Lecture 28

ACCUMULATORS

Learning Objectives

Upon completion of this chapter, the student should be able to:

- Define an accumulator.
- Explain various types of accumulators.
- Differentiate between separator and non-separator types of accumulators.
- Size an accumulator for various applications.
- Describe various applications of accumulators.
- Analyze the performance of hydraulic systems using accumulators.

1.1 Introduction

A hydraulic accumulator is a device that stores the potential energy of an incompressible fluid held under pressure by an external source against some dynamic force. This dynamic force can come from different sources. The stored potential energy in the accumulator is a quick secondary source of fluid power capable of doing useful work.

There are three basic types of accumulators:

1. Weight-loaded or gravity accumulator: Schematic diagram of weight loaded accumulator is shown in Fig. 1.1.It is a vertically mounted cylinder with a large weight. When the hydraulic fluid is pumped into it, the weight is raised. The weight applies a force on the piston that generates a pressure on the fluid side of piston. The advantage of this type of accumulator over other types is that it applies a constant pressure on the fluid throughout its range of motion. The main disadvantage is its extremely large size and heavy weight. This makes it unsuitable for mobile application.

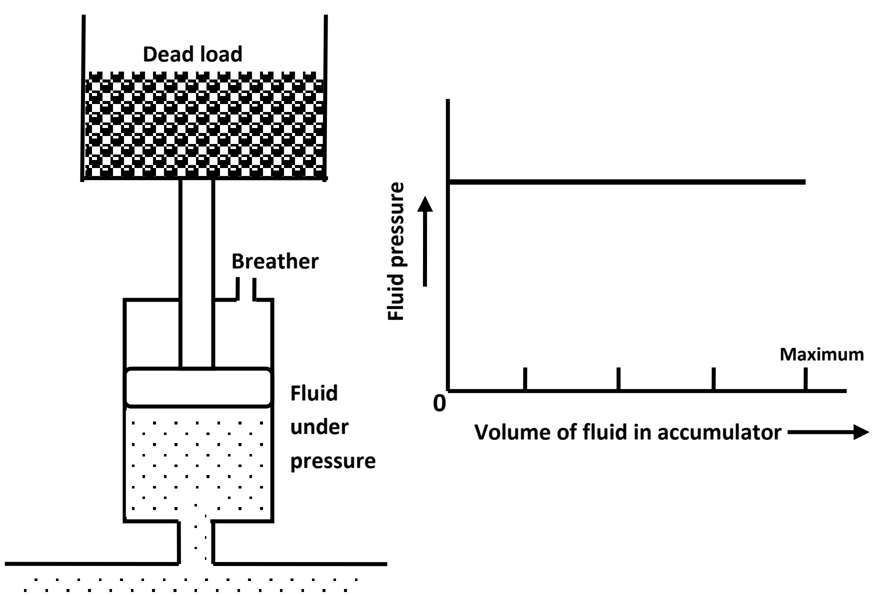

Figure 1.1 Dead weight accumulator**.**

2. **Spring-loaded accumulator:** A spring-loaded accumulator stores energy in the form of a compressed spring. A hydraulic fluid is pumped into the accumulator, causing the piston to move up and compress the

spring as shown in Fig. 1.2. The compressed spring then applies a force on the piston that exerts a pressure on the hydraulic fluid.
This type of accumulator delivers only a small volume of oil at relatively low pressure. Furthermore, the pressure exerted on the oil is not constant as in the dead-weight-type accumulator. As the springs are compressed, the accumulator pressure reaches its peak, and as the springs approach their free lengths, the accumulator pressure drops to a minimum.

