

Lecture 18

PRESSURE-CONTROL VALVES

Learning Objectives

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

- Explain various functions of pressure-control valves.
- Explain various classifications of pressure-control valves.
- Describe the working construction of various pressure-control valves.
- Differentiate between a pressure relief valve, a pressure-reducing valve, a sequence valve and an unloading valve.
- Identify the graphic symbols for various types of pressure-control valves.
- Explain different applications of pressure-control valves.
- Explain the working principle of solenoid-actuated valves.
- Calculate the pressure loss in pressure relief and unloading valves.
- Evaluate the performance of hydraulic systems using pressure-control valves.

1.1 Introduction

Hydraulic energy is produced as long as the prime mover (usually an electric motor) drives the pump, and hydraulic pressure develops by resistance to pump flow. Hence, the hydraulic system suffers damage if the pump flow is not stopped or off loaded (recirculate) back to the tank during non-action periods of the circuit. Non-action periods arise from stalling an actuator, or by reaching the end of the stroke or the circuit sequence, or during the time-delay periods of the circuit sequence.

In order to avoid hydraulic system damage, power wastage and overheating of the hydraulic fluid, circuit designers use a variety of cleverly designed systems to control maximum system pressure and pump flow during non-action periods.

Pressure-control valves are used in hydraulic systems to control actuator force ($\text{force} = \text{pressure} \times \text{area}$) and to determine and select pressure levels at which certain machine operations must occur. Pressure controls are mainly used to perform the following system functions:

- Limiting maximum system pressure at a safe level.
- Regulating/reducing pressure in certain portions of the circuit.
- Unloading system pressure.
- Assisting sequential operation of actuators in a circuit with pressure control.
- Any other pressure-related function by virtue of pressure control.
- Reducing or stepping down pressure levels from the main circuit to a lower pressure in a sub-circuit.

Pressure-control valves are often difficult to identify mainly because of the many descriptive names given to them. The function of the valve in the circuit usually becomes the basis for its name. The valves used for accomplishing the above-mentioned system functions are therefore given the following names:

- Pressure-relief valve.
- Pressure-reducing valve.
- Unloading valve
- Counterbalance valve.

- Pressure-sequence valve.
- Brake valve.

1.2 Pressure-Relief Valves

Pressure-relief valves limit the maximum pressure in a hydraulic circuit by providing an alternate path for fluid flow when the pressure reaches a preset level. All fixed-volume pump circuits require a relief valve to protect the system from excess pressure. Fixed-volume pumps must move fluid when they turn. When a pump unloads through an open-center circuit or actuators are in motion, fluid movement is not a problem. A relief valve is essential when the actuators stall with the directional valve still in shifted position.

A relief valve is similar to a fuse in an electrical system. When circuit amperage stays below the fuse amperage, all is well. When circuit amperage tries to exceed fuse amperage, the fuse blows and disables the circuit. Both devices protect the system from excess pressure/current by keeping it below a preset level. The difference is that when an electrical fuse blows, it must be reset or replaced by maintenance personnel before the machine cycles again. This requirement alerts electrician's about a possible problem before restarting the machine. Without the protection of a fuse, the electrical circuit would finally overheat and start a fire.

Similarly, in a hydraulic circuit, a relief valve opens and bypasses fluid when pressure exceeds its setting. The valve then closes again when pressure falls. This means that a relief valve can bypass fluid anytime, or all the time, without intervention by maintenance. Many fixed-volume pump circuits depend on this bypassing capability during the cycle, and some even bypass fluid during idle time. A well-designed circuit never bypasses fluid unless there is a malfunction, such as a limit switch not closing or an operator over-riding the controls. This eliminates most overheating problems and saves energy. There are two different designs of relief valves in use: direct-acting and pilot-operated. Both types have advantages and work better in certain applications.

1.2.1 Simple Pressure-Relief Valve

The most widely used type of pressure control valve is the pressure-relief valve because it is found in practically every hydraulic system. Schematic diagram of simple relief valve is shown in Fig. 1.1 and three-dimensional view is shown in Fig. 1.2. It is normally a closed valve whose function is to limit the pressure to a specified maximum value by diverting pump flow back to the tank. A poppet is held seated inside the valve by a heavy spring. When the system pressure reaches a high enough value, the poppet is forced off its seat. This permits flow through the outlet to the tank as long as this high pressure level is maintained. Note the external adjusting screw, which varies spring force and, thus, the pressure at which the valve begins to open (cracking pressure)(Fig. 1.3).

It should be noted that the poppet must open sufficiently to allow full pump flow. The pressure that exists at full pump flow can be substantially greater than cracking pressure. The pressure at full pump flow is the pressure level that is specified when referring to the pressure setting of the valve. It is the maximum pressure level permitted by the relief valve.

