

CHAPTER 4

FLUID-FLOW APPLICATIONS

Two practical aspects of fluid flow in food technology are: measurement in fluids including pressures and flow rates, and production of fluid flow by means of pumps and fans. When dealing with fluids, it is important to be able to make and to understand measurements of pressures and velocities in the equipment. Only by measuring appropriate variables such as the pressure and the velocity can the flow of the fluid be controlled. When the fluid is a gas it is usually moved by a fan, and when a liquid by a pump. Pumps and fans are very similar in principle and usually have a centrifugal or rotating action, although some pumps use longitudinal or vertical displacement.

MEASUREMENT OF PRESSURE IN A FLUID

The simplest method of measuring the pressure of a fluid in a pipe is to use a piezometer ("pressure measuring") tube. This is a tube, containing the fluid under pressure, in which the fluid is allowed to rise to a height that corresponds to the excess of the pressure of the fluid over its surroundings. In most cases the surroundings are ambient air as shown in Fig. 4.1(a).

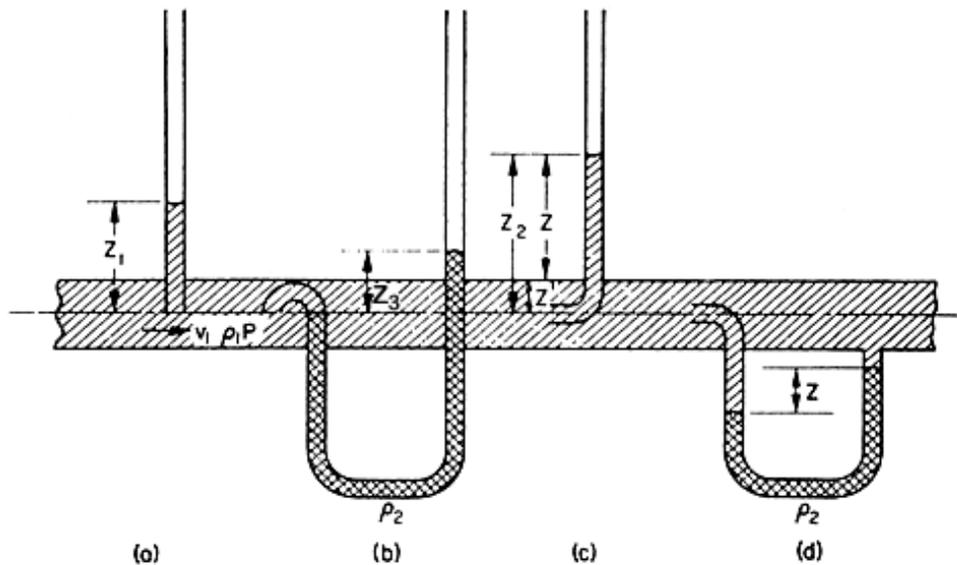


Figure 4.1. Pressure measurements in pipes.

In Fig. 4.1(a) the pressure of the fluid in the pipe is measured by allowing the fluid to rise in the vertical tube until it reaches equilibrium with the surrounding air pressure, the height to which it

rises is the pressure head existing in the pipe. This tube is called the manometer tube. The height (head) can be related to the pressure in the pipe by use of eqn. (3.3) and so we have:

$$P = Z_1 \rho_1 g$$

where P is the pressure, Z_1 is the height to which the fluid rises in the tube, ρ_1 is the density of the fluid and g the acceleration due to gravity..

A development of the piezometer is the U-tube, in which another fluid is introduced which must be immiscible with the fluid whose pressure is being measured. The fluid at the unknown pressure is connected to one arm of the manometer tube and this pressure then causes the measuring fluid to be displaced as shown in Fig. 4.1(b). The unknown pressure is then equal to the difference between the levels of the measuring fluid in the two arms of the U-tube, Z_3 . The differential pressure is given directly as a head of the measuring fluid and this can be converted to a head of the fluid in the system, or to a pressure difference, by eqn. (3.3).

