Lecture 12

HYDRAULIC ACTUATORS

Learning Objectives

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

- Explain the classification of hydraulic actuators.
- Explain various types of hydraulic cylinders.
- Describe the construction and working of double-acting cylinders.
- Derive an expression for force, velocity and power for hydraulic cylinders.
- Analyze various lever systems using hydraulic cylinders.
- Explain the importance of cylinder cushioning.
- Explain various types of cylinder mountings used in fluid power.
- Evaluate the performance of hydraulic systems using cylinders.

1.1 Introduction

Hydraulic systems are used to control and transmit power. A pump driven by a prime mover such as an electric motor creates a flow of fluid, in which the pressure, direction and rate of flow are controlled by valves. An actuator is used to convert the energy of fluid back into the mechanical power. The amount of output power developed depends upon the flow rate, the pressure drop across the actuator and its overall efficiency. Thus, hydraulic actuators are devices used to convert pressure energy of the fluid into mechanical energy.
Depending on the type of actuation, hydraulic actuators are classified as follows:

1. Linear actuator: For linear actuation (hydraulic cylinders).
2. Rotary actuator: For rotary actuation (hydraulic motor).
3. Semi-rotary actuator: For limited angle of actuation (semi-rotary actuator).

Hydraulic linear actuators, as their name implies, provide motion in a straight line. The total movement is a finite amount determined by the construction of the unit. They are usually referred to as cylinders, rams and jacks. All these items are synonymous in general use, although ram is sometimes intended to mean a single-acting cylinder and jack often refers to a cylinder used for lifting. The function of hydraulic cylinder is to convert hydraulic power into linear mechanical force or motion. Hydraulic cylinders extend and retract a piston rod to provide a push or pull force to drive the external load along a straight-line path.
Continuous angular movement is achieved by rotary actuators, more generally known as a hydraulic motor. Semi-rotary actuators are capable of limited angular movements that can be several complete revolutions but 360^o or less is more usual.

1.2 Types of Hydraulic Cylinders

Hydraulic cylinders are of the following types:

- Single-acting cylinders.
- Double-acting cylinders.
- Telescopic cylinders.
- Tandem cylinders.

1.2.1 Single-Acting Cylinders

A single-acting cylinder is simplest in design and is shown schematically in Fig.1.1. It consists of a piston inside a cylindrical housing called barrel. On one end of the piston there is a rod, which can reciprocate**.** At the opposite end, there is a port for the entrance and exit of oil. Single-acting cylinders produce force in one direction by hydraulic pressure acting on the piston. (Single-acting cylinders can exert a force in the extending direction only.) The return of the piston is not done hydraulically. In single-acting cylinders, retraction is done either by gravity or by a spring.

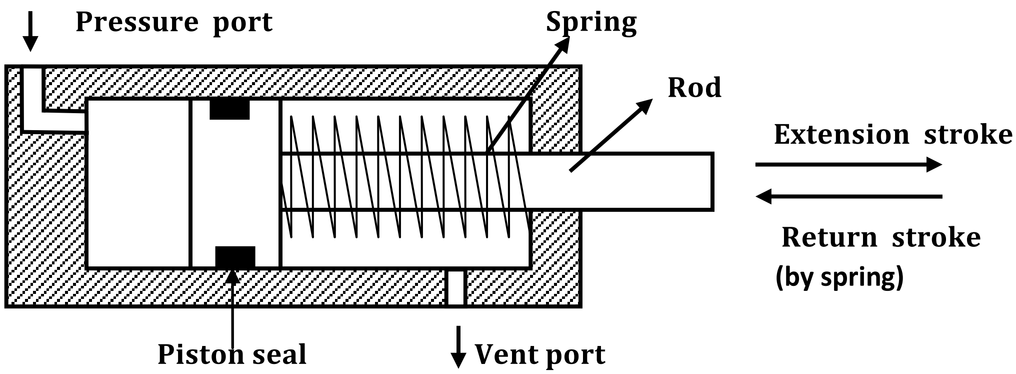


Figure 1.1 Single-acting cylinders

According to the type of return, single-acting cylinders are classified as follows:

- Gravity-return single-acting cylinder.
- Spring-return single-acting cylinder.