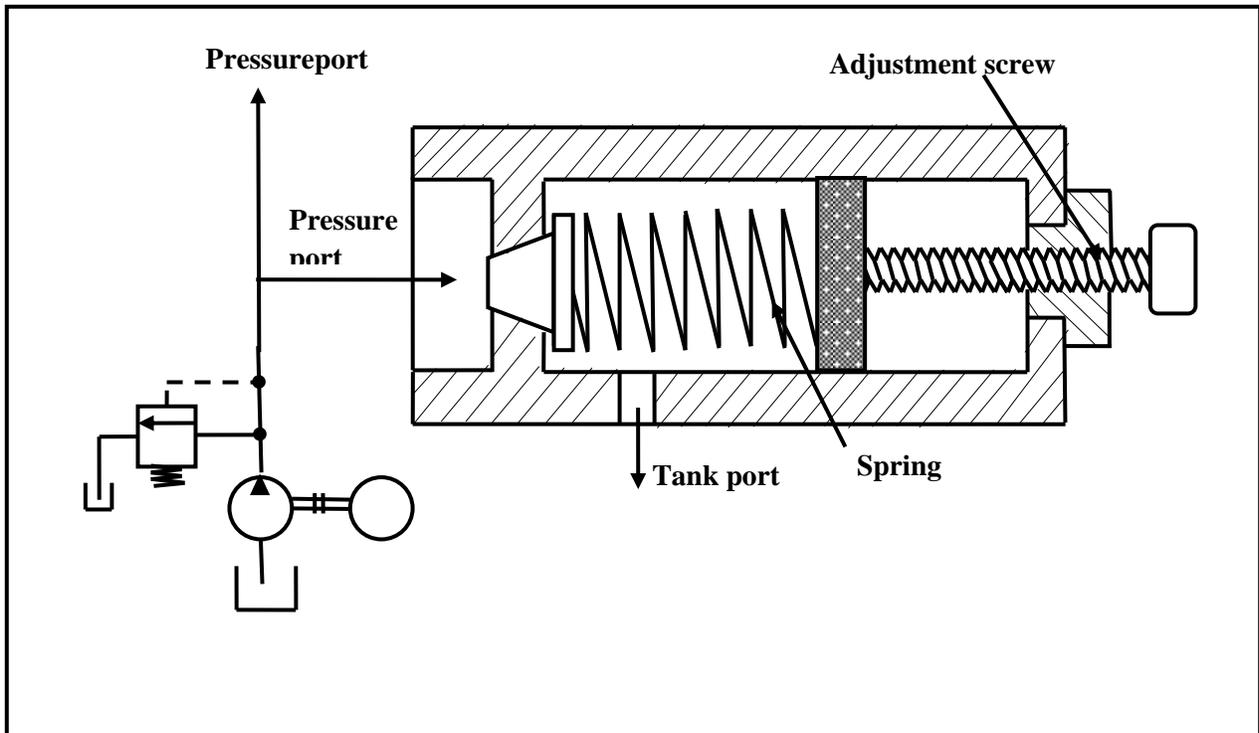


Figure 1.1 Simple pressure-relief valve.

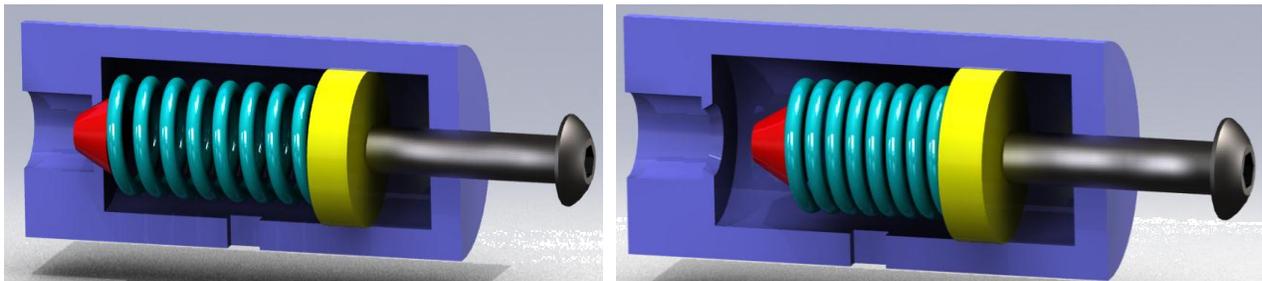


Figure 1.2 Three-dimensional view of simple pressure-relief valve.

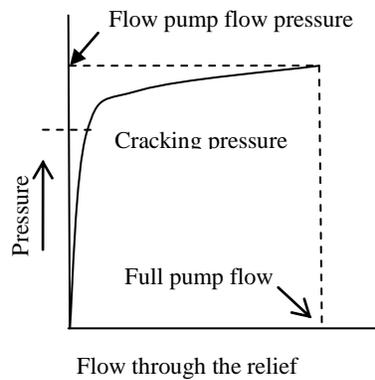


Figure 1.3 Characteristics of a relief valve.

If the hydraulic system does not accept any flow, then all the pump flow must return to the tank via the relief valve. The pressure-relief valve provides protection against any overloads experienced by the actuators in the hydraulic system. Of course, a relief valve is not needed if a pressure-compensated vane pump is used. Obviously one important function of a pressure-relief valve is to limit the force or torque produced by hydraulic cylinders or motors.

The main advantage of direct-acting relief valves over pilot-operated relief valves is that they respond very rapidly to pressure buildup. Because there is only one moving part in a direct-acting relief valve, it can open rapidly, thus minimizing pressure spikes.

1.2.2 Compound Pressure Relief Valve(Pilot-Operated Pressure Relief Valve)

A pilot-operated pressure-relief valve consists of a small pilot relief valve and main relief valve as shown in Fig. 1.4. It operates in a two-stage process:

1. The pilot relief valve opens when a preset maximum pressure is reached.
2. When the pilot relief valve opens, it makes the main relief valve open.