EXAMPLE 4.1. Pressure in a vacuum evaporator

The pressure in a vacuum evaporator was measured by using a U-tube containing mercury. It was found to be less than atmospheric pressure by 25cm of mercury. Calculate the extent by which the pressure in the evaporator is below atmospheric pressure (i.e. the vacuum in the evaporator) in kPa, and also the absolute pressure in the evaporator. The atmospheric pressure is 75.4cm of mercury and the specific gravity of mercury is 13.6.

$$\begin{aligned} \text{We have } P &= Z\rho g \\ &= 25 \times 10^{-2} \times 13.6 \times 1000 \times 9.81 \\ &= 33,354 \text{ kg m s}^{-2} \\ &= \underline{33.4 \text{ kPa}} \end{aligned}$$

Therefore the pressure in the evaporator is 33.4 kPa below atmospheric pressure and this is the vacuum in the evaporator.

For atmospheric pressure:

$$\begin{aligned} P &= 75.4 \times 10^{-2} \times 13.6 \times 1000 \times 9.81 \\ &= 100.6 \text{ kPa} \end{aligned}$$

Therefore the absolute pressure in the evaporator

$$\begin{aligned} &= 100.6 - 33.4 \\ &= \underline{67.2 \text{ kPa}} \end{aligned}$$

Although manometer tubes are used quite extensively to measure pressures, the most common pressure-measuring instrument is the Bourdon-tube pressure gauge. In this, use is made of the fact that a coiled tube tends to straighten itself when subjected to internal pressure and the degree of straightening is directly related to the difference between the pressure inside the tube and the pressure outside it. In practice, the inside of the tube is generally connected to the unknown system and the outside is generally in air at atmospheric pressure. The tube is connected by a rack and pinion system to a pointer, which can then reflect the extent of the straightening of the

tube. The pointer can be calibrated to read pressure directly. A similar principle is used with a bellows gauge where unknown pressure, in a closed bellows, acts against a spring and the extent of expansion of the bellows against the spring gives a measure of the pressure. Bellows-type gauges sometimes use the bellows itself as the spring.

MEASUREMENT OF VELOCITY IN A FLUID

As shown in Fig. 4.1(c), a bent tube is inserted into a flowing stream of fluid and orientated so that the mouth of the tube faces directly into the flow. The pressure in the tube will give a measure of velocity head due to the flow. Such a tube is called a Pitot tube. The pressure exerted by the flowing fluid on the mouth of the tube is balanced by the manometric head of fluid in the tube. In equilibrium, when there is no movement of fluid in the tube, Bernoulli's equation can be applied. For the Pitot tube and manometer we can write:

$$Z_1g + v_1^2/2 + P_1/\rho_1 = Z_2g + v_2^2/2 + P_2/\rho_1$$

in which subscript 1 refers to conditions at the entrance to the tube and subscript 2 refers to conditions at the top of the column of fluid which rises in the tube. Taking the datum level at the mouth of the tube, Z_1 is zero. If Z' is the height of the upper liquid surface in the pipe above the datum, and Z be the additional height of the fluid level in the tube above the upper liquid surface in the pipe;

$$Z_2 = Z + Z'$$

Z' may be neglected if P_1 is measured at the upper surface of the liquid in the pipe, or if Z' is small compared with Z . So:

$$Z_2 = Z$$

$$v_2 = 0 \text{ as there is no flow in the tube.}$$

$$P_2 = 0 \text{ if atmospheric pressure is taken as datum, the top of the tube is open to the atmosphere.}$$

$$Z = 0 \text{ because the datum line is at the mouth of the tube}$$

The equation then simplifies to:

$$v_1^2/2 + P_1/\rho_1 = (Z + Z')g \cong Zg$$

$$v_1^2/2g + P_1/\rho_1g \cong Z \tag{4.1}$$

This analysis shows that the differential head on the manometer measures the sum of the velocity head and the pressure head in the **flowing** liquid.

The Pitot tube can be combined with a piezometer tube, and connected across a common manometer as shown in Fig. 4.1(d). The differential head, Z , across the manometer is the velocity head plus the static head of the Pitot tube, less the static head of the piezometer tube. In other words, the differential head measures directly the velocity head of the flowing liquid or gas. This differential arrangement is known as a Pitot-static tube and it is extensively used in the measurement of flow velocities.

We can write for the Pitot-static tube:

$$Z = v^2 / 2g \quad (4.2)$$

where Z is the differential head measured in terms of the flowing fluid.