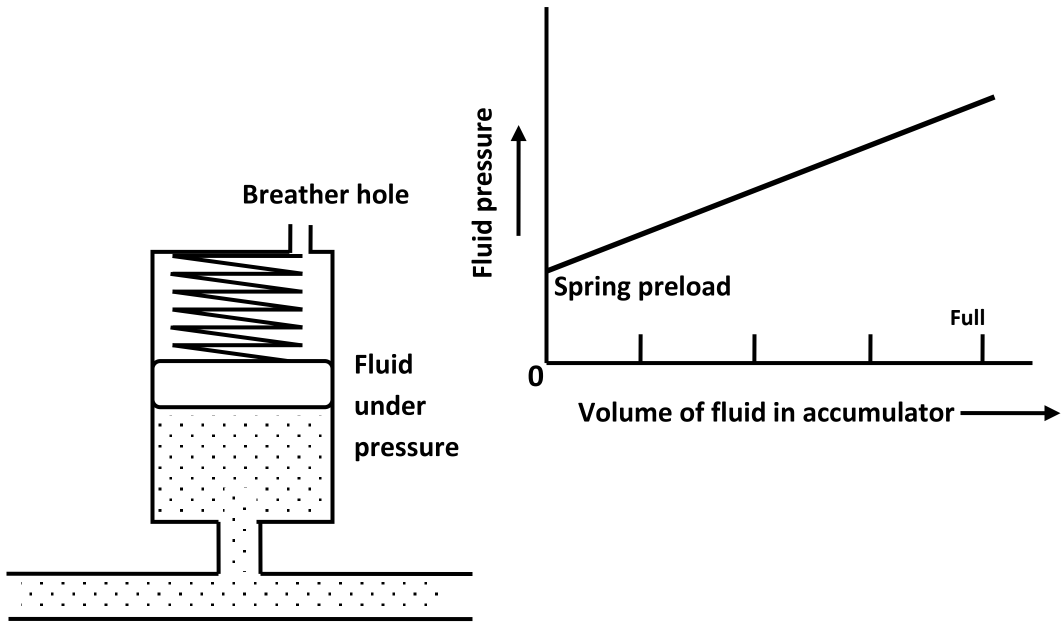

Figure 1.2 Spring-loaded accumulator.

3. Gas-loaded accumulator: A gas-loaded accumulator is popularly used in industries. Here the force is applied to the oil using compressed air. Schematic diagram of a gas loaded accumulator is shown in Fig. 1.3.A gas accumulator can be very large and is often used with water or high water-based fluids using air as a gas charge. Typical application is on water turbines to absorb pressure surges owing to valve closure and on ram pumps to smooth out the delivery flow. The exact shape of the accumulator characteristic curve depends on pressure–volume relations:

- **Isothermal (constant temperature):** This occurs when the expansion or compression of the gas is very slow. The relationship between absolute pressure p and volume V of the gas is constant:

$$pV = \text{constant} \qquad (1.1)$$

- **Isentropic (adiabatic processes):** This is where there is no flow of energy into or out of the fluid. The law that the gas obeys is given by pV^{γ} = constant, where γ is ratio of specific heat and is approximately equal to 1.4.
- **Polytropic:** This is somewhere between isothermal and isentropic. This gas change is governed by the law pV^n = constant, where n is somewhere between 1 and 1.4 and is known as the polytropic coefficient.