1.2.1.1 Gravity-Return Single-Acting Cylinder

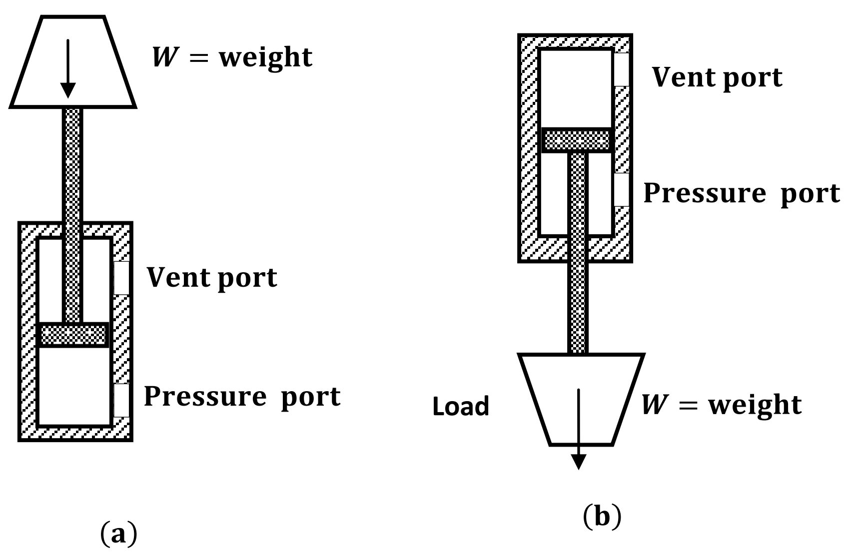


Figure 1.2 Gravity-return single-acting cylinder: (a) Push type; (b) pull type

Figure1.2 shows gravity-return-type single-acting cylinders. In the push type [Fig. 1.2(a)], the cylinder extends to lift a weight against the force of gravity by applying oil pressure at the blank end. The oil is passed through the blank-end port or pressure port. The rod-end port or vent port is open to atmosphere so that air can flow freely in and out of the rod end of the cylinder. To retract the cylinder, the pressure is simply removed from the piston by connecting the pressure port to the tank. This allows the weight of the load to push the fluid out of the cylinder back to the tank. In pull-type gravity-return-type single-acting cylinder, the cylinder [Fig. 1.2(b)] lifts the weight by retracting. The blank-end port is the pressure port and blind-end port is now the vent port. This cylinder automatically extends whenever the pressure port is connected to the tank.

1.2.1.2 Spring-Return Single-Acting Cylinder

A spring-return single-acting cylinder is shown in Fig.1.3.In push type [Fig. 1.3(a)], the pressure is sent through the pressure port situated at the blank end of the cylinder. When the pressure is released, the spring automatically returns the cylinder to the fully retracted position. The vent port is open to atmosphere so that air can flow freely in and out of the rod end of the cylinder.
Figure 1.3(b) shows a spring-return single-acting cylinder. In this design, the cylinder retracts when the pressure port is connected to the pump flow and extends whenever the pressure port is connected to the tank. Here the pressure port is situated at the rod end of the cylinder.

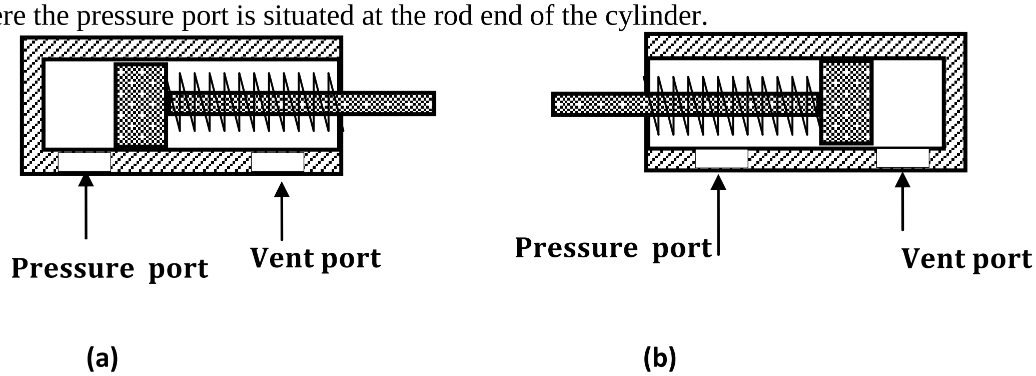


Figure 1.3 (a) Push- and (b) pull-type single-acting cylinders

1.2.2 Double-Acting Cylinder
There are two types of double-acting cylinders:

- Double-acting cylinder with a piston rod on one side.
- Double-acting cylinder with a piston rod on both sides.