EXAMPLE 4.2. Velocity of air in a duct

Air at 0°C is flowing through a duct in a chilling system. A Pitot-static tube is inserted into the flow line and the differential pressure head, measured in a micromanometer, is 0.8mm of water. Calculate the velocity of the air in the duct. The density of air at 0°C is 1.3kgm^{-3}

From eqn. (4.2) we have

$$Z = v_1^2 / 2g$$

In working with Pitot-static tubes, it is convenient to convert pressure heads into equivalent heads of the flowing fluid, in this case air, using the relationship from eqn 3.3:

$$\rho_1 Z_1 = \rho_2 Z_2.$$

Now $0.8\text{mm water} = 0.8 \times 10^{-3} \times \frac{1000}{1.3}$
 $= 0.62 \text{ m of air}$

Also $v_1^2 = 2Zg$
 $= 2 \times 0.62 \times 9.81$
 $= 12.16 \text{ m}^2\text{s}^{-2}$

Therefore $v_1 = \underline{3.5 \text{ ms}^{-1}}$

Another method of using pressure differentials to measure fluid flow rates is used in Venturi and orifice meters. If flow is constricted, there is a rise in velocity and a fall in static pressure in accordance with Bernoulli's equation. Consider the system shown in Fig. 4.2.

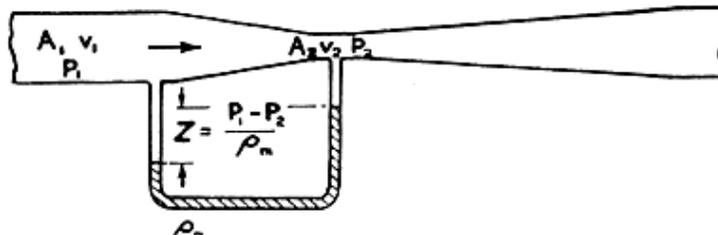


Figure 4.2 Venturi meter

A gradual constriction has been interposed in a pipe decreasing the area of flow from A_1 to A_2 . If the fluid is assumed to be incompressible and the respective velocities and static pressures are v_1

and v_2 , and P_1 and P_2 , then we can write Bernouilli's equation (eqn 3.7) for the section of horizontal pipe:

$$v_1^2/2 + P_1/\rho_1 = v_2^2/2 + P_2/\rho_2$$

Furthermore, from the mass balance, eqn. (3.5)

$$A_1v_1 = A_2v_2$$

also, as it is the same fluid

$$\rho_1 = \rho_2 = \rho$$

so that we have

$$v_1^2/2 + P_1/\rho = (v_1A_1/A_2)^2/2 + P_2/\rho$$

$$v_1^2 = [2(P_1 - P_2)/\rho] \times [A_2^2/(A_1^2 - A_2^2)]$$

By joining the two sections of a pipe to a U-manometer, as shown in Fig. 4.2, the differential head $(P_1 - P_2)/\rho$ can be measured directly. A manometric fluid of density ρ_m must be introduced, and the head measured is converted to the equivalent head of the fluid flowing by the relationship:

$$(P_1 - P_2)/\rho = Z\rho_m g / \rho$$

$$Z = (P_1 - P_2) / \rho_m g$$

If A_1 and A_2 are measured, the velocity in the pipe, v_1 , can be calculated. This device is called a Venturi meter. In actual practice, energy losses do occur in the pipe between the two measuring points and a coefficient C is introduced to allow for this:

$$v_1 = C \sqrt{[2(P_1 - P_2)/\rho] \times A_2^2/(A_1^2 - A_2^2)}$$

In a properly designed Venturi meter, C lies between 0.95 and 1.0.

The orifice meter operates on the same principle as the Venturi meter, constricting the flow and measuring the corresponding static pressure drop. Instead of a tapered tube, a plate with a hole in the centre is inserted in the pipe to cause the pressure difference. The same equations hold as for the Venturi meter; but in the case of the orifice meter the coefficient, called the orifice discharge coefficient, is smaller. Values are obtained from standard tables, for example British Standard Specification 1042. Orifices have much greater pressure losses than Venturi meters, but they are easier to construct and to insert in pipes.