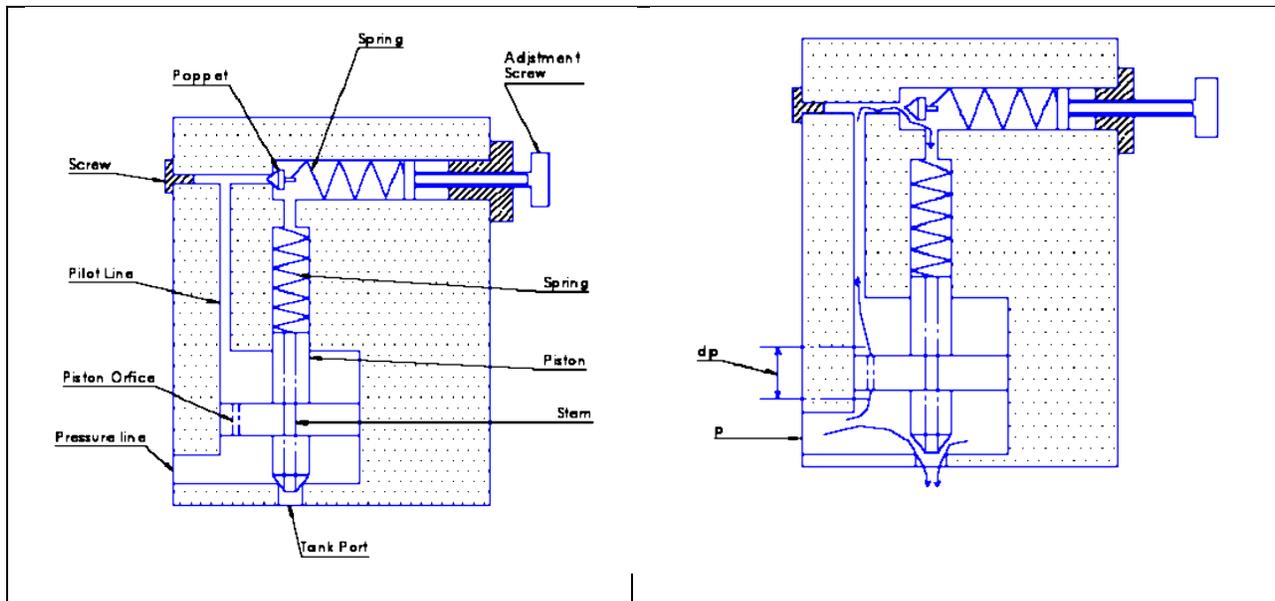


Figure 1.4Compound relief valve.

The pilot-operated pressure-relief valve has a pressure port that is connected to the pump line and the tank port is connected to the tank. The pilot relief valve is a poppet type. The main relief valve consists of a piston and a stem. The main relief piston has an orifice drilled through it. The piston has equal areas exposed to pressure on top and bottom and is in a balanced condition due to equal force acting on both the sides. It remains stationary in the closed position. The piston has a light bias spring to ensure that it stays closed. When the pressure is less than that of relief valve setting, the pump flow goes to the system. If the pressure in the system becomes high enough, it moves the pilot poppet off its seat. A small amount of flow begins to go through the pilot line back to the tank. Once flow begins through the piston orifice and pilot line, a pressure drop is induced across the piston due to the restriction of the piston orifice. This pressure drop then causes the piston and stem to lift off their seats and the flow goes directly from the pressure port to the tank.

The advantages of pilot-operated pressure-relief valves over direct-acting pressure-relief valves are as follows:

1. Pilot-operated pressure-relief valves are usually smaller than direct-acting pressure-relief valves for the same flow and pressure settings.
2. They have a wider range for the maximum pressure settings than direct-acting pressure-relief valves.
3. They can be operated using a remote while direct-acting pressure-relief valves cannot.

Graphic symbol of a pressure-relief valve is shown in Fig. 1.5. The symbol shows that the valve is normally closed (the arrow is offline). On one side of the valve, pressure is fed in (the dashed line) to try to open the valve, while on the other side, the spring tries to keep it adjustable, allowing the adjustment of pressure level at which the relief valve opens. The arrow through the spring signifies that it is adjustable, allowing the adjustment of pressure level at which the relief valve opens.

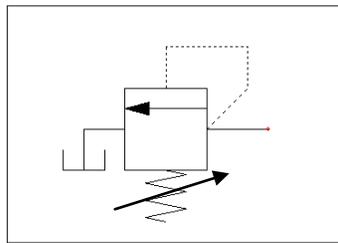


Figure 1.5 Symbolic representation of a simple pressure-relief valve.

Example 1.1

A pressure-relief valve has a pressure setting of 140 bar. Compute the kW loss across this valve if it returns all the flow back to the tank from a $0.0016 \text{ m}^3/\text{s}$ pump.

Solution: We have

$$\begin{aligned}
 \text{kW power} &= pQ \\
 &= (140 \times 10^5) \times (0.0016 \times 10^{-3}) \\
 &= 22.4 \text{ kW}
 \end{aligned}$$

Example 1.2

A pressure-relief valve contains a poppet with an area of 4.2 cm^2 on which the system pressure acts. During assembly, a spring with a spring constant of 3300 N/cm is installed in the valve to hold the poppet against its seat. The adjustment mechanism is then set so that the spring is initially compressed to 0.5 cm from its free-length condition. In order to pass full pump flow through the valve at the pressure-relief valve pressure setting, the poppet must move 0.30 cm from its fully closed position.

- (a) Determine the cracking pressure.
- (b) Determine the full pump flow pressure (pressure-relief valve pressure setting).
- (c) What should be the initial compression of the spring in pressure-relief valve if the full pump flow is to be 40% greater than the cracking pressure?