1.2.2.1 Double-Acting Cylinder with a Piston Rod on One Side
Figure 1.4 shows the operation of a double-acting cylinder with a piston rod on one side. To extend the cylinder, the pump flow is sent to the blank-end port as in Fig. 1.4(a). The fluid from the rod-end port returns to the reservoir. To retract the cylinder, the pump flow is sent to the rod-end port and the fluid from the blank-end port returns to the tank as in Fig.1.4(b).

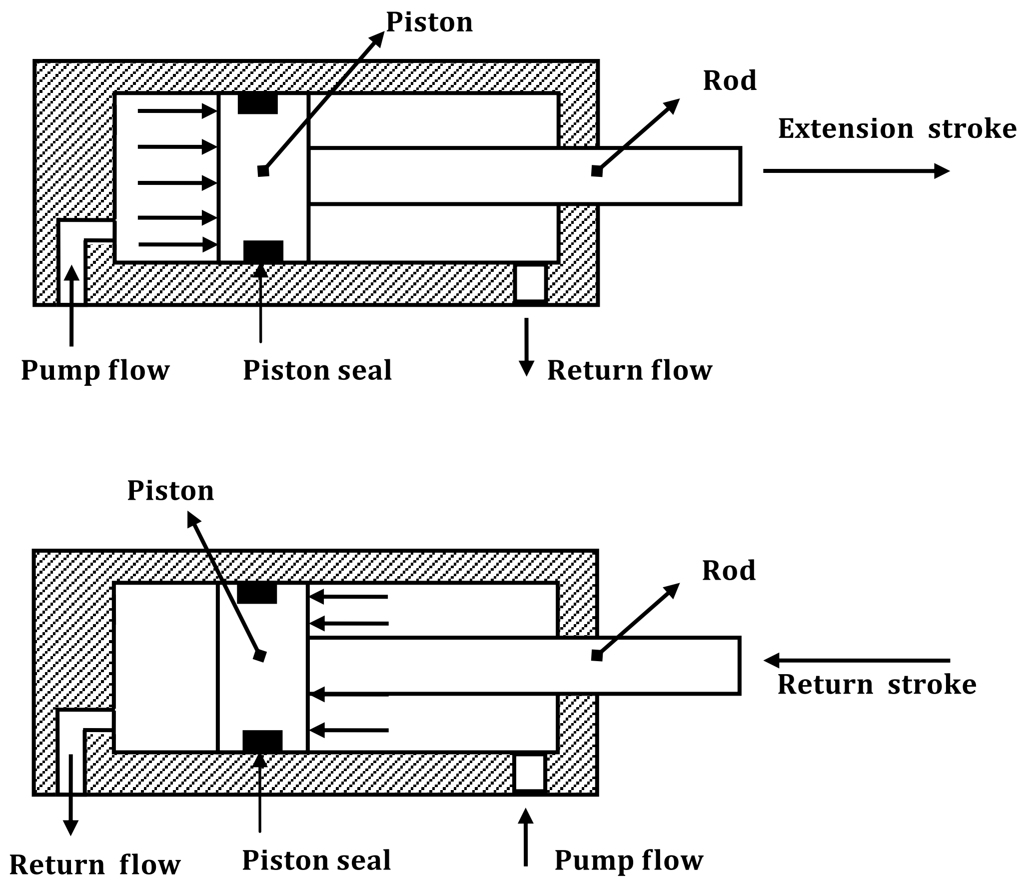


Figure 1.4 Double-acting cylinder with a piston rod on one side

1.2.2.2 **Double-Acting Cylinder with a Piston Rod on Both Sides**

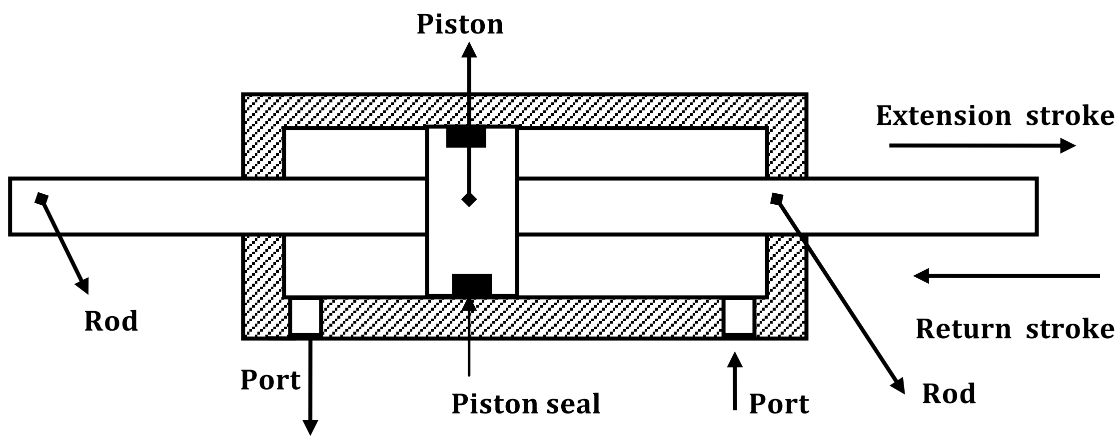


Figure 1.5 Double-acting cylinder with a piston rod on one side

A double-acting cylinder with a piston rod on both sides (Fig.1.5)is a cylinder with a rod extending from both ends. This cylinder can be used in an application where work can be done by both ends of the cylinder, thereby making the cylinder more productive. Double-rod cylinders can withstand higher side loads because they have an extra bearing, one on each rod, to withstand the loading.

1.2.3Telescopic Cylinder