Various other types of meters are used:

- propeller meters where all or part of the flow passes through a propeller, and the rate of rotation of the propeller can be related to the velocity of flow;
- impact meters where the velocity of flow is related to the pressure developed on a vane placed in the flow path;

- rotameters in which a rotor disc is supported against gravity in a tapered vertical tube and the rotor disc rises to a height in the tube which depends on the flow velocity.

PUMPS AND FANS

In pumps and fans, mechanical energy from some other source is converted into pressure or velocity energy in a fluid. The food technologist is not generally much concerned with design details of pumps, but should know what classes of pump are used and something about their characteristics.

The efficiency of a pump is the ratio of the energy supplied by the motor to the increase in velocity and pressure energy given to the fluid.

Positive Displacement Pumps

In a positive displacement pump, the fluid is drawn into the pump and is then forced through the outlet. Types of positive displacement pumps include: reciprocating piston pumps; gear pumps in which the fluid is enmeshed in rotating gears and forced through the pump; rotary pumps in which rotating vanes draw in and discharge fluid through a system of valves. Positive displacement pumps can develop high-pressure heads but they cannot tolerate throttling or blockages in the discharge. These types of pumps are illustrated in Fig. 4.3 (a), (b) and (c).

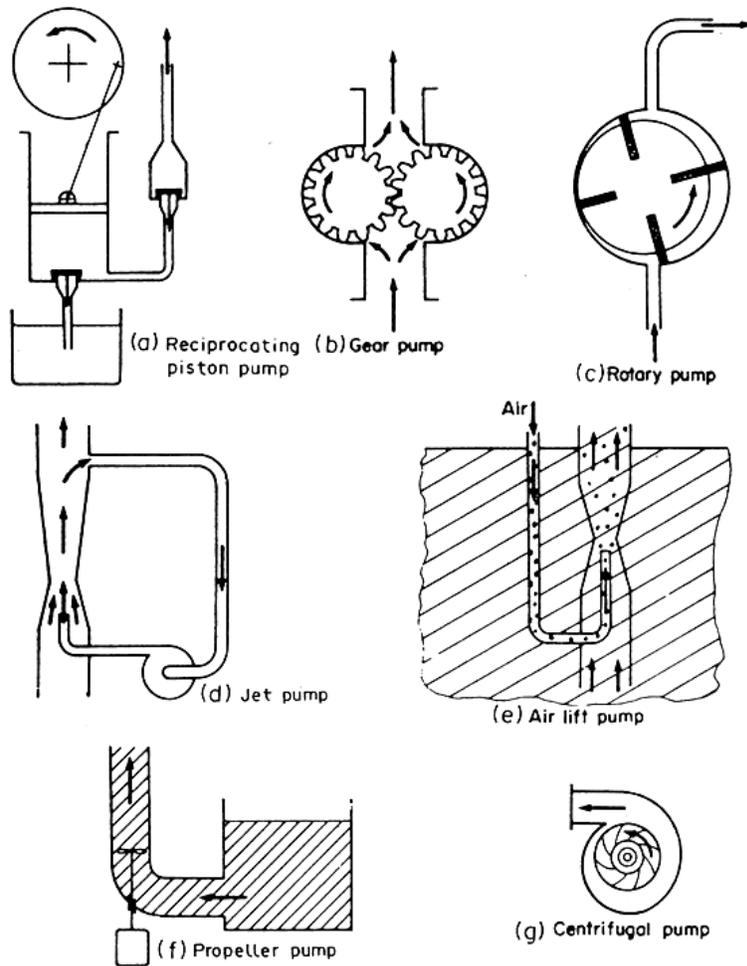


Figure 4.3 Liquid pumps

Jet Pumps

In jet pumps, a high-velocity jet is produced in a Venturi nozzle, converting the energy of the fluid into velocity energy. This produces a low-pressure area causing the surrounding fluid to be drawn into the throat as shown diagrammatically in Fig. 4.3(d) and the combined fluids are then discharged. Jet pumps are used for difficult materials that cannot be satisfactorily handled in a mechanical pump. They are also used as vacuum pumps. Jet pumps have relatively low efficiencies but they have no moving parts and therefore have a low initial cost. They can develop only low heads per stage.