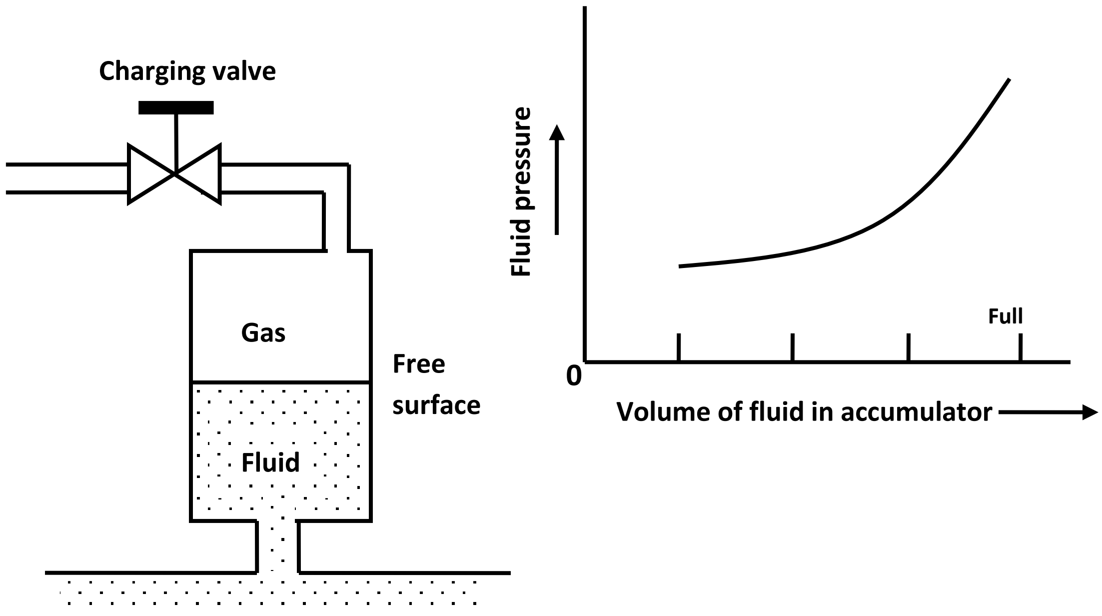

Figure 1.3 Gas-loaded accumulator.

There are two types of gas-loaded accumulators:

- **Non-separator-type accumulator:** Here the oil and gas are not separated. Hence, they are always placed vertically.
- **Separator-type accumulator:** Here the oil and gas are separated by an element. Based on the type of element used to separate the oil and gas, they are classified as follows:

(a) *Piston-type accumulator:*Schematic diagram of a piston type accumulator is shown in Fig. 1.4.It consists of a cylinder with a freely floating piston with proper seals. Its operation begins by charging the gas chamber with a gas (nitrogen) under a pre-determined pressure. This causes the free sliding piston to move down. Once the accumulator is pre-charged, a hydraulic fluid can be pumped into the hydraulic fluid port. As the fluid enters the accumulator, it causes the piston to slide up, thereby compressing the gas that increases its pressure and this pressure is then applied to the hydraulic fluid through the piston. Because the piston is free sliding, the pressure on the gas and that on the hydraulic fluid are always equal.

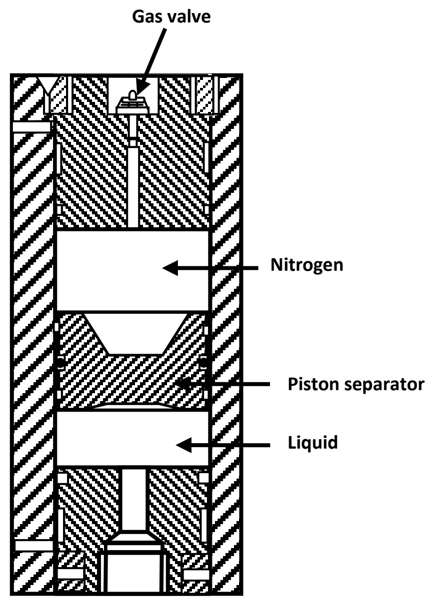

Figure 1.4 Piston-type accumulator.

(b) *Diaphragm accumulator:*In this type, the hydraulic fluid and nitrogen gas are separated by a synthetic rubber diaphragm. Schematic diagram of diaphragm accumulator is shown in Fig. 1.5. The advantage of a diaphragm accumulator over a piston accumulator is that it has no sliding surface that requires lubrication and can therefore be used with fluids having poor lubricating qualities. It is less sensitive to contamination due to lack of any close-fitting components.

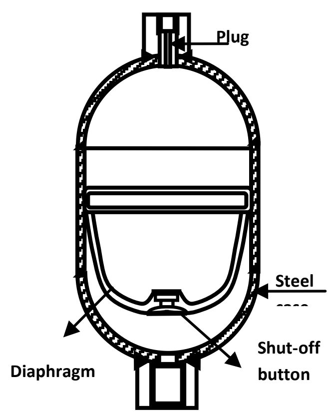

Figure 1.5 Diaphragm-type accumulator.

