Fluid Mechanics

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- Define the following terms and state their units of measurement: pressure, density, and viscosity.

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- Convert a given value of pressure expressed on the absolute, gauge or vacuum scale to the appropriate values on either of the other two scales.
- Given a pressure differential acting on a given area, calculate the force produced.
- State the factors affecting pressure of liquids and gases.

1.3 Flow

- Describe the difference between laminar flow and turbulent flow with respect to the velocity profile and pulsations.
- Define mass and volumetric flow rates.
- State the relationships between mass and volumetric flow.
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- Explain the effect of pressure and temperature on volumetric flow rate for liquids and gases.

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- Define the following terms regarding a system with flowing liquid:
  - a) Elevation head, pressure head and velocity head,
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- State the effect of fluid viscosity and velocity on a head loss in turbulent flow.
- State the effect of temperature on viscosity of liquids.
- Explain the relationship between elevation head, pressure head and velocity head in a fluid system with energy losses and additions.

- Given a simple fluid system comprised of piping with constant or varying elevation and diameter and a combination of elbows, orifices, venturis, valves, tanks and a fluid mover (e.g., pump), determine the direction of pressure and velocity changes along the system, and explain why these changes occur.

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- Describe the following terms: siphon, loop seal, and buoyancy.
- Explain the adverse effects of gas or vapour accumulation in a siphon.

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- Define two-phase flow.
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- Give examples of different forms of two phase flow in a CANDU plant.
- Define cavitation.
- Explain how cavitation can occur in a fluid system.
- Explain how each of the following can produce large pressure spikes in a fluid system: water hammer, steam hammer, and solid operation.
- Explain how the following operating practices minimise the risk of water or steam hammer:
    - a) Draining of a steam or gas system,
    - b) Venting and slow priming of a liquid system,
    - c) Slow operation of valves,
    - d) Starting up or shutting down a centrifugal pump with its discharge valve closed or crack opened,
    - e) Delay between pump start-ups and shutdowns, and
    - f) Applying cooling water to heat exchangers first.

1.7 Flow Induced Vibration

- Explain how a flowing fluid can cause equipment vibration.

2 BASIC DEFINITIONS

2.1 Introduction

Fluid systems are the backbone of nuclear power plants and the CANDU stations are no exception. We will use the term fluid as a generic term for both liquids and gases.

The fluid systems are used primarily as heat transport vehicles. An example would be the generator stator cooling system. Heat generated in the stator windings is transferred to the closed-loop stator cooling system and then to the low-pressure service water.

This module is designed to help you understand processes that occur in individual fluid handling parts and devices as well as entire systems.

In this module, we will review basic terms, concepts and laws of fluid mechanics and apply them to assorted fluid-related processes in nuclear power plants.

2.2 Pressure

Pressure is one of the basic properties of all fluids. Pressure (p) is the force (F) exerted on or by the fluid on a unit of surface area (A).

Mathematically expressed:

$$p = \frac{F}{A}$$

The basic unit of pressure is Pascal (Pa). When a fluid exerts a force of 1 N over an area of $1m^2$, the pressure equals one Pascal, i.e., 1 Pa = 1 N/m^2.

Pascal is a very small unit, so that for typical power plant application, we use larger units:

1 kilopascal (kPa) = 10^3 Pa, and

1 megapascal (MPa) = 10^6 Pa = 10^3kPa.

2.3 Density

Density is another basic fluid property. Density (ρ - Greek ro) is defined as mass (m) of a unit of volume (V). Its basic unit is kg/m^3.

Mathematically expressed:

$$\rho = \frac{m}{V}$$

For all practical purposes, liquids are considered to be incompressible, i.e., their volume and density are not affected by pressure. Although it is not absolutely true, the changes are negligible. The effect of temperature on density of liquids, however, cannot be ignored because liquids expand and contract when temperature changes.

Both pressure and temperature affect density of gases. When temperature is kept constant, an increase in pressure will increase density. When pressure is kept constant, an increase in temperature will decrease density.

2.4 Viscosity

Viscosity is another fluid property we need to understand before discussing some other aspects of mechanical equipment, such as pressure losses in piping due to friction or bearing lubrication.

Viscosity is a measure of the fluid's resistance to flow due to its internal friction.

Viscosity is measured in two ways: dynamic (absolute) and kinematic. These two parameters are related since the kinematic viscosity may be obtained by dividing the dynamic viscosity by density.

In this module, for simplicity, we will only use the absolute viscosity when explaining fluid friction in piping systems. When, in the following text we mention viscosity, it is the dynamic viscosity.

Dynamic (absolute) viscosity (μ - Greek mu) is the measure of the tangential force needed to shear one parallel plane of fluid over another parallel plane of fluid. The thicker/more viscous the fluid, the larger the area of contact, and the larger the velocity change between the layers of the fluid, the larger the tangential force.

The basic unit is the pascal·second (Pa·s). The viscosity of a fluid equals 1 Pa·s if a force of 1 N is needed to shear a 1 m^2 plane of this fluid when the velocity change between the layers of the fluid is 1m/s per 1 m. A thousand time's smaller unit is called centipoise (cP). To give you some feel for this unit, the viscosity of water at 20ºC is about 1 cP.

Viscosity of liquids is much larger than viscosity of gases or steam. For all fluids, viscosity increases with rising pressure. The effect of temperature is much bigger, though, and it depends on the type of fluid: rising temperature lowers the viscosity of a liquid, and increases the viscosity of a gas. This difference is explained below.

The resistance of fluid to shear (i.e., viscosity) depends upon its cohesion and its rate of transfer of molecular momentum. Cohesion refers to the attractive forces between neighbouring molecules. When the fluid expands due to increased temperature, the molecules get further apart, and cohesion gets weaker. Transfer of molecular momentum is caused by random movements of fluid molecules back and forth between different layers. This transfer tends to equalize the velocities of adjacent layers, and thus, it resists their relative motion. In liquids, molecules are much more closely spaced than in gases. Therefore, cohesion is the dominant cause of viscosity, and since cohesion decreases with temperature, viscosity does likewise. A gas, on the other hand, has very small cohesive forces. Most of its resistance to shear is the result of the transfer of molecular momentum. The higher the temperature, the larger this transfers because molecules move faster. Therefore, the viscosity of a gas increases with rising temperature.

3 PRESSURE

3.1 Pressure Scales

Since we live in an atmosphere of pressurised air, we have to decide on the datum, where the pressure would be zero.

One commonly used scale is the absolute scale. It starts at the point of no pressure at all, i.e., the absolute zero pressure. Readings taken on this scale are called absolute pressure and have suffix (a) added, e.g., 4 MPa (a).

A scale with zero at atmospheric pressure is known as the gauge scale. Readings made on this scale are called gauge pressure. The name reflects the fact that most gauges read zero at the atmospheric pressure. To distinguish readings on this scale, we use suffix (g). The gauge scale is the most common scale used in our plants.

Since atmospheric pressure changes constantly, it may be difficult to pinpoint the gauge pressure zero point. Therefore, we use standard atmospheric pressure set at 101.3 kPa(a). With atmospheric pressure changes being relatively small compared with pressures used in the industry, small variations are ignored.

We now can correlate the two discussed scales:

$$p(a) = p(g) + \text{atmospheric pressure}$$

3.1.1 Example 3.1:

If instrument air gauge pressure is 580-kPa (g), what is its absolute value?

$$p(a) = 580 \text{ kPa (g)} + 101.3 \text{ kPa}$$
$$= 681.3 \text{ kPa (a)}$$

The third scale, sometimes used in our plants for systems at lower than atmospheric pressure, is the vacuum scale. Vacuum is the difference between the atmospheric pressure and the absolute pressure. We use suffix (v) to distinguish it from the other pressure values. Its zero point is at the standard atmospheric pressure and it increases towards the absolute zero. The absolute zero point is also called the absolute vacuum.

From this information, we can determine mathematical expressions that relate the three scales:

$$\text{Vacuum} = -\text{Gauge pressure}$$
$$\text{i.e.,} \quad p(v) = -p(g)$$
$$\text{Vacuum} = \text{Atmospheric pressure} - \text{Absolute pressure}$$
$$\text{i.e.,} \quad p(v) = 101.3 \text{ kPa} - p(a)$$

Better yet, we will show these relationships graphically in Figure 1.

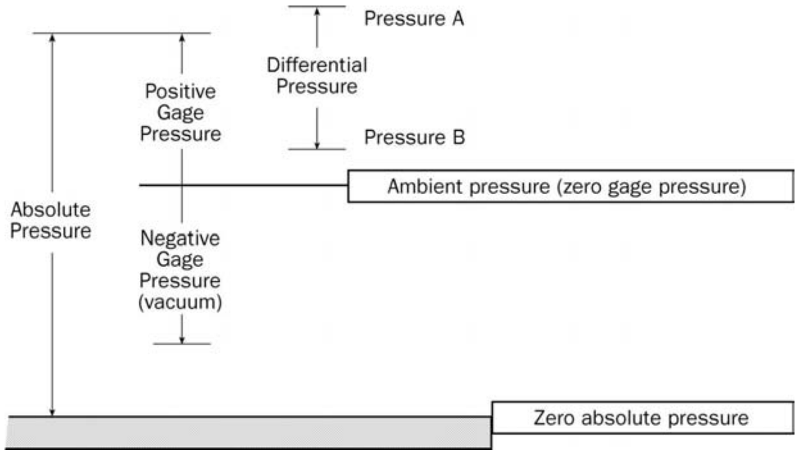

Figure 1

NOTE: The gauge and the absolute scales have a zero point but can grow indefinitely. Meanwhile, the vacuum scale has a zero point at the atmospheric pressure level but can only grow to the absolute vacuum. It has a definite, finite range of 101.3 kPa.

3.1.2 Example 3.2:

Suppose that a condenser pressure reading on the absolute scale is 4.9 kPa(a). Express this reading in the two other scales.