A telescopic cylinder (shown in Fig. 1.6) is used when a long stroke length and a short retracted length are required. The telescopic cylinder extends in stages, each stage consisting of a sleeve that fits inside the previous stage. One application for this type of cylinder is raising a dump truck bed. Telescopic cylinders are available in both single-acting and double-acting models. They are more expensive than standard cylinders due to their more complex construction.

They generally consist of a nest of tubes and operate on the displacement principle. The tubes are supported by bearing rings, the innermost (rear) set of which have grooves or channels to allow fluid flow. The front bearing assembly on each section includes seals and wiper rings. Stop rings limit the movement of each section, thus preventing separation. When the cylinder extends, all the sections move together until the outer section is prevented from further extension by its stop ring. The remaining sections continue out-stroking until the second outermost section reaches the limit of its stroke;this process continues until all sections are extended, the innermost one being the last of all.

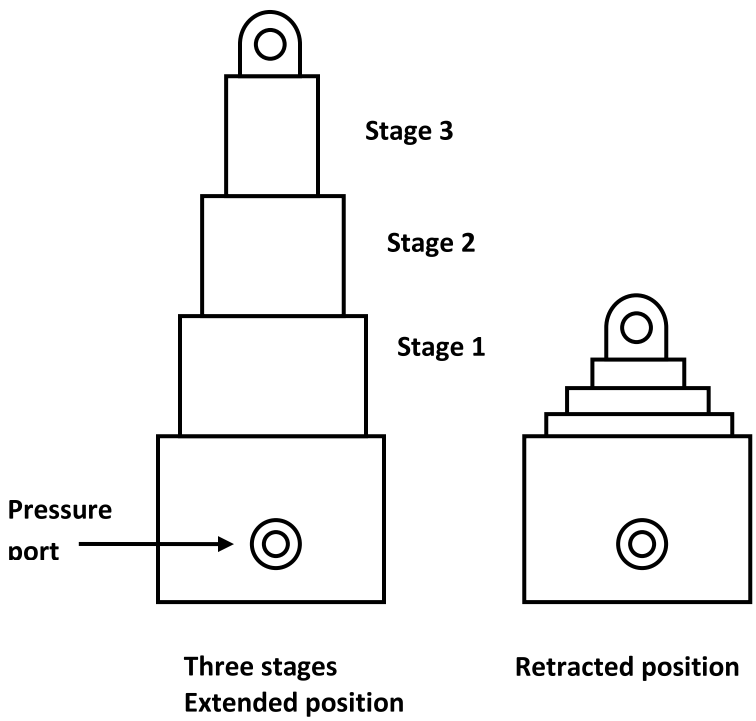


Figure 1.6 Telescopic cylinder

For a given input flow rate, the speed of operation increases in steps as each successive section reaches the end of its stroke. Similarly, for a specific pressure, the load-lifting capacity decreases for each successive section.