(c) *Bladder accumulator:* It functions in the same way as the other two accumulators. Schematic diagram of bladder accumulator is shown in Fig. 1.6. Here the gas and the hydraulic fluid are separated by a synthetic rubber bladder. The bladder is filled with nitrogen until the designed pre-charge pressure is achieved. The hydraulic fluid is then pumped into the accumulator, thereby compressing the gas and increasing the pressure in the accumulator. The port cover is a small piece of metal that protects the bladder from damage as it expands and contacts the fluid port.

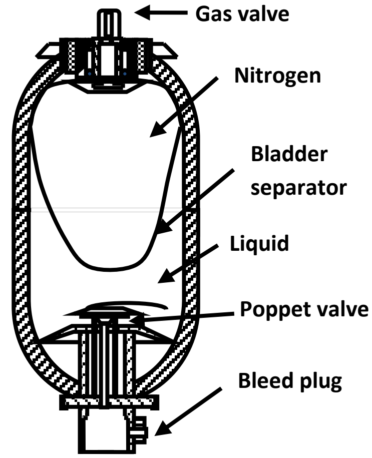

Figure 1.6 Bladder-type accumulator.

In an accumulator, at any point of time, we either compress a pre-charged gas or allow it to expand. This compression or expansion brings about a status change in the gas, which is governed by the perfect gas equation:

$$pV = mRT \qquad (1.2)$$

where $p$is the absolute pressure in bar, V is the gas volume in m^3, m is the mass in kg and R is the universal gas constant. (The most common gas used in industry is nitrogen.) For the particular gas and the accumulator, the value of mR is constant and the gas equation is written as

$$\frac{pV}{T} = \text{constant}$$

or

$$\frac{p_0V_0}{T_0} = \frac{p_1V_1}{T_1} \qquad (1.3)$$

When the change takes place over a long period of time, the temperature of the gas remains constant and such a change is called isothermal, resulting in the equation

$$p_0V_0 = p_1V_1 = p_2V_2 \qquad (1.4)$$

When the change occurs instantaneously, there is no time for heat transfer from the work to the environment.Such a change is called isentropic or reversible adiabatic and is given by

$$p_0V_0^n = p_1V_1^n = p_2V_2^n \qquad (1.5)$$

All changes between isothermal and isentropic are called polytropic. The pressure–volume diagram shown in Fig. 1.7 helps us to understand how the volume variation as a function of pressure depends on the value of the polytropic exponent n that for nitrogen is contained within the limits $1 \le n \le 1.4$. The value of n is taken to be equal to 1 if the compression and expansion process takes place under the isothermal process. For adiabatic conditions, the value of n is taken equal to 1.4.

Isothermal conditions can be considered to exist if the accumulator is used as a volume compensator, leakage compensator and pressure compensator or as a lubrication compensator. In all other cases, such as energy accumulation, pulsation damping, emergency power source, dynamic pressure compensator, shock absorber, hydraulic spring, etc., expansion and compression process may be considered to take place under “adiabatic” conditions. Generally, the adiabatic condition is considered to exist if the compression or expansion period is less than 3 min.

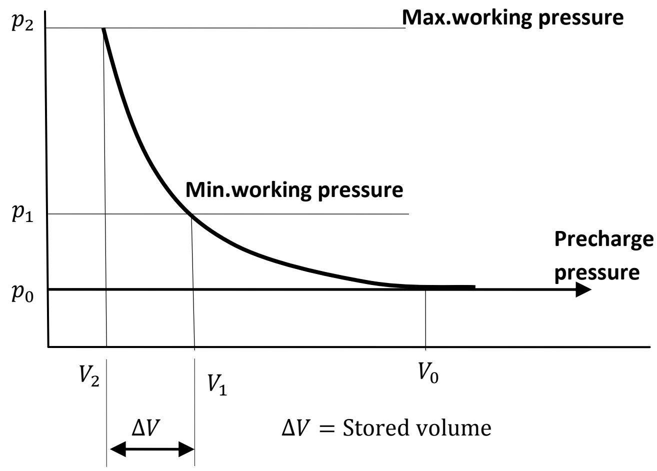

Figure 1.7 Pressure–volume diagram**.**

1.2 Accumulator Selection

After ascertaining the type of accumulator that is appropriate for the purpose envisaged, what remains is determining the volume of the form of "high pressure fluid." Accumulators are manufactured to a variety of pressure ratings and the one chosen should be rated for a pressure more than the maximum system working pressure p_2.