Vacuum:

$p(v) = 101.3 \text{ kPa} - p(a)$

$p(v) = 101.3 - 4.9 = 96.4 \text{ kPa}(v)$

Gauge pressure:

$p(g) = - p(v) = - 96.4 \text{ kPa}(g)$

3.1.3 Example 3.3:

Moderator header low-pressure alarm comes at 166 kPa(g). Express it in the other scales.

Since the pressure is outside the vacuum scale, that scale cannot be used. The only conversion is to the absolute scale.

$p(a) = p(g) + 101.3 = 166 + 101.3 = 267.3 \text{ kPa}(a)$

3.2 Pressure Differential

Now that we know how to measure pressure, we can turn our attention to situations where a pressure (p), or a pressure differential (Δp), exerted over an area (A) produces a force (F) that must be considered. We can calculate forces using the basic formula for pressure:

Since: $p = \frac{F}{A}$, hence: $F = p \cdot A$

Or for a pressure differential:

$$F = \Delta p \cdot A = (p_1 - p_2) \cdot A$$

NOTE: We have to be careful to use pressures expressed in the same scale and the area in m^2.

3.2.1 Example 3.4:

In an air-operated valve (AOV), the area of the actuator diaphragm is 0.1 m^2. What minimum force must the spring exert on the diaphragm to counteract the force generated by the throttled instrument air at a pressure of 200 kPa(a).

Since the spring compartment is at the atmospheric pressure, the pressure difference acting on the diaphragm against the spring will be the gauge pressure of the instrument air.

$$\Delta p = p(g) = p(a) - 101.3 =$$

$$= 200 - 101.3 = 98.7 \text{ kPa(g)}$$

Hence, the force produced by this pressure differential:

$$F = \Delta p \cdot A = 98.7 \cdot 0.1 = 9.87 \text{ N}$$

3.2.2 Example 3.5:

Some rooms and spaces in the plants are kept at sub atmospheric pressure in order to either prevent the spread of contamination or because they are a part of the suction system of large fans. It takes an effort by operating staff to open the door into one of these areas. For instance, a fan room is at about 0.7 kPa vacuum. What is the force exerted on the door by the pressure differential? The door has an area of about 2 m^2.

We can use the formula for a pressure differential derived above:

$$F = (p_1 - p_2) \cdot A$$

where: p_1 is the atmospheric pressure, and p_2 is the subatmospheric pressure in the fan room. Since the atmospheric pressure is given as zero gauge pressure, we have to express the fan room pressure as gauge pressure as well.

$$p_2 = 0.7 \text{ kPa(v)} = -0.7 \text{ kPa(g)}$$

Substituting into the formula for the force, we obtain:

$$F = (p_1 - p_2) \cdot A = [0 - (-0.7)] \cdot 2 = 1.4 \text{ kN} = 1400 \text{ N}$$

There are some other instances in our plants where we are concerned about the pressure differential.

One of them concerns globe valves. In a closed position, the valve plug will often be subjected to a pressure differential. The pressures below and above the plug will be different and will result in an axial force along the stem.

If the pressure is higher above the stem, it will assist us in a tight closure of the valve. If it is higher under the stem, it will assist us in opening the valve. Both variants can be found in our plants, depending on our objective.

3.3 Factors Affecting Pressure of Fluids

Liquids and gases have many common characteristics but also differ in many respects. When we want to review the factors affecting their pressure, we have to consider them separately. For simplicity, we will assume the fluid is stagnant. Pressure of a flowing fluid is discussed in later sections.

Let's start with liquids. To see what affects the pressure of a liquid, we will consider a liquid in a partially filled tank, with a gas atmosphere above the liquid (Figure 2).

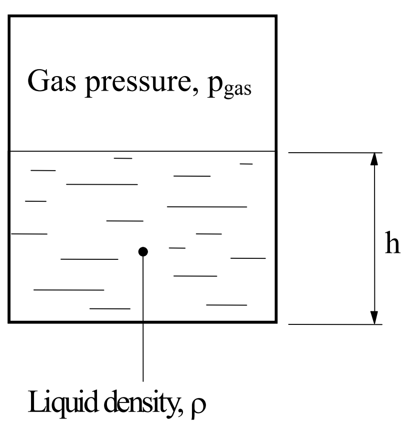

Figure 2

The pressure at a point in the tank will depend on the following:

- Pressure of the gas or vapour above the liquid (p_{gas});
- Weight of the liquid above the considered point which, in turn, will depend on:

- height (h) of the liquid column/head above the point,
- density (ρ) of the liquid, and
- gravitational acceleration (g).

Mathematically expressed, static pressure of a liquid:

$$p = p_{gas} + \rho \cdot g \cdot h$$

Now, let's turn our attention to gases. Any gas will expand and fill the entire volume of the tank. The weight of gas is usually negligible. Therefore, the gas will exert an equal pressure on all surfaces of the tank. The factors affecting the gas pressure are:

- Gas mass (m);
- Absolute temperature (T)—explained in the Thermodynamics course;
- Tank volume (V), and
- Gas constant (R) specific to a given gas.

Mathematically expressed:

$$p = \frac{m \cdot R \cdot T}{V} = \rho \cdot R \cdot T$$

This equation is called the Ideal Gas Law. From this equation, you can see that gas pressure rises with increasing mass and temperature of the gas and decreases with increasing volume.

Up to this point in the course, we have assumed stagnant (not moving) fluids. In the next sections, we will deal with flowing fluids.

4 FLOW

4.1 Laminar versus Turbulent Flow

Experiments show that a fluid moving along a channel, (e.g., a pipe) can flow in parallel paths (laminar flow) or there can be a varying amount of mixing (turbulent flow). These two types of flow are described below for the simplest case of a straight channel with a round cross-section, e.g., a pipe. Figure 3 illustrates the difference between the two types of flow with respect to the velocity profile.

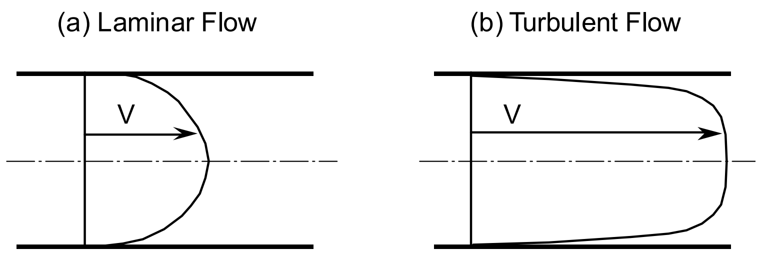

Figure 3

In the laminar flow, the fluid behaves as if it were flowing in a concentric nest of thin cylinders one inside another. Due to fluid's viscosity, the cylinder next to the wall is stationary, while the one in the centre of the pipe is moving with the highest velocity. There is no mixing between the layers of fluid and velocity does not pulsate.

In the turbulent flow, there is random mixing between the layers of fluid. Due to the mixing, the velocity distribution is much more uniform across the pipe cross-section. The mixing has a positive effect on heat transfer. The negative effect of this mixing is velocity and pressure pulsations. They can be transferred to piping and equipment and cause vibrations.

The type of flow (laminar versus turbulent) is determined by the fluid's properties (viscosity and density), velocity and the geometry of the channel through which the fluid is flowing. Laminar flow is promoted when:

- Dynamic viscosity is large (frictional forces resist mixing);
- Density is small (a given volume of fluid has less kinetic energy to overcome friction);
- Velocity is small (less kinetic energy to overcome friction), and
- The channel width is small (wall proximity makes mixing, i.e., movement across channel, more difficult).

In power plants, most fluids (water, steam, and compressed gases) have low viscosities, and they usually flow through relatively wide channels at high velocity. Also, they often change flow direction (e.g., in a pipe elbow or around heat exchanger tubes), which promotes mixing of layers.

For these reasons, turbulent flow is very common in power plants. Laminar flow is extremely rare. For example, it occurs in the oil film in a plain bearing, where the tight clearance between the shaft and the bearing surface (a few tenths of a millimetre at most) does not allow mixing of layers.

Unless otherwise noted, we will assume from this point on that the term fluid velocity means the average velocity across the channel. If the fluid had this velocity in all the points across the channel, the quantity of the fluid passing through the channel would be the same as the actual total flow. .

4.2 Mass and Volumetric Flow Rate

We have already stated that fluid systems are the backbone of CANDU plants. To characterize the fluid flow, we have to specify the quantity of the fluid flowing through a given location in the system per unit of time. This is called the flow rate. Since fluid quantity can be expressed as volume or mass, there are two types of flow rates: volumetric and mass.

Volumetric flow rate ($\dot{\mathbf{V}}$) is the volume of the fluid passing through a given cross section in a unit of time.

The basic unit is m^3/s. If m^3/s is too large, a smaller unit dm^3/s or equal litre/second (l/s) is used.

$$1\ m^3/s = 10^3\ dm^3/s = 10^3\ l/s$$

Volumetric flow rate is a function of the fluid velocity (v) and the cross section of the channel through which the fluid is flowing, e.g., a pipe, (A). Figure 4 illustrates this for a simple case of flow through a straight pipe.

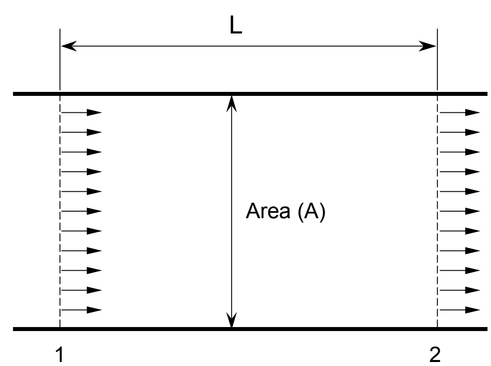

Figure 4

Let's mark two cross sections 1 and 2 on the pipe. The distance between them is L. We will follow a layer of fluid passing through the cross section 1 and, a moment later, through cross section 2 over the distance L. Assuming all fluid particles move at the same velocity, we conclude that the volume of fluid that passed through cross section 1 was:

$$V = A \cdot L$$

Per unit of time, it will be:

$$\dot{V} = \frac{V}{t} = \frac{A \cdot L}{t}$$

Since L/t is the average velocity of the fluid (v), the volumetric flow rate can be expressed as:

$$\dot{V} = A \cdot v$$

Mass flow rate ($\dot{m}$) is the mass of fluid passing through a given cross section in a unit of time. Its basic unit is kg/s.