Solution:**(a) Cracking pressure:**

Force required to fully close is the product of initial displacement and spring constant

$$F_{\text{valve closed}} = K S_{\text{initial}} = 3200 \text{ N/cm} \times 0.50 \text{ cm} = 1600 \text{ N}$$

Now we can calculate the cracking pressure knowing the cracking force

$$\begin{aligned} p_{\text{cracking}} A_{\text{poppet}} &= 1600 \text{ N} \\ \Rightarrow p_{\text{cracking}} (4.20 \times 10^{-4} \text{ m}^2) &= 1600 \text{ N} \\ \Rightarrow p_{\text{cracking}} &= 381 \times 10^4 \text{ N/m}^2 = 3.81 \text{ MPa} \end{aligned}$$

(b) Full pump flow pressure (pressure-relief valve pressure setting):

Force required to fully open is the product of final displacement and spring constant

$$F_{\text{fully open}} = K S_{\text{fully open}} = 3200 \text{ N/cm} \times 0.8 \text{ cm} = 2560 \text{ N}$$

Now this force must be equal to product of full pump pressure and area of poppet.

$$\begin{aligned} p_{\text{full pump flow}} A_{\text{poppet}} &= 2560 \text{ N} \\ \Rightarrow p_{\text{full pump flow}} (4.20 \times 10^{-4} \text{ m}^2) &= 2560 \text{ N} \\ \Rightarrow p_{\text{full pump flow}} &= 610 \times 10^4 \text{ N/m}^2 = 6.10 \text{ MPa} \end{aligned}$$

(c) Initial compression of spring:

$$F_{\text{valve closed}} = K l = 3200 l = p_{\text{cracking}} A_{\text{poppet}}$$

Now cracking pressure can be calculated as follows

$$p_{\text{cracking}} = \frac{\text{Force}}{\text{Area}} = \frac{3200 l}{4.20 \times 10^{-4}} = 762 \times 10^4 l$$

Also we know that force required to fully open is given by product of full pump flow and area of poppet.

$$\begin{aligned} F_{\text{fully open}} &= K (l + 0.3) \\ &= 3200(l + 0.3) \\ &= 3200l + 960 \\ &= p_{\text{full pump flow}} A_{\text{poppet}} \end{aligned}$$

Now

$$p_{\text{full pump flow}} = \frac{3200l + 960}{4.20 \times 10^{-4}} = (762l + 229)10^4$$

We can now calculate the ratio of pump full flow pressure to cracking pressure as

$$\frac{p_{\text{full pump flow}}}{p_{\text{cracking}}} = \frac{(762l + 229)10^4}{(762l)10^4} = 1.40$$

Solving we get $l = 0.75 \text{ cm}$.

Example 1.3

A pressure-relief valve has a pressure setting of 200 bar. Determine the power loss across the valve if all the pump flow of 120 L/min flows back to the reservoir through this valve.

Solution:

Pump flow $Q = 120 \text{ L/min} = 2 \text{ L/s} = 0.002 \text{ m}^3/\text{s}$

Pressure setting of the valve = 200 bar = $200 \times 10^5 \text{ N/m}^2$

Therefore, the power loss across the pressure-relief valve is

$$\frac{200 \times 10^5 \times 0.002}{1000} = 40 \text{ kW}$$

Example 1.4

A pressure-relief valve contains a poppet with a 3.87 cm^2 area on which the system pressure acts. The poppet must move 0.381 cm from its fully closed position in order to pass pump flow at the pressure-relief valve setting (full pump flow pressure). The pressure required to overcome the external load is 68.95 bar. Assume that the pressure-relief valve setting is 50% higher than the pressure required to overcome the external load. If the valve-cracking pressure is 10% higher than the pressure required to overcome the external load, find the following:

(a) The required spring constant of the compression in the valve.

(b) The required initial compression of the spring from its free length condition as set by the spring adjustment mechanism of the pressure-relief valve.

Solution:

a) At full pump flow pressure, spring force equals hydraulic force on the poppet: Total spring compression (S) = Initial compression (L) + Full poppet stroke

$$\Rightarrow k(L + 0.00381) = 4002.5 \text{ N}$$

$$\Rightarrow kL + 0.00381 k = 4002.5 \text{ N}$$

Also at cracking pressure, spring force equals hydraulic force on the poppet. Thus, we have

Spring force = Cracking force

$$kL = 0.00381 k$$

$$= 1.1 \times 68.95 \times 10^5 \text{ N/m}^2 \times 3.87 \times 10^{-4} \text{ m}^2$$

$$= 2935.8 \text{ N}$$

Substituting values of k in $kL + 0.00381 k = 4002.5 \text{ N}$, we get

$$2935.8 + 0.00381 k = 4002.5 \text{ N}$$

$$\Rightarrow k = 279986.22 \text{ N/m}$$

(b) From part (a), we have

$$k = 279986.22 \text{ N/m}$$

$$kL = 2935.8 \text{ N}$$

This implies

$$279986.22 \times L = 2935.8 \text{ N}$$

$$\Rightarrow L = \frac{2935.8}{279986.22} \text{ m} = 0.0104 \text{ m} = 1.04 \text{ cm} = 10.4 \text{ mm}$$

1.3 Pressure-Reducing Valve

The second type of valve is a pressure-reducing valve. This type of valve (which is normally open) is used to maintain reduced pressures in specified locations of hydraulic systems. It is actuated by downstream pressure and tends to close as this pressure reaches the valve setting. Schematic diagram of pressure reducing valve is shown in Fig. 1.6, symbolic representation is shown in Fig. 1.7 and three-dimensional view is shown in Fig. 1.8.