Air-lift Pumps

If air or gas is introduced into a liquid it can be used to impart energy to the liquid as illustrated in Fig. 4.3 (e). The air or gas can be either provided from external sources or produced by boiling within the liquid. Examples of the air-lift principle are:

- Air introduced into the fluid as shown in Fig. 4.3(e) to pump water from an artesian well.
- Air introduced above a liquid in a pressure vessel and the pressure used to discharge the liquid.
- Vapours produced in the column of a climbing film evaporator.
- In the case of powdered solids, air blown up through a bed of powder to convey it in a "fluidized" form.

A special case of this is in the evaporator, where boiling of the liquid generates the gas (usually steam) and it is used to promote circulation. Air or gas can be used directly to provide pressure to blow a liquid from a container out to a region of lower pressure. Air-lift pumps and air blowing are inefficient, but they are convenient for materials which will not pass easily through the ports, valves and passages of other types of pumps.

Propeller Pumps and Fan

Propellers can be used to impart energy to fluids as shown in Fig. 4.3 (f). They are used extensively to mix the contents of tanks and in pipelines to mix and convey the fluid. Propeller fans are common and have high efficiencies. They can only be used for low heads, in the case of fans only a few centimetres or so of water.

Centrifugal Pumps and Fans

The centrifugal pump converts rotational energy into velocity and pressure energy and is illustrated in Fig. 4.3(g). The fluid to be pumped is taken in at the centre of a bladed rotor and it then passes out along the spinning rotor, acquiring energy of rotation. This rotational energy is then converted into velocity and pressure energy at the periphery of the rotor. Centrifugal fans work on the same principles. These machines are very extensively used and centrifugal pumps can develop moderate heads of up to 20m of water. They can deliver very large quantities of fluids with high efficiency. The theory of the centrifugal pump is rather complicated and will not be discussed. However, when considering a pump for a given application, the manufacturers will generally supply pump characteristic curves showing how the pump performs under various conditions of loading. These curves should be studied in order to match the pump to the duty required. Figure 4.4 shows some characteristic curves for a family of centrifugal pumps.