1.2.4 Tandem Cylinder

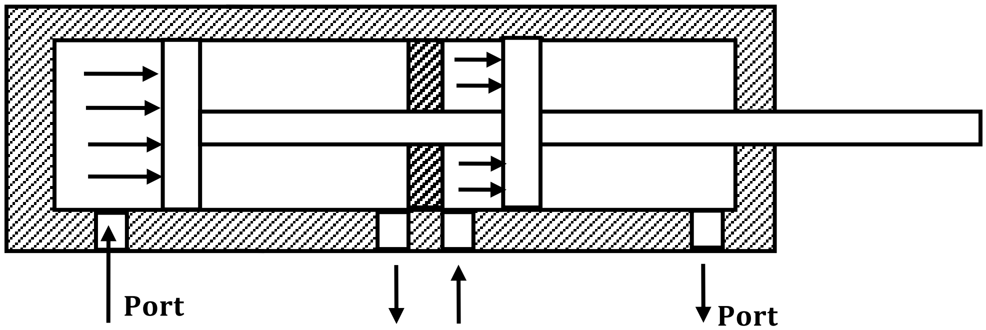


Figure 1.7 Tandem cylinder

A tandem cylinder, shown in Fig. 1.7, is used in applications where a large amount of force is required from a small-diameter cylinder. Pressure is applied to both pistons, resulting in increased force because of the larger area. The drawback is that these cylinders must be longer than a standard cylinder to achieve an equal speed because flow must go to both pistons.

1.2.4.1 Through-Rod Cylinders

These are similar in construction to the standard double-acting cylinders, but have a cylinder rod extending through both cylinder end caps. Although it is possible to have both the piston rods with different diameters at each end of the cylinder, generally the rods have the same diameters. The main applications of through-rod cylinders are as follows: the same speed is required in both the directions, both ends of the rod can be utilized to do work and the non-working end is used to indicate or signal the position of the load. In some applications, the rod is fixed at both the ends and the cylinder body carrying the load moves on the rod.

A major problem in the manufacture of through-rod cylinders is achieving the correct alignment and concentricity of cylinder bore, piston, end caps and rods. Any misalignment can result in excessive seal wear and premature cylinder failure.

1.2.4.2 Displacement Cylinders

A displacement-type hydraulic cylinder shown in Fig. 1.8 consists of a rod that is displaced from inside a tube by pumping hydraulic fluid into the tube. The volume of the rod leaving the tube is equal to the volume of fluid entering the tube, hence the name “displacement cylinder.”

The rod of the displacement cylinder is guided by bearings in the nose or neck of the cylinder body. A collar on the end of the rod prevents it from being ejected and limits the stroke of the cylinder. Elastomer seals in the neck prevent any leakage of fluid along the outside of the rod. This design is a single-acting “push” or extension cylinder, which has to be retracted by gravity, a spring or some external force. The bore of the cylinder body does not require machining other than that for the neck bearing and the inlet port; the manufacturing cost is, therefore, low when compared with other types or hydraulic cylinders.

The maximum thrust exerted by a displacement cylinder is given by

$$\text{Maximum thrust} = \text{Pressure} \times \text{Rod area} = p \times \frac{\pi d^2}{4}$$

where d is the diameter of the rod. The extending speed of the rod is given by

$$\text{Rod speed} = \frac{\text{Flow rate of fluid entering the cylinder}}{\text{Area of cylinder rod}}$$

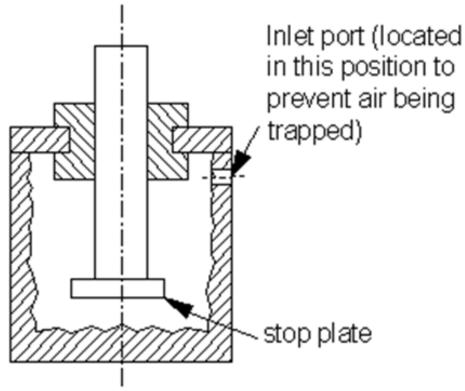


Figure 1.8 Displacement cylinders

Example 1.1

A displacement-type cylinder has a rod of 65 mm diameter and is powered by a hand pump with a displacement of 5 mL per double stroke. The maximum operating pressure of the system is to be limited to 350 bar. (a) Draw a suitable circuit diagram showing the cylinder, pump and any additional valving required. (b) Calculate the number of double pumping strokes needed to extend the cylinder rod by 50 mm. (c) Calculate the maximum load that could be raised using this system.

Solution:

(a) The circuit diagram is given in Fig. 1.9.

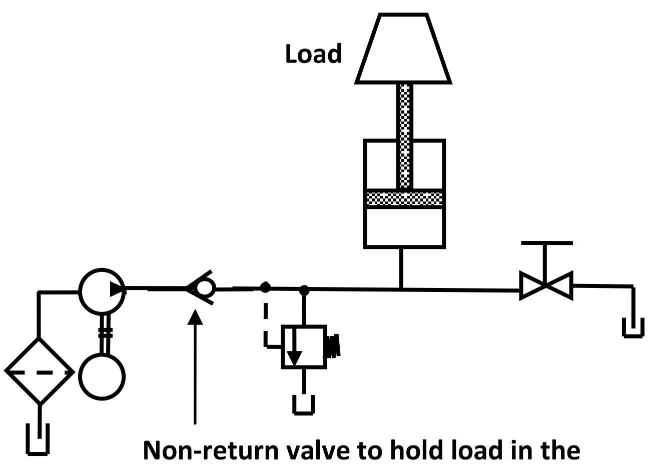


Figure 1.9

(b) The volume of rod displaced is equal to the volume of fluid entering the cylinder. Let the rod diameter be *d*, the distance rod extends be *L*, the displacement per double stroke of pump be *V* and the number of double pump strokes be *S*. Then