A pressure-reducing valve uses a spring-loaded spool to control the downstream pressure. If the downstream pressure is below the valve setting, the fluid flows freely from the inlet to the outlet. Note that there is an internal passageway from the outlet which transmits outlet pressure to the spool end opposite the spring. When the outlet (downstream) pressure increases to the valve setting, the spool moves to the right to partially block the outlet port. Just enough flow is passed to the outlet to maintain its preset pressure level. If the valve closes completely, leakage past the spool causes downstream pressure to build up above the valve setting. This is prevented from occurring because a continuous bleed to the tank is permitted via a separate drain line to the tank.

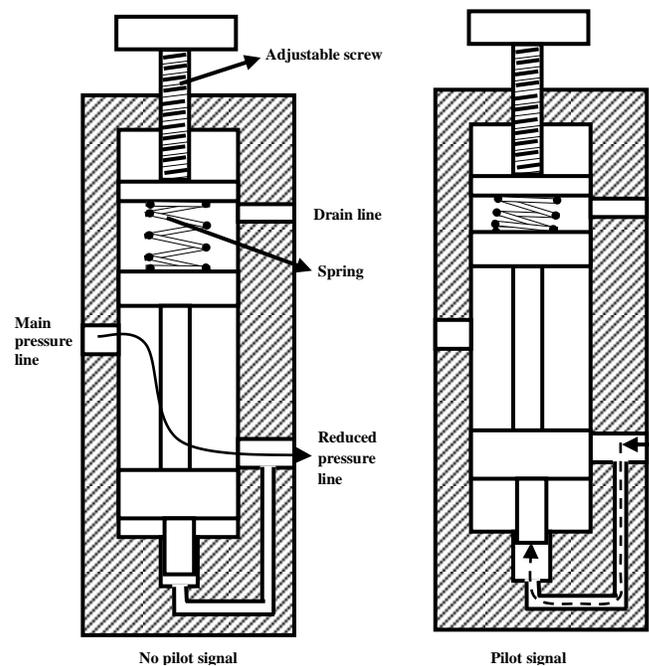


Figure 1.6 Pressure-reducing valve.

Reverse free flow through the valve is only possible if the pressure exceeds the valve setting. The valve then closes, thus making reverse flow impossible. Therefore, pressure-reducing valves are often equipped with a check valve for reverse free flow.

External forces acting onto a linear actuator increase the pressure between the pressure-reducing valve and the actuator. In some systems, it is therefore desirable to relieve excess fluid from the secondary system to the tank in order to maintain a constant downstream pressure, regardless of such external forces.

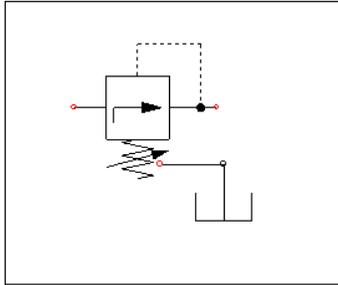


Figure 1.7 Symbolic representation of a pressure-reducing valve.

A reducing valve is normally open. It reads the downstream pressure. It has an external drain. This is represented by a line connected from the valve drain port to the tank. The symbol shows that the spring cavity has a drain to the tank.

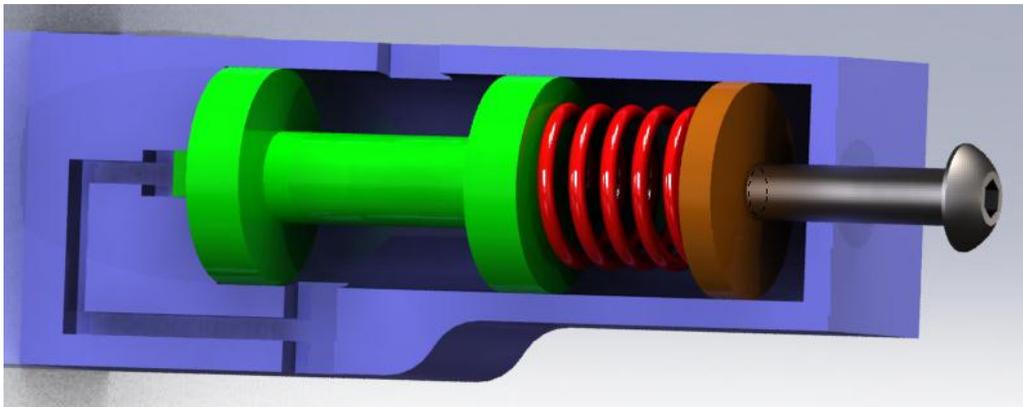


Figure 1.8 Three-dimensional view of a pressure-reducing valve.