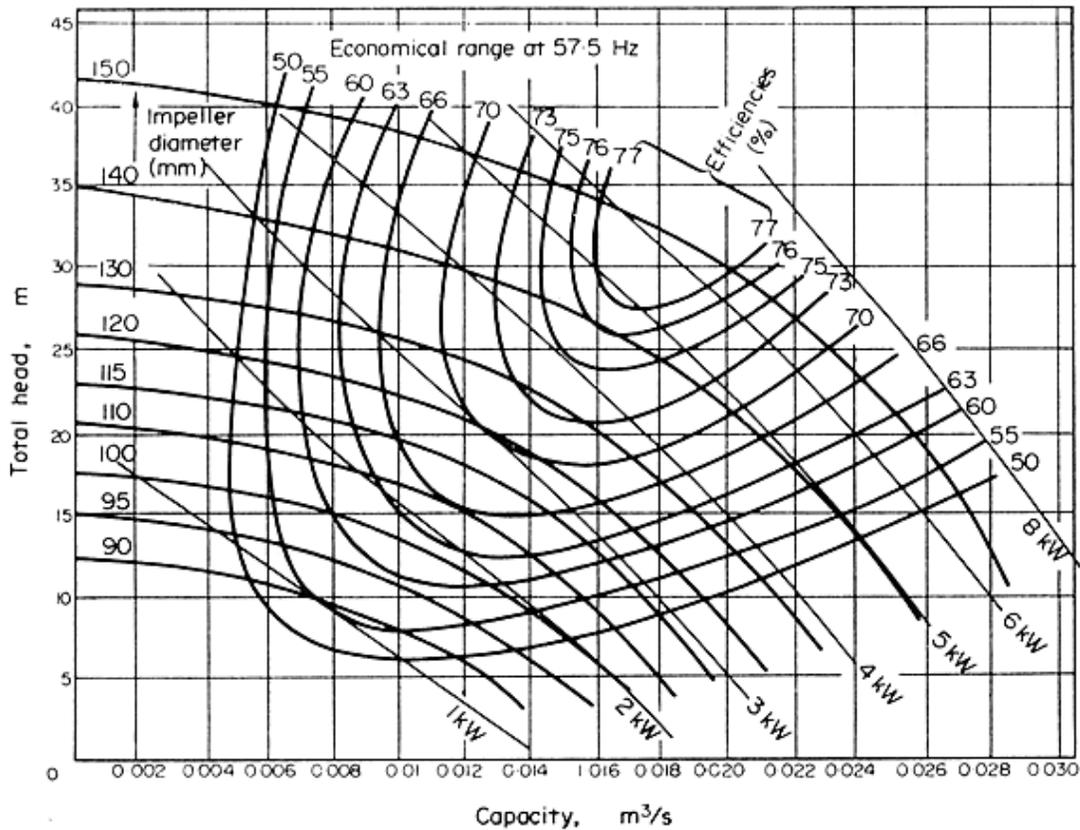


Figure 4.4 Characteristic curves for centrifugal pumps

Adapted from Coulson and Richardson, *Chemical Engineering*, 2nd. Edition, 1973

For a given centrifugal pump, the capacity of the pump varies with its rotational speed; the pressure developed by the pump varies as the square of the rotational speed; and the power required by the pump varies as the cube of the rotational speed. The same proportional relationships apply to centrifugal fans and these relationships are often called the "fan laws" in this context.

EXAMPLE 4.3. Centrifugal pump for raising water

Water for a processing plant is required to be stored in a reservoir to supply sufficient working head for washers. It is believed that a constant supply of $1.2\text{m}^3\text{min}^{-1}$ pumped to the reservoir, which is 22m above the water intake, would be sufficient. The length of the pipe is about 120m and there is available galvanized iron piping 15cm diameter. The line would need to include eight right-angle bends. There is available a range of centrifugal pumps whose characteristics are shown in Fig.4.4. Would one of these pumps be sufficient for the duty and what size of electric drive motor would be required?

Assume properties of water at 20°C are density 998 kg m^{-3} , and viscosity 0.001 Nsm^{-2}

$$\begin{aligned} \text{Cross-sectional area of pipe } A &= (\pi/4)D^2 \\ &= \pi/4 \times (0.15)^2 \\ &= 0.0177\text{ m}^2 \end{aligned}$$

$$\begin{aligned}\text{Volume of flow } V &= 1.2 \text{ m}^3\text{min}^{-1} \\ &= 1.2/60 \text{ m}^3\text{s}^{-1} \\ &= 0.02 \text{ m}^3\text{s}^{-1}\end{aligned}$$

$$\begin{aligned}\text{Velocity in the pipe} &= V/A \\ &= (0.02)/(0.0177) \\ &= 1.13 \text{ ms}^{-1}\end{aligned}$$

$$\begin{aligned}\text{Now (Re)} &= (Dv\rho/\mu) \\ &= (0.15 \times 1.13 \times 998)/0.001 \\ &= 1.7 \times 10^5\end{aligned}$$

and so the flow is clearly turbulent.

From Table 3.1, the roughness factor ϵ is 0.0002 for galvanized iron and so roughness ratio,

$$\epsilon/D = 0.0002/0.15 = 0.001$$

So from Fig. 3.8,

$$f = 0.0053$$

Therefore the friction loss of energy from Eqn. 3.17

$$\begin{aligned}&= (4fv^2/2) \times (L/D) \\ &= [4fv^2L/2D] \\ &= [4 \times 0.0053 \times (1.13)^2 \times 120]/(2 \times 0.15) \\ &= 10.8 \text{ J.}\end{aligned}$$

For the eight right-angled bends, from Table 3.2 we would expect a loss of 0.74 velocity energies at each, making $(8 \times 0.74) = 6$ in all. There would be one additional velocity energy loss because of the unrecovered flow energy discharged into the reservoir.

$$\begin{aligned}\text{Velocity energy} &= v^2/2 \\ &= (1.13)^2/2 \\ &= 0.64 \text{ J}\end{aligned}$$

$$\begin{aligned}\text{So total loss from bends and discharge energy} &= (6 + 1) \times 0.64 \\ &= 4.5 \text{ J}\end{aligned}$$