We can derive the formula for the mass flow rate using the formula for the volumetric flow rate and by converting volume to mass using density (ρ).

Since $\rho = \frac{m}{V}$, then $m = V \cdot \rho$

If we divide the both sides of the above equation by time, we get the flow rates. The final formula for the mass flow rate is:

$$\dot{m} = \dot{V} \cdot \rho = A \cdot v \cdot \rho$$

Although we have used a pipe to discuss the flow rates, the concepts apply equally well to channels with cross sections of any shape, e.g., rectangular ducts.

Both types of flow rates are commonly used to characterise system conditions in our plants. In the next two sections, we will discuss the factors that affect these flows. This knowledge will help you, in your daily work, foresee what happens to these flow rates when a system parameter changes or diagnose the cause of their change.

4.3 The Continuity Principle

The continuity principle is one of the basic laws of fluid mechanics. From Figure 4, you can infer that:

If there are no leaks, feed or bleed of fluid between cross sections 1 and 2, and no change to the fluid inventory between these two locations, then the mass of fluid passing through cross section 1 must also pass through cross section 2 in the same period of time.

We can broaden this statement to say that the mass flow rate in a system must be constant at all cross sections, provided there are no leaks, no feed, no bleed and no storage.

Mathematically expressed:

$$\dot{m} = \text{constant} \quad \text{or} \quad \dot{m}_1 = \dot{m}_2$$

We can intuitively feel that if the mass flow rate is constant across all cross sections, whether or not they increase or decrease, then something else has to change. To simplify further, we will consider only liquids at a constant temperature. Two following examples will help us.

4.3.1 Example 3.6:

Figure 5 is an example of a pipe reducer. We want to investigate what happens at cross sections 1 and 2.

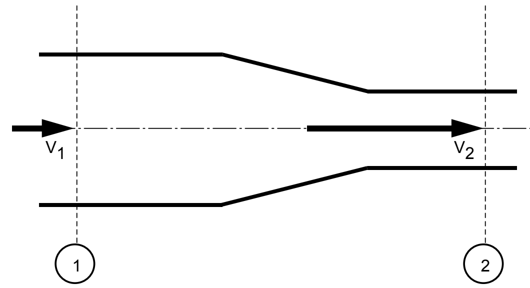

Figure 5

Using the Continuity Principle, the mass flow rate at 1 and 2 must be the same, i.e.:

$$\dot{m}_1 = \dot{m}_2$$

We have expressed the mass flow rate as

$$\dot{m} = A \cdot v \cdot \rho$$

Substitution into the continuity equation gives:

$$A_1 \cdot v_1 \cdot \rho_1 = A_2 \cdot v_2 \cdot \rho_2$$

Since the density of the liquid is not changing, then $\rho_1 = \rho_2$ and the above equation is

$$A_1 \cdot v_1 = A_2 \cdot v_2$$

Conclusion: Because the cross section A_2 is smaller than A_1, velocity v_2 has to be higher than v_1 to maintain the flow rate.

4.3.2 Example 3.7:

Figure 6 shows a centrifugal pump with the same size suction and discharge piping. Let's determine velocity change between suction and discharge.

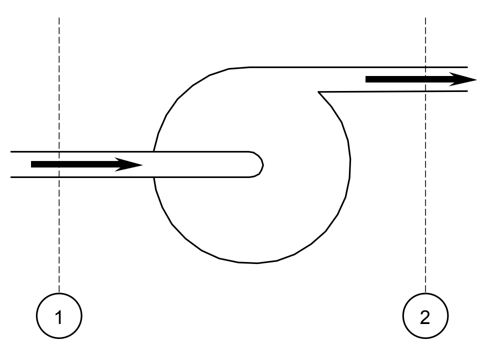

Figure 6

We assume no liquid is added, removed or stored in the pump. Hence, mass flow rates are identical at the pump suction and discharge. The Continuity Principle applies, i.e.:

$$\dot{m}_1 = \dot{m}_2$$

$$A_1 \cdot v_1 \cdot \rho_1 = A_2 \cdot v_2 \cdot \rho_2$$

Since $A_1 = A_2$ and $\rho_1 = \rho_2$, we can infer that $v_1 = v_2$, i.e., suction and discharge velocities must be equal.

4.4 Effect of Pressure and Temperature

We have stated that the Continuity Principle for the mass flow rate is universally applicable. It is equally valid for liquids and gases and is also valid even if pressure and temperature change across the system. However, the same cannot be said about the volumetric flow rate. We have to consider whether the system fluid is a liquid or a gas. We also have to consider whether it was just pressure or temperature that has changed or if both changed.

We will start with the effect of pressure on liquid systems. Liquids are deemed incompressible and therefore, density and the volumetric flow rate do not change.

Gases, on the other hand, are compressible. Therefore, an increase in pressure will decrease the volumetric flow rate. Conversely, a pressure decrease will allow gas to expand, which will increase the volumetric flow rate.

Temperature affects liquids and gases in the same way. Both liquids and gases expand with rising temperature and the volumetric flow rate will therefore increase. A decrease in temperature will have an opposite effect.

5 ENERGY IN A FLOWING FLUID

5.1 Energy, Pressure and Head of Flowing Fluid

In this section, we will discuss various types of mechanical energy possessed by a flowing fluid, and the relationship among them. This knowledge will help you understand the changes in pressure and velocity that occur as a fluid flows through a system.

We will first consider a simplified case—a friction-free (zero viscosity) fluid flowing through a straight, horizontal pipe (Figure 7). Later in the module, we will examine more complex fluid systems handling a viscous fluid.

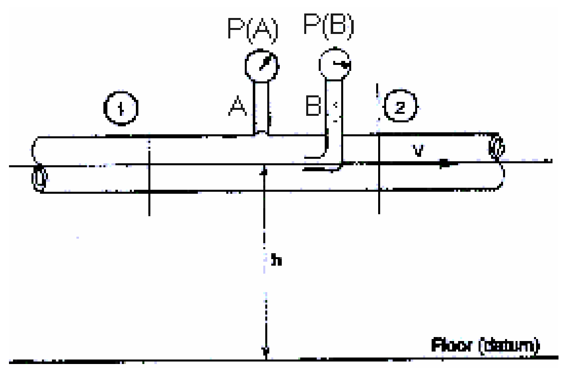

Figure 7

The fluid in the pipe has some:

- potential energy due to its elevation,
- pressure energy because it is pressurised,
- kinetic energy because it is moving, and
- thermal energy due to its temperature and state of aggregation (liquid or gas).

The fluid has other forms of energy too (e.g., chemical), but they usually stay constant, and therefore can be ignored.

For liquids, we can also ignore thermal energy because it changes very little, unless the liquid is undergoing a heat transfer process in a heat exchanger. Here is why it is so. Because liquids' compressibility is very small, the pressurisation of a liquid requires relatively little work, much the same way as the compression of a very stiff spring whose deflection is very small even when a large force is applied. Since a relatively small amount of energy is added to the liquid during this process, its thermal energy (hence, temperature) rises very little.

Due to their large compressibility, steam and gases experience much larger thermal energy changes than liquids when subjected to a given pressure change. For these compressible fluids, heat must be taken into account. For simplicity, the rest of this module will focus on liquids.

In our case, each of the three forms of energy of the flowing liquid can be converted into either of the other two. Such changes constantly occur in fluid systems.

It is customary to convert the three forms of energy into an equivalent head of liquid in meters: elevation head (h_e), pressure head (h_p) and velocity head (h_v). Figure 7 shows them all.

Elevation head is the fluid elevation above some arbitrarily chosen level or datum. In practical work, we always deal with differences in elevation, so the datum we work from is not important as long as it is applied consistently. In Figure seven t is shown at the bottom of the diagram and h_e is measured to the middle of the pipe.

This head is proportional to the liquid's potential energy measured relative to this datum.

Pressure head is the height of a column of liquid that can be supported by liquid pressure. This head is measured relative to the central axis of the channel, as shown in Figure 7 as the pressure in tube A.

We usually use the atmospheric pressure as a reference. Therefore, the pressure head is assumed to be zero when the liquid is at atmospheric pressure.

Velocity head is the height of a column of liquid that can be supported when the liquid is forced to stop (as done by vertical tube B in Figure 7), that is when kinetic energy gets converted into potential energy.

This head is proportional to the kinetic energy of the moving fluid. If the fluid is not moving, the velocity head is zero.

The sum of all three heads: the elevation head, velocity head and the pressure head, is called the total head (h_t).

$$h_e + h_p + h_v = h_t$$

We will now derive the formulas for the pressure and velocity heads. This derivation is not a testable material. The formulas show the relationship between the two heads and liquids pressure density and velocity. The formulas will be frequently used throughout this module and the next one.

The relationship between pressure head and pressure can be derived from the formula for hydrostatic pressure exerted by a column of liquid of a given height (h_p in this case).

$$p = \rho \cdot g \cdot h_p$$

Hence, pressure head:

$$h_p = \frac{p}{\rho \cdot g}$$

The formula for velocity head can be derived from the Law of Conservation of Energy applied to a liquid that enters a vertical pipe or tube (like in Figure 7) where it slows down to standstill. Ignoring friction, we can deduce that during this process, liquid kinetic energy gets converted completely into potential energy, i.e.:

$$\frac{m \cdot v^2}{2} = m \cdot g \cdot h_e$$

Hence:

$$h_e = \frac{v^2}{2 \cdot g}$$

Since the kinetic energy of a flowing fluid can be converted into pressure energy, you can infer that fluid velocity can affect pressure readings. For example, if we measure the pressures at tubes A and B in the system shown in Figure 7, manometer B would indicate a higher pressure because the flowing fluid would be pushing the fluid inside the manometer. This observation brings us to the different types of pressure exerted by a flowing fluid: static, dynamic and total.