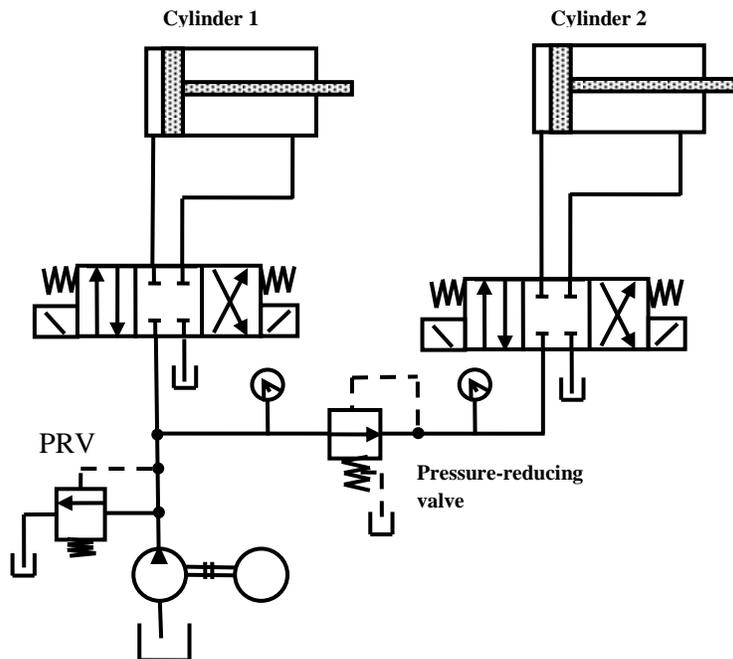


Figure 1.9 Application of a pressure-reducing valve.

Figure 1.9 shows an application for a pressure-reducing valve. Here two cylinders are connected in parallel. The circuit is designed to operate at a maximum pressure p_1 , which is determined by the relief valve setting. This is the maximum pressure at which cylinder 1 operates. By the function of the machine, cylinder 2 is limited to pressure p_2 ($p_2 < p_1$). This can be accomplished by placing a pressure-reducing valve in the circuit in the location shown in Fig. 1.9. If the pressure in the cylinder 2 circuit rises above p_2 , the pressure-reducing valve closes partially to create a pressure drop across the valve. The valve then maintains the pressure drop so that the outlet pressure is not allowed to rise above p_2 setting.

The disadvantage of this method is that the pressure drop across the reducing valve represents the lost energy that is being converted into heat. If the pressure setting of the reducing valve is set very low relative to the pressure in the rest of the system, the pressure drop is very high, resulting in excessive heating of the fluid. When the hydraulic oil becomes too hot, its viscosity reduces causing increased component wear.

Example 1.5

The primary part of a circuit is operating at 180 bar. A secondary circuit supplied from the primary circuit via a pressure-reducing valve requires a constant flow of 30 L/min at 100 bar. Find the power loss over pressure-relief valve. Comment on the type of cooling.

Solution: The power loss over the pressure-reducing valve is

$$\frac{(180 - 100) \times 30}{600} = 4 \text{ kW}$$

4 kW heat cannot be dissipated by natural cooling and heat exchanger may be required. In practice, the cost of fitting a heat exchanger and operating costs should be weighed against alternative circuitry such as a two-pump system.

1.4 Unloading Valves

Unloading valves are pressure-control devices that are used to dump excess fluid to the tank at little or no pressure. A common application is in high-low pump circuits where two pumps move an actuator at a high speed and low pressure. The circuit then shifts to a single pump providing a high pressure to perform work.

Another application is sending excess flow from the cap end of an oversize-rod cylinder to the tank as the cylinder retracts. This makes it possible to use a smaller, less-expensive directional control valve while keeping pressure drop low.

1.4.1 Direct-Acting Unloading Valve

A direct-acting unloading valve consists of a spool held in the closed position by a spring. The spool blocks flow from the inlet to the tank port under normal conditions. When a high-pressure fluid from the pump enters at the external-pilot port, it exerts force against the pilot piston. (The small-diameter pilot piston allows the use of a long, low-force spring.) When the system pressure increases to the spring setting, the fluid bypasses to the tank (as a relief valve would function). When the pressure goes above the spring setting, the spool opens fully to dump the excess fluid to the tank at little or no pressure.

1.4.2 Pilot-Operated Unloading Valve

A pilot-operated unloading valve has less pressure override than its direct-acting counterpart. So it does not dump part of the flow prematurely.

A pilot-operated unloading relief valve is the same as a pilot-operated relief valve with the addition of an unloading spool. Without the unloading spool, this valve would function just like any pilot-operated relief valve. Pressure buildup in the pilot section would open some flow to the tank and unbalance the poppet, allowing it to open and relieve excess pump flow.

Schematic diagram of unloading valve is shown in Fig. 1.10. In a pilot-operated unloading valve; the unloading spool receives a signal through the remote-pilot port when pressure in the working circuit goes above its setting. At the same time, pressure on the spring-loaded ball in the pilot section starts to open it. Pressure drop on the front side of the unloading spool lowers back force and pilot pressure from the high-pressure circuit forces the spring-loaded ball completely off its seat. Now there is more flow going to the tank than what the control orifice can keep up with. The main poppet opens at approximately 20 psi. Now, all high-volume pump flow can go to the tank at little or no pressure drop and all horsepower can go to the low-volume pump to do the work. When pressure falls approximately 15% below the pressure set in the pilot section, the spring-loaded ball closes and pushes the unloading spool back for the next cycle.

An unloading valve requires no electric signals. This eliminates the need for extra persons when troubleshooting. These valves are very reliable and seldom require maintenance, adjustment or replacement. An unloading valve unloads the pump when the desired pressure is reached. It allows rapid discharge of pressurized oil near atmospheric pressure. As soon as the system pressure reaches the setting pressure that is available at the pilot port, it lifts the spool against the spring force. When the spool is held by the pilot pressure, the delivery from the pump goes to the tank. An unloading valve is used to perform operations such as stamping, coining, punching, piercing, etc.