However, the values of the following basic parameters should be established before proceeding further: Working pressures p_1 and p_2. The value of p_2 is found from the ratio $p_2 / p_0 \leq 4$ .The maximum gas pre-charge pressure is found from the relationship $p_0 \leq 0.9 p_1$ or $p_0 \geq 0.25 p_1$. The gas pre-charge pressure must be as close as possible to the minimum working pressure p_1 to obtain maximum storage. Special values for p_0 are used in pulsation damping and shock absorber applications ($p_0 = 0.8 p_1$). Other parameters to be determined are the volume of fluid ΔV that needs to be stored ($\Delta V = 0.75 V_0$), the maximum required flow rate and the operating temperature.

1.2.1 Sizing Accumulators for Isothermal Condition

For isothermal condition, the Boyle–Mariotte law can be rewritten in terms of V_1 and V_2 as

$$V_1 = V_0 \left(\frac{p_0}{p_1} \right) \tag{1.6}$$

and

$$V_2 = V_0 \left(\frac{p_0}{p_2} \right) \tag{1.7}$$

The difference between V_1 at the minimum operating pressure p_1 and V_2 at the maximum operating pressure p_2 gives the amount of the stored fluid ΔV. Thus,

$$\Delta V = V_1 - V_2 = V_0 \left(\frac{p_0}{p_1} \right) - V_0 \left(\frac{p_0}{p_2} \right)$$

$$\Rightarrow \Delta V = V_0 \left(\frac{p_0}{p_1} - \frac{p_0}{p_2} \right)$$

$$\Rightarrow V_0 = \frac{\Delta V}{p_0 / p_1 - p_0 / p_2} \tag{1.8}$$

In the above equations, V_1 and V_2 are nitrogen volumes at the pressures p_1 and p_2, and V_0 is the nitrogen pre-charge volume at the pressure p_0 in liters. It is the maximum volume of gas that can be stored in the accumulator. The size of the accumulator, while conforming to the standard available sizes, should be at least 5–10% more than this volume V_0. Any increase in the value of ΔV results in a corresponding increase in the size of the accumulator. Likewise any decrease in the value of p_0 or the value of $(p_1 - p_2)$ requires an accumulator of higher volume.

1.2.2 Sizing Accumulators for Adiabatic Condition

Starting from the basic formula $p_0V_0^n = p_1V_1^n = p_2V_2^n$, it can be shown that for adiabatic conditions, the values of maximum nitrogen volume V_0 at the pre-charge pressure p_0 and the stored volume of oil are given by the following equations:

$$\Delta V = V_0\left[\left(\frac{p_0}{p_1}\right)^{0.7143} - \left(\frac{p_0}{p_2}\right)^{0.7143}\right]$$

$$\Rightarrow V_0 = \frac{\Delta V}{[(p_0/p_1)^{0.7143} - (p_0/p_2)^{0.7143}]} \qquad (1.9)$$

Here, the value of the polytropic exponent n is taken equal to 1.4 and therefore $1/n$ becomes 0.7143. Here again intermediate values can be used for more accurate results.