Static pressure (p_s) is the pressure exerted by a static fluid. When a fluid is flowing, static pressure must be measured on a plane parallel to the local flow direction (e.g., the inlet to vertical tube A in Figure 7). Due to this orientation, the flowing fluid neither enters, nor leaves the stagnant column. Therefore, fluid velocity has no effect on the pressure measurement. This is the pressure measured by the pressure gauges in the plant.

Dynamic pressure (p_d) is the net pressure increase that can be derived from a complete conversion of the velocity head into pressure head or, in other words, kinetic energy into pressure energy. To effect this energy conversion, the pressure gauge must be fitted such that its inlet is perpendicular to the direction of flow and pointing against it.

Total pressure (p_t) is the pressure exerted on a plane normal to the local flow direction (the inlet to vertical tube B in Figure 7). It is equal to the sum of the static and dynamic pressures, i.e.:

$$p_t = p_s + p_d$$

From Figure 7, you can see that the concept of head is applicable to liquids only. Unlike liquids, gases and steam fill out containers entirely. Therefore, a gas would not create a stagnant column of a certain height in a measuring tube (A or B in Figure 7), but would leak out of the system through that tube.

The concepts of static, dynamic and total pressure, however, apply to all types of fluids—not exclusively liquids.

We must be absolutely comfortable with the concept of equivalency between energy (per kg of fluid), pressure and head. All are used interchangeably in describing operational states of components and systems in our plants. The following example will help us understand the concept:

5.1.1 Example 5.1:

A typical average flow velocity in our water systems is about 5 m/s. What are the equivalent velocity head and dynamic pressure, assuming that water density (ρ) is 1,000 kg/m^3?

Velocity head:

$$h_v = \frac{v^2}{2 \cdot g} = \frac{5^2}{2 \cdot 9.81} \cong 1.27 \text{ m}$$

The equivalent dynamic pressure (p_d) is the pressure exerted by a column of water whose height is equal to the velocity head, i.e.:

$$p_d = \rho \cdot g \cdot h_v = 1{,}000 \cdot 9.81 \cdot 1.27 \cong 12{,}500 \text{ Pa} = 12.5 \text{ kPa}$$

What are the numbers telling us?

First, let's consider the magnitude of the velocity head/dynamic pressure. With our typical liquid system velocities, dynamic pressure is about one eighth of the atmospheric pressure. The atmospheric pressure would support a column of water at room temperature about 10 meters high. Many systems operate at much higher pressures.

For example, average heat transport system pressure is about 9.6 MPa, i.e., almost 800 times more than the calculated dynamic pressure. Boiler pressure (≅ 4.2 MPa) is about 320 times higher. Even the LP service water system pressure (≅ 600 kPa) is 48 times higher than its dynamic pressure. We can deduce that dynamic pressure is usually a very small part of total pressure.

Secondly, the velocity head and dynamic pressure change with the square of liquid velocity. For example, if the velocity doubles, the equivalent velocity head and dynamic pressure quadruples.

Thirdly, the formula for dynamic pressure used in the above example is incorrect for gases and steam. Their compressibility means that when dynamic pressure is building up (when the fluid is slowing down), their density and temperature increase, whereas for liquids they stay practically constant.

It is important to realize that this section covers frictionless fluids. Since the fluids used in the plants are viscous, let's review the energy and head losses due to friction.

5.2 Energy Loss and Head Loss

The Law of Conservation of Energy is universally applicable. We have also shown that the various types of energy within flowing fluid can be converted one into the other. What, then, is meant by an energy and head loss?

Because of viscosity, there is friction within the fluid as well as friction of the fluid against the piping or ducting walls. This friction converts into heat some of the pressure energy of the flowing fluid and raises the temperature of the fluid and piping. This phenomenon can be critical in the operation of some equipment.

For instance, we should not operate a boiler feed pump against a closed discharge valve. Churning of feed water in the pump would result in so much heat generation due to friction that we would destroy the pump if we left it running against a closed discharge valve for too long. In some cases, damage can happen in less than a minute!

The magnitude of energy/head loss due to friction depends on several factors. We will focus on the three major factors: fluid velocity, its pattern, and fluid viscosity.

The effect of velocity is significant because in turbulent flow, friction losses increase with the square of velocity. For examples, if velocity doubles, the head loss quadruples.

For a given velocity, the head loss increases when the flow is disturbed. This happens in the locations where the flow changes direction and/or velocity or mixes with another flow or stagnant fluid. Examples of such locations are elbows, tees, reducers and diffusers, and pipe connections to vessels. Heat exchanger tubes, turbine/compressor blades, pump/fan vanes, orifices, nozzles and valves (particularly when throttling) also disturb the flow as they force the flowing fluid to change its direction and/or velocity. In all these cases, fluid turbulence (internal mixing) is increased. In addition, the velocity pattern (profile) of the flow is not as smooth as the one shown on Figure 3. Eddies (vortices) form in the fluid, and their interaction with the surrounding fluid increases friction.

The effect of viscosity is predictable. The head loss will increase with the increase in viscosity, i.e., the thicker the fluid, the higher the loss.

5.3 Conservation of Energy in Flowing Liquid

We have reviewed all the types of energy that a flowing liquid can have, including losses due to fluid friction:

- potential energy/elevation head;
- pressure energy/pressure head;
- kinetic energy/velocity head;
- friction loss/head loss.

We have also confirmed that these energies can be converted one into the other.

Let us apply the Law of Conservation of Energy to a system shown in Figure 8.

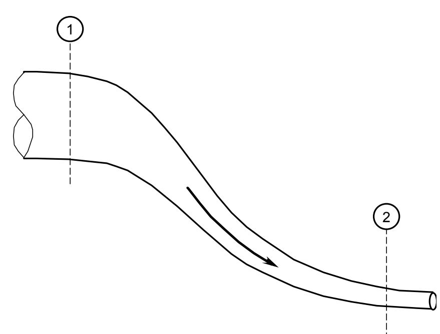

Figure 8

If no energy were entering or leaving the system, the sum of energies/heads at the cross section 1 would have to be equal to the sum at the cross section 2. Indeed, some useful energy entering cross section 1 has been converted/lost to heat due to fluid friction between 1 and 2.

If we do add or remove some energy/head between cross sections 1 and 2, we have to account for it. An example of addition would be a pump put between 1 and 2, while an example of removal would be heat removal (cooling) between 1 and 2.

We can now write a simple formula expressing this conservation of energy.

$$h_{e1} + h_{p1} + h_{v1} + h_{added} - h_{removed} = h_{e2} + h_{p2} + h_{v2} + h_{loss}$$

This equation is commonly called Bernoulli's equation.

We can substitute for the individual energies/heads and write this equation with all terms in meters:

$$h_{e1} + \frac{v_1^2}{2 \cdot g} + \frac{p_1}{\rho \cdot g} + h_{added} - h_{removed} - h_{loss} = h_{e2} + \frac{v_2^2}{2 \cdot g} + \frac{p_2}{\rho \cdot g}$$

5.4 Pressure and Velocity Changes in a Fluid System

We will use the concepts presented in the previous section to demonstrate graphically, with the use of grade lines, what happens to liquid pressure and velocity in a real system with elbows, reducers, orifices, venturis, valves, tanks, and pumps. We will start with individual system components and then we will apply our conclusions to a simple system.

We will use two different grade lines: one, which shows total energy (energy grade line) and one, which shows pressure energy (pressure grade line).

The energy grade line is sketched relative to a horizontal datum at which potential energy is assumed zero. The vertical distance between the datum and the channel centreline represents the liquid's potential energy (gh). Therefore, the vertical distance between the channel centreline and the energy grade line shows the sum of pressure (p/ρ) and kinetic energies ($v^2/2$).

The pressure grade line is sketched relative to the channel centreline and represents pressure energy. Hence, the vertical distance between the two grade lines represents the liquid's kinetic energy.

Let's recall our discussion on equivalency between liquid energy, pressure and head. Based on that, we can conclude that the pressure grade line also represents the pressure head or static pressure. The energy grade line represents a sum of the elevation, pressure and velocity heads. The elevation head is below the channel centreline; the other two above it. Hence, the elevation of the energy line above the channel centreline represents total pressure, while the vertical distance between the two grade lines represents the dynamic pressure/velocity head.

The next few figures will clarify the concept of these grade lines. For clarity, the kinetic energy component is exaggerated. Figure 9 shows a straight piece of pipe with a constant diameter.

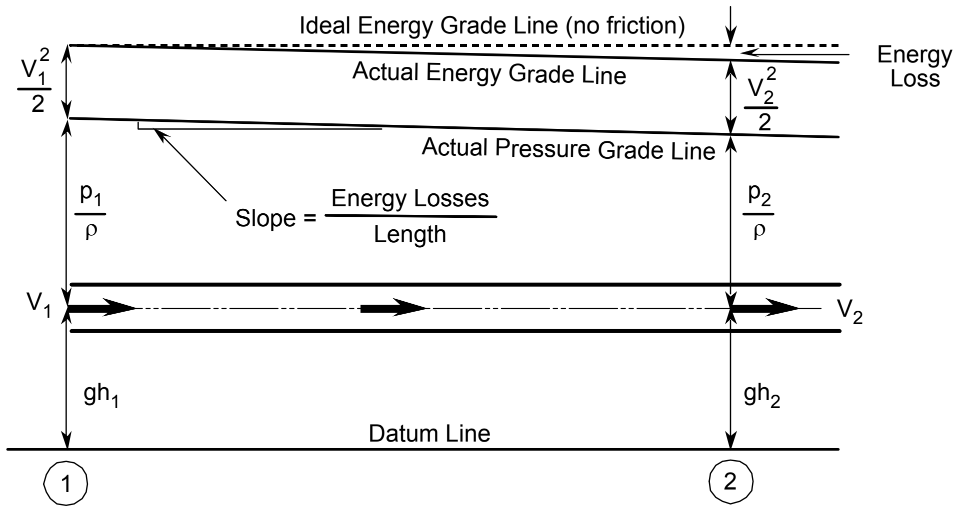

Figure 9

We will discuss what happens between cross sections 1 and 2. Obviously, there is no change in diameter, therefore the velocity and the velocity head will not change. Similarly, there is no change in the elevation head. Since we are not adding or removing any energy, the total energy/head must be the same at 1 and 2. However, there will be gradually increasing friction losses along the pipe. This means that the pressure/pressure head will be gradually decreasing.