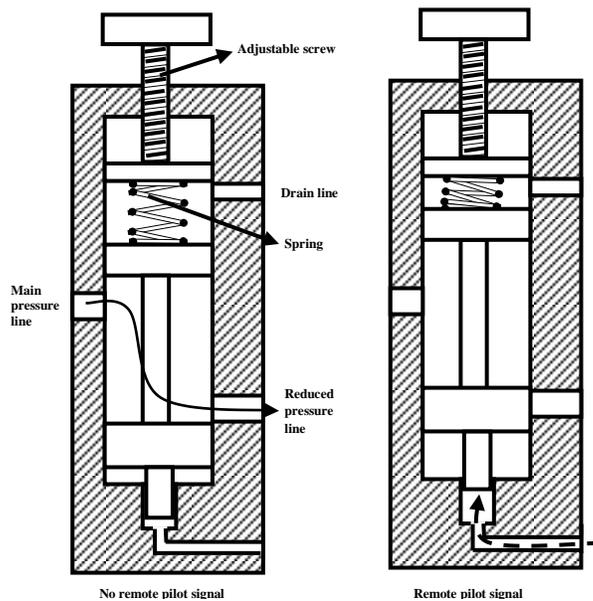


Figure 1.10 Unloading valve.

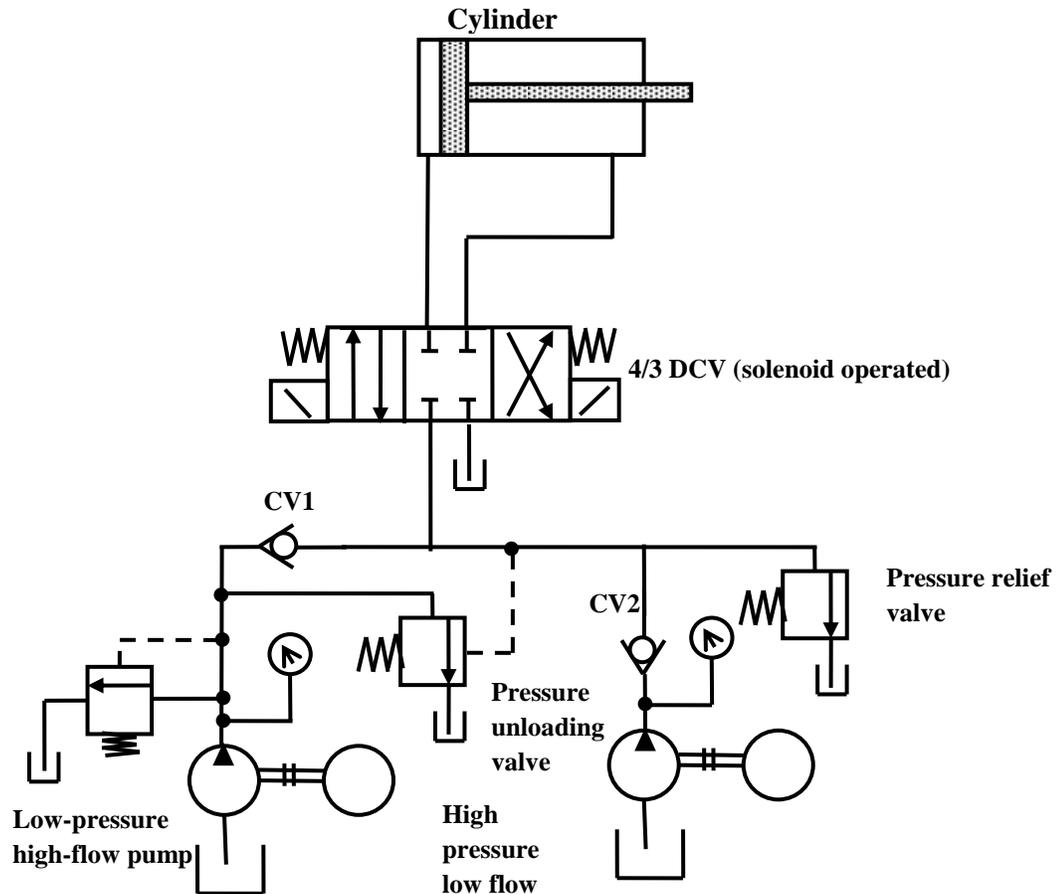


Figure 1.11 Application of unloading valve in a punching press (high–low circuit).

Figure 1.11 shows the application of unloading valve in a punching press. It is a circuit that uses a high-pressure, low-flow pump in conjunction with a low-pressure, high-flow pump. In a punching press, the hydraulic cylinder must extend rapidly over a great distance with low-pressure, high-flow requirements. This rapid extension of cylinder occurs under no external load (when the punching tool approaches the sheet metal). But during punching operation for short motion, the pressure requirements are high due to punching load. During this cylinder travel, high-pressure, low-flow requirements are needed.

When punching operation begins, the increased pressure opens the unloading valve to unload the low-pressure pump. The purpose of relief is to protect the high-pressure pump from over pressure at the end of the cylinder stroke and when direction control valve (DCV) is in its spring centered mode. The check valve protects the low-pressure pump from high pressure, which occurs during punching operation that occurs at the end of cylinder extension and when the DCV is in its spring centered mode.

The above circuit given in Fig. 1.11 eliminates the necessity of having a very expensive high-pressure, high-flow pump.

Example 1.6

Consider a 100 kN press as shown in Fig. 1.22. Weight of the tool = 5 kN. Cylinder bore = 80 mm. Cylinder rod = 60 mm. (a) Find the pressure at annulus side to balance tools. (b) Find the pressure to achieve 100 kN pressing force. (c) If an over-center valve is used instead of a counterbalance valve, what is the pressure to achieve 100 kN pressing force. Comment on the results obtained.