1.2.3 Sizing Accumulators for Emergency Reserve

This is a typical application where both isothermal and adiabatic conditions prevail due to slow storage and quick discharge. For this condition, the accumulator volume is given by

$$V_0 = \frac{\Delta V(p_2/p_0)}{[(p_2/p_1)^{0.7143} - 1]}$$

$$\Rightarrow \Delta V = V_0 p_0 \frac{\left[\left(\frac{p_2}{p_1}\right)^{0.7143} - 1\right]}{p_2} \qquad (1.10)$$

1.2.4 Sizing Accumulators for Pulsation Damping

Pulsation damping is typically an adiabatic condition because both storage and discharge have to be accomplished in a very short time. Because pressure pulsation is a phenomenon associated with piston pumps, the stored volume ΔV is a product of the pump displacement q in liters and a constant $\boldsymbol{k}$ that depends on whether the pump is single-acting or double-acting and the number of pistons involved. Pressure pulsation is highest in a single-acting single-piston pump delivering large flows at high pressures. Here the k factor is about 0.69. A single-piston double-acting pump has the same k factor as that of a double-piston single-acting pump whose k factor is equal to 0.29. A three- or four-piston single-acting pump has a k factor of 0.12. For any other pump configuration, an average k factor of 0.05 can be taken with reasonable accuracy.

The stored volume is given by

$\Delta V = kq$ where q is the pump flow rate in LPM/RPM × number of piston. Now

$$V_0 = \frac{\Delta V}{[(p_0/p_1)^{0.7143} - (p_0/p_2)^{0.7143}]} \qquad (1.11)$$

where$p_1 = (p - x)$ and $p_2 = (p + x)$. Here, p is the average working pressure in bar and x is given by $(a \times p)/100$ bar , where a is percentage of pulsation.

1.2.5 Sizing Accumulators for Hydraulic Line Shock Damping

A suitable accumulator can neutralize water hammering in pipes due to shock waves caused by sudden closure of valves. Typical applications can be found in water, fuel and oil distribution circuits. The volume of the accumulator required to absorb the shock waves is given by

$$V_0 = \frac{4Qp_2(0.0164L\,2t)}{1000\ \ (p_2 2 p_1)}$$

where Q is the flow rate in LPM;p_2 is the maximum pressure in bar;L is the length of the pipe in meters;t is the acceleration, deceleration or the valve shut-off time in s and p_1 is the operating pressure with free flow in bar. In some applications such as hydraulic lift trucks, accumulators may be used to absorb hydraulic shocks when the valve shifts or to absorb load-induced pressure surges when the truck runs over uneven ground.

1.2.5.1 Influence of Variation in Temperature on Accumulator Volume

The nitrogen pre-charge pressure in an accumulator is based on the expected maximum rise in the circulating hydraulic oil temperature. This temperature can drop due to changes in environmental factors resulting in a comparable drop in the pre-charge pressure. According to Gay Lussac's law, this variation in pressure affects the volume resulting in lower accumulator capacity. It is therefore necessary to have an accumulator of higher volume so that the useful volume ΔV remains unaffected.

1.2.5.2 Influence of Pressure on Accumulator Volume

The fact that n, the value of adiabatic index, lies between 1 and 1.4 is true for perfect gases. But nitrogen used in accumulators does not behave like a perfect gas when pressure increases and this affects the value of n and consequently the accumulator volume V_0. So for pressures between 200 bar and 350 bar, the value of adiabatic index n may be assumed to lie in the range 1.5–1.6.

1.2.6 Sizing of Additional Gas Bottles

Sometimes the size V_0 as determined by Eqs. (1.6)–(1.12) may be more than the available accumulator sizes or the size so determined is too big for accommodation within the frame of the machine. Also sometimes it may become necessary to maintain a small difference between p_1 and p_2, which results in a higher stored volume ΔV and a much larger accumulator volume V_0. In such cases, it is convenient to get required volume by additional bottles.

For example, if an application requires 43 L of fluid to be discharged adiabatically between 70 and 55 bar, the total volume required would be close to 434 L. The volume requirement is high because the pressure difference is small. If a 22.5 cm bore piston accumulator can hold 125 L, then auxiliary gas bottles can be installed some distance away to meet the balance of volume requirement.

In applications such as energy reserve volume compensation and hydraulic line shock damping, it is recommended that a higher pre-charge pressure $p_0 = 0.97p_1$ be maintained. After obtaining the value of V_0 in the normal way, it must be split into two portions: The minimum indispensable portion that is contained in the accumulator and the portion that is contained in additional gas bottles.