The next components we will discuss will be a reducer and a venturi in a straight horizontal pipe (Figure 10).

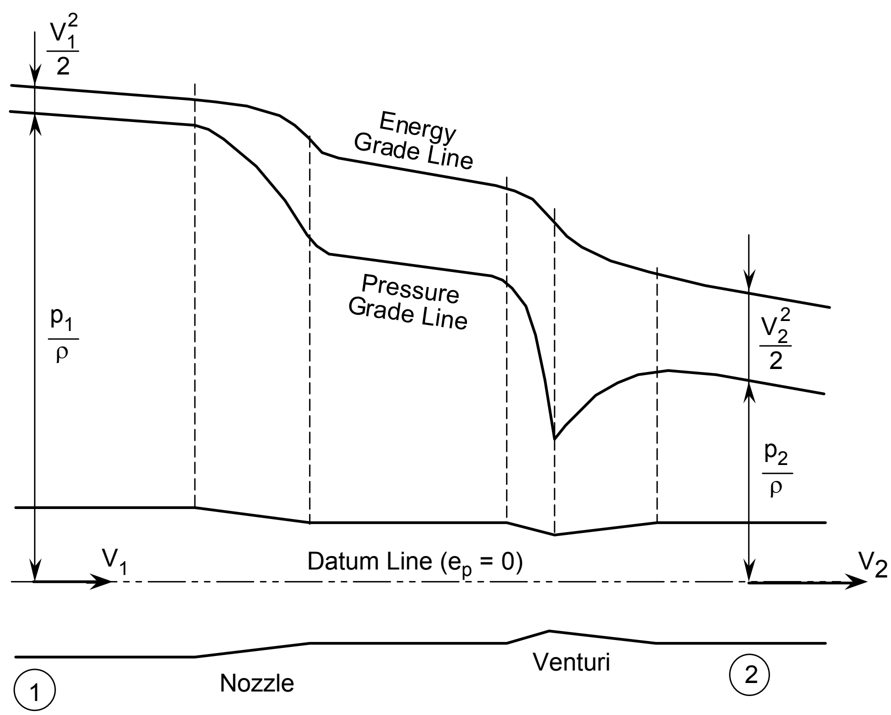

Figure 10

The energy grade line slopes down because of accumulating friction losses. There is a steeper drop at the reducer due to increasing velocity and decreasing diameter, the latter disturbing the flow pattern. The disturbing effect continues over a certain distance past the reducer because streamlining of the flow takes some time. The grade line is curved downwards because friction losses are a function of velocity squared, and the velocity increases as the liquid flows through the reducer.

The pressure grade line is parallel to the energy grade line within the constant-diameter section of the pipe where kinetic energy stays constant, and falls faster within the diffuser section where some pressure energy gets converted into kinetic energy. This grade line is curved downwards even more than the other grade line because kinetic energy, like friction losses, is also proportional to velocity squared.

In the following straight length of pipe, both grade lines are steeper than in the initial straight pipe because the diameter is smaller and the velocity is higher. Then, in the venturi, the grade lines will initially drop due to decreasing diameter and increasing velocity. They are, again, curved for the same reason as in the reducer. In the expanding part of the venturi, the velocity is decreased due to the diameter increase and some kinetic energy/velocity head converts back into pressure. However, this recovery is not complete because some pressure energy gets lost due to friction in the venturi.

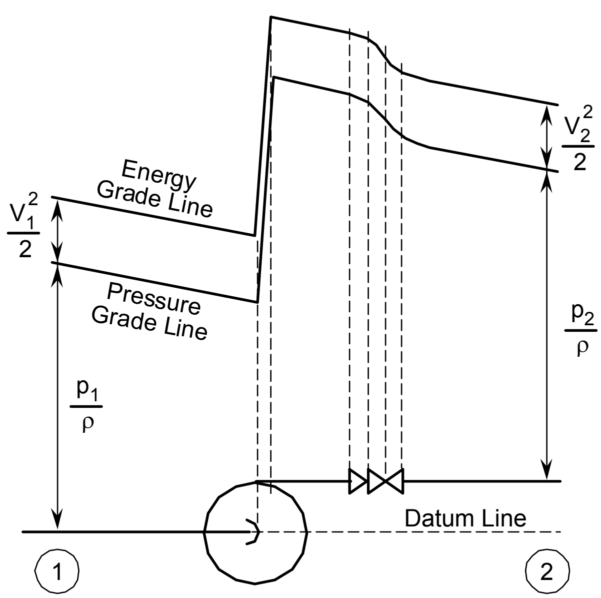

Figure 11

Our next system component is a centrifugal pump in horizontal piping with a non-return/throttle valve shown in Figure 11. The pump has the same suction and discharge-piping diameter.

In the pump, both grade lines rise sharply due to the energy added by the pump to the liquid. Although velocity changes within the pump, it stays constant before and after the pump because the piping size is identical. (We are ignoring the velocity changes within the pump). Both grade lines have a steep drop across the valves due to increased friction losses. In general, the flow path through valves is torturous. Fluid has to change direction and the cross section changes sometimes more than once. The velocity head increases in the valves and decreases past the valves in larger diameter piping. Some pressure recovery occurs similar to the venturi effect previously described.

Figure 12 shows a constant diameter pipe with a vertical rise and two 900 elbows. It also has a valve and an orifice.

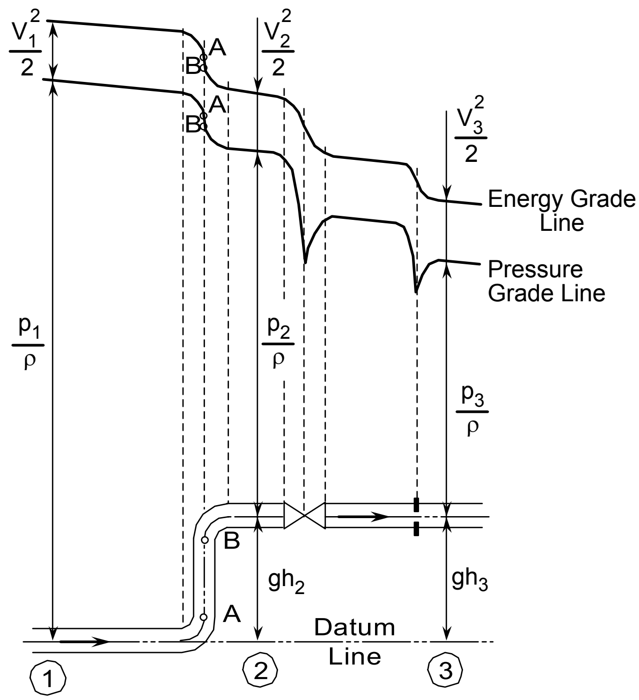

Figure 12

The energy grade line will be gradually sloping down along the straight horizontal sections of the pipe. The locations of steeper drops will be due to increased friction losses in two elbows, the valve and the orifice.

The elevation head will increase at the vertical section between points A and B. Since some friction loss occurs in that section, the energy and pressure grade lines decrease between these points.

The velocity head will temporarily increase inside the valve and the orifice due to narrower passages. Some of the pressure drops in the valve and the orifice will be recovered.

Finally, we can put all of the above examples together. Figure 13 shows a simple system and the corresponding energy and pressure grade lines.

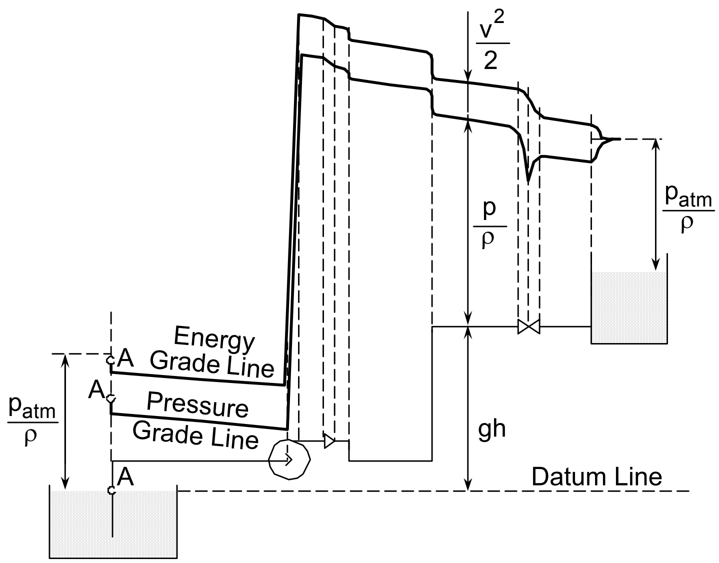

Figure 13

In this example, the absolute pressure scale is used because of subatmospheric pressure in the pump suction line. This pressure is subatmospheric because of the pump location above the suction tank level and friction losses at the entrance to the suction pipe and inside it. If we used the gauge pressure scale, the suction line pressure would be negative. The corresponding pressure grade line would be below the datum, which would reduce the clarity of the drawing.

Notice that the total energy at the liquid surface in the suction tank equals the pressure energy because the liquid is stationary (no kinetic energy) and located on the datum line (no potential energy). The total energy at point A located inside the suction pipe is reduced due to friction that occurs upstream of point A. Pressure at this point is below atmospheric because some pressure energy is lost due to friction and some is converted into kinetic energy.