Rod volume displaced = Fluid volume entering

$$\Rightarrow \frac{d^2}{4} \times L = V \times S$$

Substituting values given in the problem and showing units for each value we get

$$\frac{65^2}{4}\ \text{mm}^2 \times 50\ \text{mm} = 5\ \text{mL} \times S$$

$$\Rightarrow \frac{65^2}{4} \times 50\ \text{mm}^3 = 5S\ \text{mL}$$

The units on both sides of the equation must be the same.

Note:

1 mL = 1×10^{-3} L

1 L = 1×10^{-3} m^3

1 mL = 1×10^{-6} m^3

1 mm^3 = 1×10^{-9} m^3

Thus, for the dimensional equality

$$\frac{65^2}{4} \times 50 \times 10^{-9}(\text{m}^3) = 5\times 10^{-6}(\text{m}^3) \times S$$

or

$$\frac{65^2}{4} \times 50\ (\text{m}^3) = 5\times 10^3\ (\text{m}^3) \times S$$

Therefore,

$$S = \frac{65^2 \times 50}{4 \times 5 \times 10^3} = 33.17 \text{ double strokes}$$

(c) We have

Maximum thrust = Pressure × Rod area

Substituting the values given into the problem and showing units we get

$$\text{Maximum thrust} = 350 \times 10^5 \times \frac{65^2}{4} \times 10^{-6}\left(\frac{\text{N}}{\text{m}^2}\times \text{m}^2\right)$$

$$= 35 \times \frac{65^2}{4}\ \text{N} = 116080\ \text{N} = 116.080\ \text{kN}$$

Example 1.2

A three-stage displacement-type telescopic cylinder is used to tilt the body of a lorry (Fig. 1.10). When the lorry is fully laden, the cylinder has to exert a force equivalent to 4000 kg at all points in its stroke. The outside diameters of the tubes forming the three stages are 60, 80 and 100 mm. If the pump powering the cylinder delivers 10 LPM, calculate the extend speed and pressure required for each stage of the cylinder when tilting a fully laden lorry.

Solution:

First-stage

First-stage diameter = 100 mm

$$\text{First-stage speed} = \frac{\text{Quantity flowing}}{\text{Area}}$$

$$= \frac{10\times 10^{-3}}{(\pi/4)\times(0.1)^2}\left(\frac{\text{m}^3}{\text{min}\times \text{m}^2}\right) = \frac{4}{\pi} = 1.27\ \text{m/min}$$

First-stage pressure = $\dfrac{\text{Load}}{\text{Area}}$

$$= \frac{4000 \times 9.81}{(\pi/4) \times (0.1)^2}\ \text{N/m}^2 = 5 \times 10^6\ (\text{N/m}^2) = 50\ \text{bar}$$

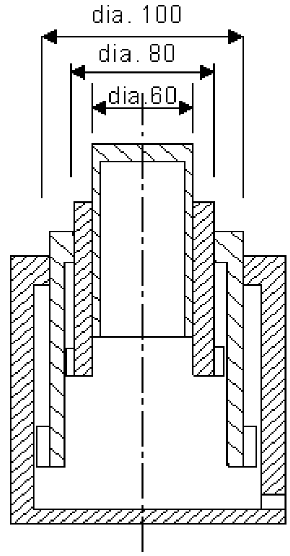


Figure 1.10

Second-stage:

Second-stage diameter = 80 mm

Second-stage speed = $\dfrac{\text{Quantity flowing}}{\text{Area}}$

$$= \frac{10 \times 10^{-3}}{(\pi/4) \times (0.08)^2}\left(\frac{\text{m}^3}{\text{min} \times \text{m}^2}\right) = 1.99\ \text{m/min}$$

Second-stage pressure = $\dfrac{\text{Load}}{\text{Area}}$

$$= \frac{4000 \times 9.81}{(\pi/4) \times (0.08)^2}\ \text{N/m}^2 = 7.81 \times 10^6 (\text{N/m}^2) = 78.1 \text{bar}$$