Energy to move 1kg water against a head of 22 m of water is

$$\begin{aligned}E &= Zg \\ &= 22 \times 9.81 \\ &= 215.8 \text{ J.}\end{aligned}$$

Total energy requirement per kg:

$$\begin{aligned}E_{\text{tot}} &= 10.8 + 4.5 + 215.8 \\ &= 231.1 \text{ J}\end{aligned}$$

and theoretical power requirement

$$= \text{Energy} \times \text{volumetric flow} \times \text{density}$$

$$\begin{aligned} &= (\text{Energy/kg}) \times \text{kg s}^{-1} \\ &= 231.1 \times 0.02 \times 998 \\ &= 4613 \text{ J s}^{-1}. \end{aligned}$$

Now the head equivalent to the energy requirement

$$\begin{aligned} &= E_{\text{tot}}/g \\ &= 231.1/9.81 \\ &= 23.5 \text{ m of water,} \end{aligned}$$

and from Fig. 4.4 this would require the 150mm impeller pump to be safe at the speed of 57.5 cycles⁻¹, and the pump would probably be fitted with a 7.5kW motor.

SUMMARY

1. Pressure in fluids can be measured by instruments such as the piezometer tube, the U-tube and the Bourdon tube.
2. Velocity can be measured by instruments such as the Pitot tubes - static tubes where:

$$v^2 = 2gZ$$

and Venturi meters where:

$$\begin{aligned} v_1^2 &= [2(P_1 - P_2)/\rho] \times [A_2^2/(A_1^2 - A_2^2)] \\ &= 2(P_1 - P_2) A_2^2 / \rho(A_1^2 - A_2^2) \end{aligned}$$

3. Basic pumps for liquids include reciprocating, gear, vane and centrifugal types. Fans for air and gases are usually either centrifugal or axial flow (propeller) types.

PROBLEMS

1. The difference in levels between a fluid in the two legs of a U-tube is 4.3cm. What differential pressure is there between the surfaces of the fluid in the two legs if the fluid in the tube is (a) water, (b) soyabean oil and (c) mercury?
(a) 0.42kPa (b) 0.38kPa (c) 5.74 kPa
2. A Pitot tube is to be used for measurement of the rate of flow of steam at a pressure of 300 kPa above atmospheric pressure, flowing in a 10cm diameter pipe. If it is desired to measure flow rates in this pipe of between 300 and 600 kg h^{-1} , what would be the differential pressures across the tube, in mm of water?
(For 300 kg h^{-1} , $\Delta P = 3.48\text{mm water}$; For 600 kg h^{-1} , $\Delta P = 13.9\text{mm water}$)
3. If across a 2cm diameter orifice measuring the flow of brine of density 1080 kg m^{-3} in a 5cm diameter pipe, the differential pressure is 182 Pa, estimate the mass rate of flow of the brine. Take the orifice discharge coefficient as 0.97.
(688 kg h^{-1})
4. A Venturi meter is being used to determine the flow of soyabean oil at 65°C in a pipe. The particular pipe is 15cm in diameter, which decreases to 6cm in the throat of the Venturi. If the differential pressure is measured as 14cm of water, estimate the flow rate of the soyabean oil.
(Volume = 0.17 m^3h^{-1} ; mass = 153 kg h^{-1})

5. A volume of $0.5\text{m}^3\text{h}^{-1}$ of water is being pumped at a velocity of 1.1ms^{-1} from the bottom of a header tank, 3m deep, down three floors (a total fall of 10m from the bottom of the header tank) into the top of a water pressure tank which is maintained at a pressure of 600kPa above atmospheric. Estimate the theoretical pump power required, ignoring pipe friction.
(0.1 hp)
6. In the pumping system of worked Example 4.3, the actual pump selected for the duty would pump more water than the $1.2\text{m}^3\text{min}^{-1}$ needed for the duty. By plotting a capacity curve for the system, varying the flow rate and determining the total head for each selected rate, determine from the interaction of this curve and the pump characteristic curve, the expected flow rate. Assume flow is turbulent.
(Flow rate = $1.44\text{m}^3\text{min}^{-1}$)
7. Using the same flow rate as in worked Example 4.3 and the same piping system, determine the total head against which a pump would have to operate if the pipeline diameter were halved to 7.5cm diameter.
(76.7m water)