Friction losses also occur at the entrance to the discharge tank where the liquid exiting the pipe mixes with the liquid in the tank. These losses bring the energy grade line to the atmospheric level. As the liquid loses its kinetic energy, pressure energy rises, though this conversion is hampered by the friction losses. At the points on the liquid surface in the tank where velocity is about zero, the two grade lines join.

The amount of kinetic energy possessed by the flowing liquid is exaggerated in this drawing for clarity. In a real system, the two grade lines are much closer to each other.

This concludes the section on energy exchange in fluid systems. This material should help us understand changes in liquid pressure and velocity when a system condition (e.g., valve position) changes.

The above information pertains to liquid systems. Behaviour of vapours and gases is more complex due to their compressibility, which affects their density and causes temperature (hence, thermal energy) changes during compression or expansion. Accounting for these two variables is complicated and beyond the objectives of this course.

6 OTHER PHENOMEMON

6.1 Siphon

The system shown in Figure 14 is called a siphon. Siphon lifts the liquid to an elevation higher than its free surface and then discharges it at a lower elevation than the level of the liquid. The top point (S) of the siphon is referred to as summit.

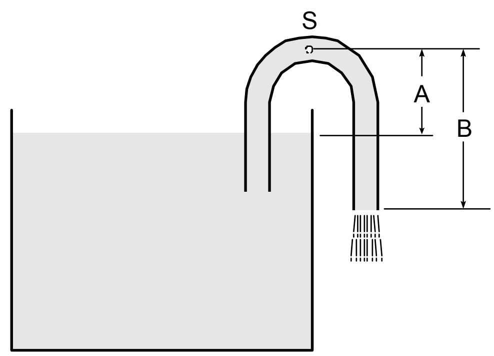

Figure 14

The principle of siphon operation is simple: gravity pulls the liquid in the outlet pipe down. This creates a low pressure at the summit (S) of the pipe bend. The atmospheric pressure then pushes fresh liquid from the tank into the siphon. To compensate for friction, B must exceed A. The larger the difference is, the faster the liquid flows.

We must realise that a siphon is a tremendous labour-saving device. Atmospheric pressure and gravity do the work that otherwise would have to be supplied by electric motors driving pumps.

The performance of the siphon is limited by the low pressure that occurs near the summit. A siphon does not work satisfactorily when the pressure at the summit is close to the vapour pressure of the handled liquid. When the summit pressure drops below the vapour pressure, there will be local boiling at the summit and the vapour will interrupt the siphon. Even before the vapour pressure is reached, gases dissolved in the liquid may be released. Solubility of gases in liquids decreases when pressure drops. This may cause the gases to come out of solution as bubbles—a familiar process that happens, for example, when a bottle of a carbonated drink is opened

By the virtue of their low density, the released gases/vapour will accumulate at the summit. This is a buoyancy phenomenon and will be explained in a moment. By filling the top portion of the pipe, they will interfere with the flow. When the whole diameter is filled, the siphon will stop.

Large industrial siphons, that operate continuously, employ vacuum pumps at the summit in order to remove gases that may interrupt or limit the siphon.

There are two notable applications of siphon in nuclear plants. In the Condenser Circulating Water (CCW) system, cooling water flows up into the condensers, then, from the outlet water box, falls into the discharge duct, and out into the lake. Although the siphon does not do the whole pumping job, it significantly reduces

CCW pump power requirements and operating costs. The CCW pumps have to supply only enough energy to overcome friction in the system. The Vacuum Priming System, connected to the condenser water boxes, establishes and maintains the siphon.

Another example of siphon use is the dousing system in the vacuum building. Figure 15 shows the system in a poised state.

The dousing water tank has riser pipes that connect it with the upper chamber. The risers and upper chamber are the initial leg of the siphon.

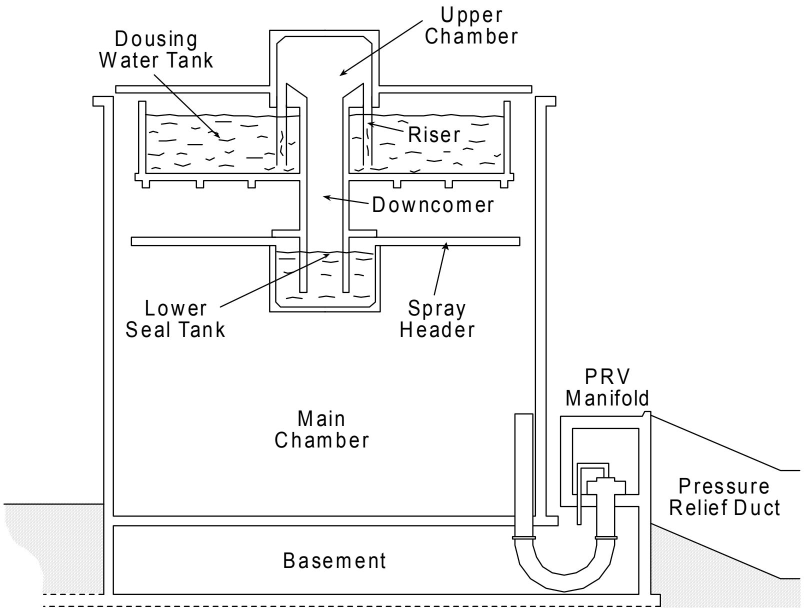

Figure 15

The upper chamber is the summit of the siphon and is isolated from the main chamber of the vacuum building. Vacuum in the upper chamber must be maintained in order to get rid of gases that come out of solution in dousing water.

If a LOCA occurred and large quantities of steam entered the vacuum building, the pressure in the main chamber would rise. Water in the dousing water tank would be pushed up into the risers and flow down to the lower seal tank. The water in this tank isolates the upper chamber from the main chamber and prevents air and steam from flowing upward into the summit of the siphon. Water then flows from the lower seal tank into the spray headers. The downcomer and lower seal tank are the longer/final leg of the siphon.

6.2 Loop Seal

Loop seals are basically U-shape pipes with the bend at the lowest point, much like upside down siphons. The bend is filled with liquid to prevent gases from entering the system that the loop seal is connected to.

They are typically found on drainage and sewage systems to prevent noxious gases from entering the environment.

An example from nuclear plants is illustrated in Figure 15 in the vacuum building. The lower seal tank acts as a loop seal preventing air and steam from entering the upper chamber from the main chamber.

6.3 Buoyancy

The resultant force exerted on a body by a static fluid in which it is submerged or floating is called the buoyant force or buoyancy.

Buoyancy is governed by the Archimedes' Principle which states that a body, floating or immersed in a fluid, is acted upon by a buoyant force equal to the weight of the fluid displaced. That force always acts vertically upwards.

If the body is heavier than the volume of the displaced fluid, it will sink. If it is equal it will float in the fluid and, if it is lighter, it will rise to the surface. A body does not refer to just a solid object. It can also be a bubble of a gas or even a pocket of the same fluid that is lighter or heavier due to a temperature difference between the surrounding fluid and the pocket, or due to a change of state (boiling or condensation).

There are many examples in the plants where we rely on buoyancy to initiate and/or continue some important processes.

For example, in steam generators, the vapour bubbles formed rise to the water surface due to buoyant forces acting on them.

Another example is the CCW flow through the condensers. The water picks heat from condensing steam and at the same time, the siphon lowers its pressure. The result is a release of dissolved gases that rise to the top of the water boxes, again due to buoyancy forces. Normally, the vacuum priming system removes them to maintain the siphon.

7 TWO-PHASE FLOW

Two-phase flow is the flow of two phases of a fluid, the liquid phase and the gas/vapour phase.

A two-phase flow can be produced in one or more of the following ways:

- Vapour is generated from a liquid by adding heat or by exposing it to pressures below vapour pressure;
- Liquid can be generated by condensing vapour either due to cooling and/or increasing pressure above vapour pressure;
- Gases dissolved in a liquid come out of solution under certain temperature /pressure conditions.
- Gas bubbles can be entrained in a liquid due to turbulence or vortex in a suction tank, or a large leak in a sub-atmospheric system.

Another important consideration is the size and shape of gas/vapour and liquid phases because this affects the hydraulic and thermal performance of their mixture, and may lead to various operational problems. For example, small vapour bubbles in a liquid may cause cavitation, whereas big pockets can lead to steam hammer. Both these problems are explained later in this module. The following list gives a few examples of different forms of a two-phase flow:

- Small gas/vapour bubbles in a flowing liquid;
- Large pockets of gas/vapour that can even separate the liquid flow;
- A vapour film separating the liquid from a hot surface transferring heat to the fluid;
- Small liquid droplets (like mist) or large liquid slugs in a steam/ gas flow;
- A stratified flow of the liquid at the bottom and the vapour/gas above it.

Here are a few examples from the plants:

Vapour bubbles are generated during cavitation in light and heavy water systems. We will discuss cavitation in detail in the following section. Another example is boiling in steam generators.

Small gas bubbles are produced during CCW flow through the condensers. During this process, the solubility of gases in water drops because water pressure drops and temperature rises. Air bubbles can also form due to air ingress to the sub atmospheric part of a liquid handling system, e.g., the suction piping of the condensate extraction pumps.

Large vapour/steam pockets in a liquid system or liquid slugs in a steam/gas system are a result of some serious operational problems. Details are discussed in the sections on water and steam hammer later in this module.

A thin vapour film can form during abnormal operating conditions on the surface of some fuel elements in the reactor. This dangerous situation is discussed in the thermodynamics course.

Small water droplets (mist) are present in wet steam in the steam turbines and various steam systems. They lead to a number of operational problems, such as erosion.

A stratified flow occurs in the oil drain lines from the turbine generator bearings. These lines are oversized to prevent bearing flooding. Oil flows at the bottom, and air with oil vapour is above. A stratified flow can also develop in inadequately drained steam/gas pipes when steam/gas velocity is too small to break the condensate into slugs or droplets.

Some of the forms of a two-phase flow (e.g., wet steam) are tolerated but others can lead to accidents or accelerated equipment wear.