Third-stage:

Third-stage diameter = 60 mm

Third-stage speed = $\dfrac{\text{Quantity flowing}}{\text{Area}}$

$$= \frac{10 \times 10^{-3}}{(\pi/4) \times (0.06)^2}\left(\frac{\text{m}^3}{\text{min} \times \text{m}^2}\right)$$

$$= 3.54\ \text{m/min}$$

Third-stage pressure = $\dfrac{\text{Load}}{\text{Area}}$

$$= \frac{4000 \times 9.81}{(\pi/4) \times (0.06)^2}\ \text{N/m}^2 = 13.9 \times 10^6 = 139\ \text{bar}$$

Telescopic cylinders are made in a standard range for vehicle applications. Although non-standard cylinders can be obtained, they tend to be very expensive if ordered as a single piece.

1.3Standard Metric Cylinders

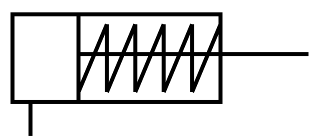
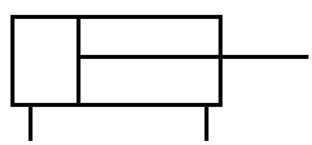
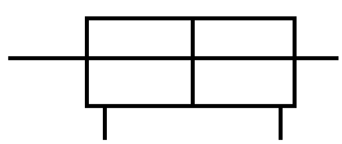
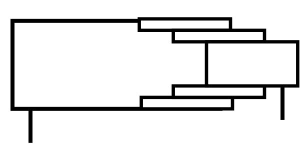
Table 1.1gives preferred sizes for the cylinder bore and rod diameter of metric cylinders. Most cylinder manufacturers have based their standard range of metric cylinders on these recommendations, offering two rod sizes for each cylinder bore.

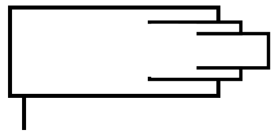
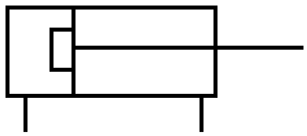
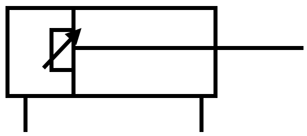
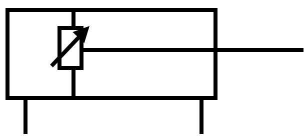
A number of combinations have a piston rod to piston diameter ratio in the region of 0.7, which gives an annulus area of approximately one-half of the full bore area. This area ratio is of use in regenerative circuits to give similar values of speed and thrust on both the extension and retraction strokes. Table 1.2 gives the graphical symbols for various kinds of cylinders.

Table 1.1 Recommended cylinder bore and rod sizes

Piston diameter (mm)		40	50	63	80	100	125	140	160	180	200	220	250	280	320
Piston rod diameter (mm)	Small	20	28	36	45	56	70	90	100	110	125	140	160	180	200
	Large	28	36	45	56	70	90	100	110	125	140	160	180	200	220

Table 1.2 Graphical symbols of different linear actuators

S. No.	Graphical Symbols	Explanation
1.		Single-acting cylinder with unspecified return
2.		Single-acting cylinder with spring return
3.		Double-acting cylinder –single piston rod
4.		Double-acting cylinder –doublepiston rod
5.		Telescopic cylinder–double acting

6.		Telescopic cylinder–single acting
7.		Double-acting cylinder– fixed cushion on one side
1.		Double-acting cylinder–variable cushion on one side
9.		Double-acting cylinder–variable cushion on both sides

1.4Cylinder Force, Velocity and Power

The output force (*F*) and piston velocity (*v*) of double-acting cylinders are not the same for extension and retraction strokes.

