank given in Problem 8.13, determine:
(a) the depth of kerosene now in the tank;
(b) the force on each supporting pad;
(c) the pressure on the tank base.
(a) 2 m (b) 17.5 kN (c) 15.7 kPa (gauge)

8.15 For the hydraulic jack illustrated in Figure P8.15, determine:
(a) the fluid pressure;
(b) the ram force *F*.
(a) 637 kPa (gauge) (b) 5 kN

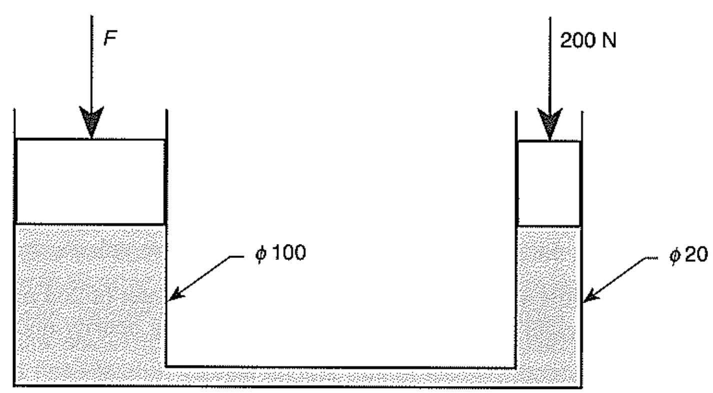

Fig. P 8.15

8.16 The pressure-gauge calibrator given in Self-test problem 8.2 has a mass of 2.5 kg placed on the carrier. The pressure gauge reading is 38 kPa. Determine the percentage error in the gauge reading.
8.73% too low

CHAPTER 9

Components and their selection

Objectives

On completion of this chapter you should be able to:

- describe the various common components used in a fluid system and their purposes;
- explain, with the aid of a sketch, the operating principles of the components described;
- list the main features and advantages and disadvantages of the various components;
- describe the factors that should be taken into account in the selection of the various components.

Introduction

Fluid systems involve a number of components including pipes, fittings, valves, tanks and so on. The various common components found in fluid systems will now be discussed and their main features emphasised. The factors to be considered when selecting components are also listed.

9.1 *PIPES, TUBES AND DUCTS*

Pipes, tubes and ducts are used to transport fluid. There is no essential difference between a pipe and a tube, usage of one term over the other depends primarily on established practice. Ducts are usually made of thin-wall material such as sheet metal and are used for low-pressure gases (for example air-conditioning or ventilation ducts). Channels, culverts and drains are used to transfer a liquid (usually water) that is not under pressure but flows under the influence of gravity. In this case there is usually a free surface.