7.1 Cavitation

Cavitation is the formation of vapour bubbles in the low-pressure areas of a system and the subsequent collapse of these bubbles when they reach higher-pressure areas.

The pressure has to fall below the vapour pressure that corresponds to the liquid temperature in order to start the boiling and it has to increase above the vapour pressure to cause the collapse.

When the bubbles collapse, very high implosion velocities and pressures are generated. Such high and numerous impacts can show up as:

- Vibration with all its attendant consequences, e.g., fatigue;
- Pitting due to repeated pounding;
- Noise.

Critical regions for the development of cavitation in a liquid-handling system are sudden cross-section contractions and enlargements, and changes in flow direction.

Figure 16 is an example of a sudden contraction. It shows the pressure distribution in a nozzle where: p_1 is the upstream fluid pressure, p_2 the downstream pressure and p_{vap} the vapour pressure of the fluid.

Vapour bubbles will be produced in the region of the pipe where the pressure is below the saturation pressure. The bubbles will collapse further along the pipe when the pressure increases above the saturation pressure.

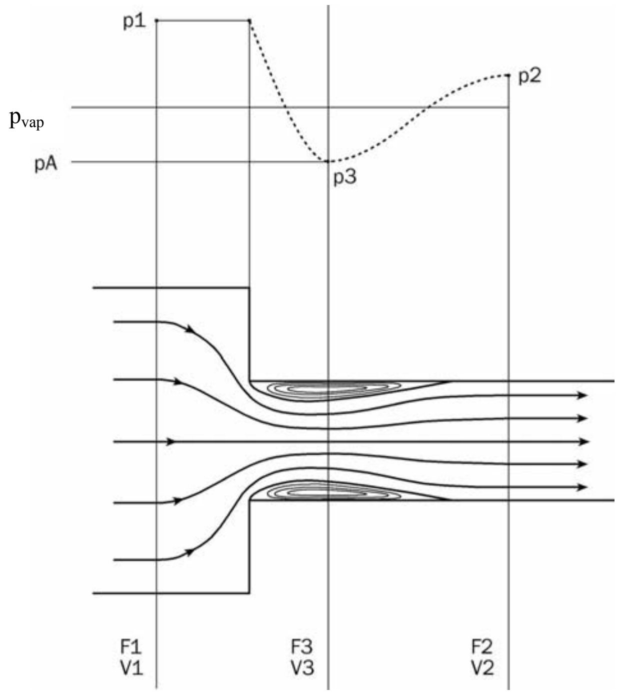

Figure 16

Cavitation does not necessarily lead to damage, even if it does generate noise and mild vibrations. It depends on the intensity of cavitation (the number and size of the bubbles produced) and on the location of the collapse. Strong cavitation will have many bubbles collapse on, or very close to, the surface. This accelerates pitting and produces high vibration. In the extreme case, the vibration can be destructive very quickly (minutes-hours).

Typical potential sites of cavitation are:

- Suction channels of pumps;
- Centrifugal pump impellers;
- Sharp elbows and tees;
- Downstream of partly-open valves;
- Sudden changes in flow area, e.g., orifices.

Most of the above potentials for cavitation are designed into the systems and plant staff cannot influence them. There are, however, instances when some operating practices can induce cavitation. Increasing throttling, operating at lower pressures and higher temperatures can get us below the vapour pressure of the system liquid. Details are explained in the next module.

7.2 Water Hammer

Water hammer is a potentially dangerous and damaging phenomenon during which extremely high-pressure shocks are produced. Typical scenarios involve:

- Sudden deceleration (in the extreme case, stopping) of a fluid column;

- Impact of water slugs carried by steam or gas (Figure 17) when they strike obstacles like elbows, valves, headers and tanks (often called water impact).

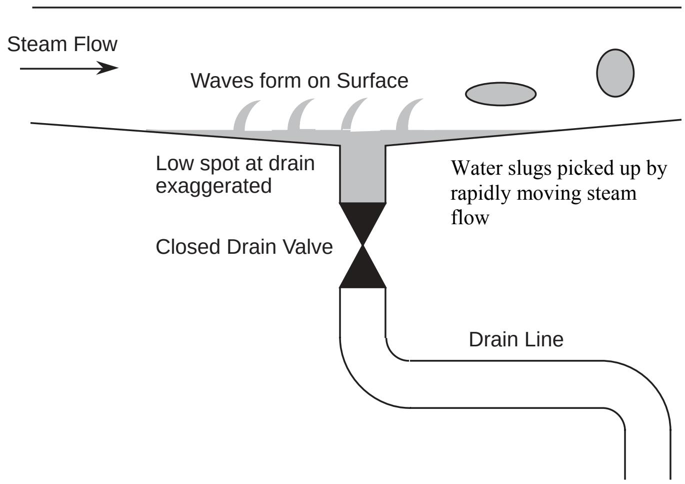

Figure 17

In the first case, large forces must be exerted on the fluid to decelerate it rapidly, as governed by the Second Law of Dynamics. These forces produce high-pressure waves (shocks) that propagate through the fluid in all directions. This process is described below.

When a moving fluid meets an obstacle, the kinetic energy is converted into the pressure energy. Because of the elasticity of the system, only a portion of the energy is dissipated in the first blow by friction and vibration.

The rest is temporarily stored as pressure energy in the fluid (it acts like a compressed spring). This energy is then converted back into kinetic energy when the fluid moves in the opposite direction until it meets another obstacle on its way back. Another pressure wave is then generated, resulting in another blow, although a weaker one, and a portion of energy is again dissipated. This may go on back and forth several times until all kinetic energy of the fluid is dissipated.

Although the name "water hammer" suggests association with water, this violent process can happen in any fluid system. However, because of the much higher density (hence, mass) of liquids, it is most dangerous in liquid systems—particularly those that have large amounts of kinetic energy due to the mass and velocity of the liquid.

Water hammer can inflict severe damage. In the extreme case, water hammer can rupture the affected equipment. If the system contains hot pressurised water or steam, the problem can quickly evolve into a serious life-threatening situation. In less severe cases, the violent piping movement caused by the shocks can damage the pipe supports and hangers, tear off valve actuators or their fluid supply lines, or ruin the piping insulation.

Even when there is no damage, witnessing a water hammer in the field can be an unforgettable experience. Deafening hammering noise and violent shaking of the system gives a very strong impression of involved forces.

There have been numerous instances of water hammer incidents in the plants. In one case, a steam header was not properly drained and the in-rush of steam picked large slugs of water and carried them into the piping. Some valves moved 0.20 m and the whole piping system shook violently.

Apart from proper operating practices, (which will be discussed in one of the following sections), there are some design configurations that will prevent or at least mitigate water hammer:

- An orifice put into the system will dissipate excess kinetic energy. However, it is in the system all the time and introduces a pressure head loss.
- A water-hammer arrestor is a tank with an internal gas cushion that absorbs some pressure surges and thus minimises hammering. This solution is limited to small systems.
- Standpipes (Figure 18) or surge tanks are used in low-pressure systems; otherwise they would have to be extremely tall or located high above the system. They again can compensate for rapid pressure changes. Pressure increase will be limited to the height of the standpipe or the tank.

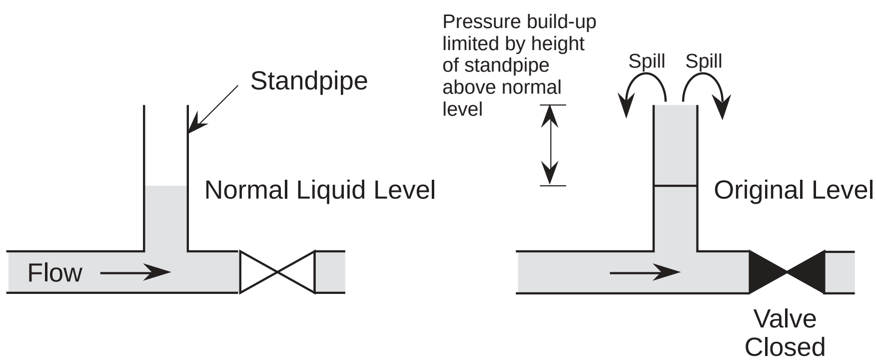

Figure 18

7.3 Steam Hammer

Steam hammer is the collapse of steam pockets resulting in water rushing to fill the created voids. The collapse causes pressure waves that can result in equipment damage.

Steam hammer is also called condensation-induced water hammer.

Steam hammer typically occurs in lines that have large amounts of pressurised liquids close to the saturation temperature. An example would be drains in steam lines.

When a drain valve is opened, pressure close to the valve will fall. When it falls below the saturation pressure, vapour pockets will form at the valve. Liquid behind the vapour pocket starts moving towards the valve due to pressure difference caused by opening the valve. Pressure near the valve will recover quickly and will cause a violent collapse of the formed vapour pocket. The resulting collisions of the liquid rushing in to fill the voids send pressure waves through the system. These pressure waves cause collapse of other steam pockets as they pass. Once a wave passes, another vapour pocket is formed. This cyclic pocket formation and collapse continues as the low and high-pressure waves reflect back and forth at the speed of sound in that particular fluid. Assuming no damage to the system, the waves propagate through the system until friction dissipates their energy.

Severe steam hammer can also occur in the CCW system on a CCW pump trip if the vacuum breakers fail (the breakers admit a controlled amount of air to act as a cushion). Upon a CCW pump trip, the water flow decreases. Because the condensers are located above the pumps, the ascending flow (it is moving up against gravity) slows down faster than the flow descending into the discharge duct.

This can result in the formation of very low-pressure vapour pockets as the water flows separate. Due to the low temperature of the CCW water (10-20°C), the corresponding vapour pressure is about 1-2 kPa(a).The high vacuum of the vapour pockets will draw water back to collapse them (causing steam hammer).

Some serious steam hammer incidents happened in the plants. In one instance, a large and rapid pressure drop in the deaerator resulted in violent flashing into steam of the water in the deaerator storage tank. This flashing created a water surge. When the moving mass of water hit the storage tank end wall, the storage tank moved 0.15m off its position, shearing the bolts holding the tank to the pedestal. Obviously, some enormously large forces can result from steam hammer incidents.