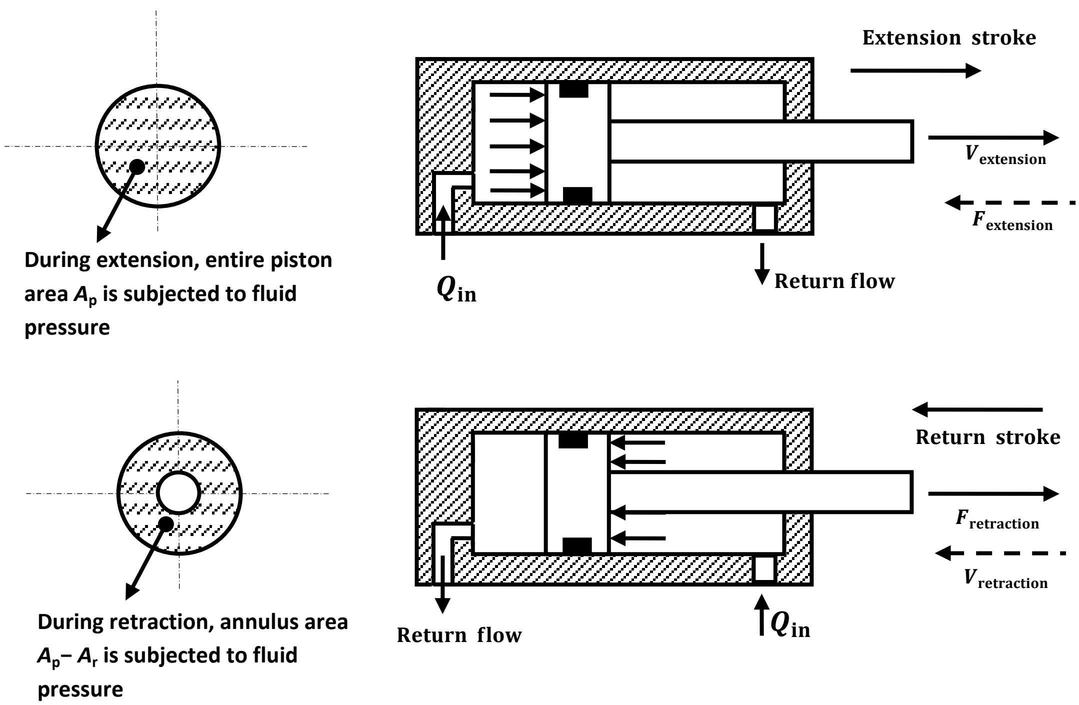


Figure 1.11 Effective area during (a) extension strokes and (b)retraction strokes

During the extension stroke shown in Fig.1.11(a),the fluid pressure acts on the entire circular piston area A_p. During the retraction stroke, the fluid enters the rod-end side and the fluid pressure acts on the smaller annular area between the rod and cylinder bore (A_p−A_r) as shown by the shaded area in Fig.1.11(b) (A_r is the area of the piston rod). Due to the difference in the cross-sectional area, the velocity of the piston changes.Because $A_p$is greater than (A_p−A_r), the retraction velocity (v_{ret}) is greater than the extension velocity (v_{ext}) for the same flow rate.

During the extension stroke, the fluid pressure acts on the entire piston area (A_r), while during the retraction stroke, the fluid pressure acts on the annular area (A_p−A_r). This difference in area accounts for the difference in output forces during extension and retraction strokes. Because A_r is greater than A_p−A_r), the extension force is greater than the retraction force for the same operating pressure.

Force and velocity during extension stroke

Velocity $$v_{\text{ext}} = \frac{Q_{\text{in}}}{A_{\text{p}}}$$

Force

$$F_{\text{ext}} = p \times A_{\text{p}}$$

Force and velocity during retraction stroke

Velocity

$$v_{\text{ext}} = \frac{Q_{\text{in}}}{A_{\text{p}} - A_{\text{r}}}$$

Force,

$$F_{\text{ext}} = p \times (A_{\text{p}} - A_{\text{r}})$$

Power developed by a hydraulic cylinder (both in extension and retraction) is

$$\text{Power} = \text{Force} \times \text{Velocity} = F \times V$$

In metric units, the kW power developed for either extension or retraction stroke is

$$\begin{aligned} \text{Power (kW)} &= v_{\text{p}}\,(\text{m/s}) \times F\ (\text{kN}) \\ &= Q_{\text{in}}\,(\text{m}^3/\text{s}) \times p\ (\text{kPa}) \end{aligned}$$

Power during extension is

$$P_{\text{ext}} = F_{\text{ext}} \times v_{\text{ext}} = p \times A_{\text{p}} \times \frac{Q_{\text{in}}}{A_{\text{p}}} = p \times Q_{\text{in}} \tag{1.1}$$

Power during retraction is

$$\begin{aligned} P_{\text{ret}} &= F_{\text{ret}} \times v_{\text{ret}} \\ &= p \times (A_{\text{p}} - A_{\text{r}}) \times \frac{Q_{\text{in}}}{A_{\text{p}} - A_{\text{r}}} \\ &= p \times Q_{\text{in}} \end{aligned} \tag{1.2}$$

Comparing Equation. (1.1) and (1.2), we can conclude that the powers during extension and retraction strokes are the same.