7.4 Minimising Water or Steam Hammer

There are a number of good operating practices that minimise the risk of water or steam hammer:

- Draining of a steam or gas system;
- Venting and slow priming of a liquid system;
- Slow operation of valves;
- Starting up or shutting down a centrifugal pump with its discharge valve closed or cracked open;
- Delay between pump start-ups and shutdowns;
- Applying cooling water to a heat exchanger first.

Let's discuss them individually to show how water or steam hammer can be minimised.

Draining liquid from a steam or gas system prevents accumulation of liquid. If we do not carefully drain the system, we will most probably experience formation of water slugs. These slugs will be picked up and driven by the steam or gas and will result in water hammer/impact. In steam systems, the warm-up rate should be small enough not only to avoid thermal stresses, but also to prevent overloading of the drain valves.

Also, by minimising the amount of condensate, proper draining of a steam system reduces the risk of steam hammer upon opening of the drain valves.

Venting and slow priming of liquid systems will prevent water hammer. If priming proceeds too fast, the in-rushing liquid will have high kinetic energy and any obstacles to the flow—like elbows, valves and headers—will suffer a strong impact.

Venting is important as well. If it is not sufficient, gas or vapour in the system may temporarily block the liquid flow, which can result in pressure pulsations. Pressure pulses can lead to water hammer or steam hammer if the vapour is close to its saturation pressure.

Slow operation of valves will allow the kinetic energy of the liquid to be gradually converted into pressure energy and friction losses during closing, and a gradual increase of kinetic energy during opening. Valves that need many turns of the stem to close or open them (like gate and globe valves) cannot cause water hammer. However, butterfly, ball and plug valves can be closed or opened very quickly. One quarter of a turn will bring them from fully open to fully closed or vice versa. We have to be careful when we operate those types of valves.

Starting up or shutting down a centrifugal pump with its discharge valve closed or cracked open will help us prevent water hammer because the flow in the system will be changing gradually.

Delays between pump start-ups and shutdowns in a system with more then one pump will also prevent the onset of a water hammer. The delay gives the system time to dissipate the energy of the pressure waves caused by a start-up or a shutdown of the previous pump.

The last good practice we will discuss is the application of cooling water to heat exchangers first. In this case, we are concerned with a steam hammer problem. If during the start-up, the cooling water flow is not established before the admission of steam or hot water at a temperature higher than the saturation temperature of the cooling water, there is a danger of steam pocket formation in the cooling liquid. When later the cooling flow is established, thereby raising its pressure, the steam pockets will abruptly condense. This will result in violent collisions of water columns previously separated by the steam pockets. Similarly, when we are shutting down a heat exchanger, we should close the steam or hotter liquid supply before we close the cooling flow.

7.5 Solid Operation

Solid operation is the operating mode in which the system is completely filled with a liquid. There are no voids or tanks with gas/vapour cushion in the system. This is a typical mode of operation of many liquid systems in the plants. Examples are: the heat transport system with no pressurizer or when the pressurizer is isolated, and the recirculated (demineralized) cooling water system. Any change in temperature will cause expansion or contraction of system liquid that will be different than the expansion/contraction of piping. This difference in expansion/contraction has to be accommodated. If the temperature in the system increases, some liquid has to be bled off to prevent high pressure. If the temperature decreases, liquid has to be fed in to prevent flashing of some of the liquid in the system to vapour, which could lead to steam hammer upon a subsequent increase in system pressure. This bleeding and feeding is particularly critical during start-up and shutdown when temperature changes may be large.

Large pressure spikes in solid operation can come either from fast temperature changes or from fast flow velocity changes (i.e., water hammer). Pressure spikes due to flow velocity changes are particularly dangerous and are not limited to solid operation only. Pressure spikes caused by flow changes are much faster than pressure spikes due to temperature changes. We have discussed water and steam hammer in the previous two sections and we will talk about pressure spikes more in the modules on pumps and valves. Both adverse precursors of large pressure spikes, i.e., temperature and fluid flow changes, have been recognised and preventive measures reflected in operating procedures.

8 FLOW-INDUCED VIBRATIONS

Vibrations were discussed in the previous module. One cause of vibration that we have not yet discussed is the flow of fluids.

Fluid-induced vibration can originate from a number of system conditions, e.g.:

- High turbulence;
- Cavitation;
- Pressure pulsation;
- After-effects of water or steam hammer.

Cavitation and water/steam hammer were explained earlier in this module.

High turbulence can also excite vibration. An inherent feature of a turbulent flow is a random pulsation of pressure. The process generates a broad spectrum of frequencies, which rise with increasing fluid velocity. The formation and shedding of eddies in places where fluid is forced to change flow direction abruptly causes additional pressure pulsations. Examples of equipment where this occurs are valves, elbows, orifices and heat exchangers tubes. The broad spectrum of frequencies generated by a turbulent flow increases the risk of resonance.

Additional pressure pulsations originate from the operation of fluid handling equipment like pumps, turbines, compressors and fans. In these machines, blades and vanes force the fluid to flow around them. For example, in centrifugal pumps, pressure downstream of each impeller vane is somewhat lower than in the middle of each passage between the vanes. When the impeller rotates, the pressure of the liquid delivered by the pump pulsates at the frequency at which the vanes pass by the pump discharge. Thus, this frequency depends on the number of impeller vanes and rotational speed (RPM).

In the module on vibration, we discussed resonance and determined that it occurs when a forced frequency is equal to one of the natural frequencies of the object.

An object can be any part of a fluid system, e.g., a section of piping, pump, tube bundle in a heat exchanger, or even the fluid itself. If one of the natural frequencies of that object is close to a frequency of the flow-induced vibration, resonance may increase vibration to a dangerous level.

9 SUMMARY

This concludes our review of fluid mechanics principles. We should be comfortable with the basic fluid properties, like pressure, density, viscosity, mass and volumetric flow rates, elevation, pressure and velocity heads, head losses, and how they affect each other. We are also knowledgeable of basic fluid mechanics processes in various simple plant components, like elbows, orifices, venturis, valves and pumps. We understand and can recognise some operating problems associated with fluid mechanics, like flow induced vibrations, cavitation, water hammer and steam hammer. We have reviewed some good operating practices to avoid these problems. In conclusion, this module gives us a good base for looking in detail at some most common components in CANDU power plants. This is done in the next modules.

10 ASSIGNMENT QUESTIONS

1. Define the following terms and state their units of measurement:
    a) Pressure,
    b) Density, and
    c) Viscosity.
2. Convert the following values of pressure between pressure scales:
    a) 5.0 kPa(a) to the vacuum scale and the gauge pressure scale,
    b) 170.0 kPa(g) to the absolute pressure scale,
    c) 40.0 kPa(v) to the absolute and gauge pressure scales.
3. A hydraulic relief valve has a valve piston area of 0.004 m^2. It is spring-loaded to retain it in the closed position during normal operation of the system. This spring force acts upon the upstream part of the valve piston over an area of 0.020 m^2. The relief valve is designed to lift if the hydraulic fluid pressure exceeds 15 MPa. Calculate the spring force necessary to just keep the relief valve closed at this pressure.
4. State the factors which affect the static pressure exerted at the base of a column of liquid.
5. State the factors which affect the pressure of a gas in a container.
6. Describe the difference between laminar flow and turbulent flow with respect to:
    a) the velocity profile of the flow, and
    b) velocity and pressure pulsations.
7. Define mass flow rate, and give its basic units of measurement.
8. Define volumetric flow rate, and give its basic units of measurement.
9. State the relationship between mass and volumetric flow rates.
10. State the Continuity Principle as it applies to mass flow rate.
11. Water flows into a leak free system through a pipe of cross sectional area 100 cm^2, at a velocity of 4 m/s. This water flows out of the system through a pipe of cross sectional area 200 cm^2. Using the Continuity Principle, determine the velocity of the water leaving the system.
12. Explain the effect of pressure and temperature on volumetric flow rate for:
    a) liquids, and
    b) gases.

13. Define the following terms regarding a system with flowing liquid:
    a) Elevation head, pressure head and velocity head,
    b) Static pressure, dynamic pressure and total pressure, and
    c) Energy loss and head loss.
14. State the effect of fluid viscosity and velocity on a head loss in turbulent flow.
15. State the effect of temperature on viscosity of liquids.
16. Explain the relationship between elevation head, pressure head and velocity head in a fluid system with energy losses and additions.
17. Explain what happens to the pressure and velocity associated with fluid flow in each of the following systems:
    a) A straight horizontal pipe of constant diameter,
    b) A straight horizontal pipe fitted with a reducer and a venturi,
    c) A centrifugal pump with a straight suction pipe and a discharge pipe containing a non-return/throttle valve,
    d) A constant diameter pipe with a vertical rise, a valve, an orifice and two 90-degree elbows.
18. Define and describe the following terms:
    a) Siphon,
    b) Loop seal, and
    c) Buoyancy.
19. Explain the adverse effects of gas or vapour accumulation in a siphon.
20. Define two-phase flow.
21. Describe the five common forms of two-phase flow and, for each of them, give an example from a CANDU plant.
22. Define cavitation and explain how it can occur in a fluid system.
23. List three potential sites of cavitation in a CANDU plant.
24. Define each of the following, and explain why each can produce large pressure spikes in a fluid system:
    a) Water hammer,
    b) Steam hammer, and
    c) Solid operation.

25. Explain how the following operating practices minimize the risk of water or steam hammer:

    a) Draining of a steam or gas system,

    b) Venting and slow priming of a liquid system,

    c) Slow operation of valves,

    d) Starting up or shutting down a centrifugal pump with its discharge valve closed or crack opened,

    e) Delay between pump startups and shutdowns, and

    f) Applying cooling water to heat exchangers first.

26. Explain how a flowing fluid can excite equipment vibration due to:

    a) High turbulence, and

    b) Blade or vane passing, e.g., in a gas turbine or a centrifugal pump.