In part (c), use an over-center valve with a 2:1 pilot input ratio set at 23 bar to balance the tools instead of the counterbalance valve.

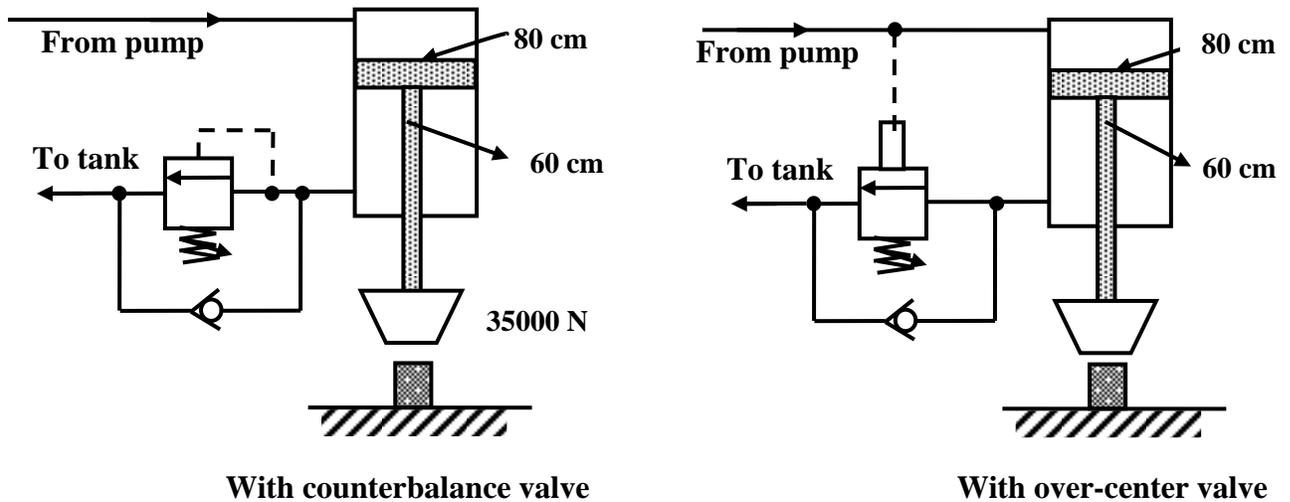


Figure 1.22

Solution:

Full bore area $A_p = 0.082 \times \pi/4 = 0.005 \text{ m}^2$

Annulus area $A_A = (0.0082 - 0.0062) \times \pi/4 = 0.0028 \text{ m}^2$

Case 1: Using counterbalance valve:

Pressure at annulus side to balance tools $= \frac{5 \times 10^3}{0.0028} \times 10^{-5} = 17.8 \text{ bar}$

Suggested counterbalance valve setting $= 17.8 \times 1.3 = 23 \text{ bar}$

Pressure at the full bore side of cylinder to overcome counterbalance $= 23 \times 0.0028/0.005 = 13 \text{ bar}$

Pressure to achieve 100 kN pressing force $= \frac{100 \times 10^3 \times 10^{-5}}{0.005} + 13 = 213 \text{ bar}$

Case 2: Using over-center valve (brake valve): Let us use an over-center valve with a 2:1 pilot input ratio set at 23 bar to balance the tools instead of the counterbalance valve.

Pressure on the pilot required to open the valve $= 23/2 = 11.5 \text{ bar}$

Pressure at the full bore side to drive down the tooling $= 11.5 \text{ bar}$

Pressure required to achieve 100 kN pressing force is

$$\frac{(100 - 5) \times 10^3 \times 10^{-5}}{0.005} = 190 \text{ bar}$$

This is greater than 11.5 bar pressure needed to pilot the over-center valve open. Therefore, there will be no back-pressure set up on the annulus side of the piston during the pressing operation.

Example 1.7

(a) An unloading valve is used to unload the $0.0016 \text{ m}^3/\text{s}$ pump. If the pump discharge pressure during unloading equals 2 bar, how much hydraulic kW power is being wasted?

(b) In the counterbalance circuit shown in Fig. 1.13, load to be lifted is 10 kN and a cylinder bore area of 0.002 m^2 (equivalent to 50 mm diameter) is used. Find the counterbalance valve setting.

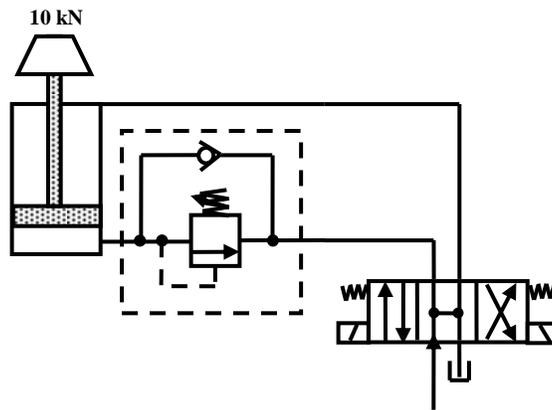


Figure 1.13

Solution:

(a) We have

$$\begin{aligned} \text{kW power} &= pQ \\ &= (2 \times 10^5) \times (0.0016 \times 10^{-3}) \\ &= 0.32 \text{ kW} \end{aligned}$$

(b) We have

$$\text{Load-induced pressure} = \frac{10 \times 10^3}{0.002 \times 10^5} = 50 \text{ bar}$$

The counterbalance valve setting should be $50 \times 1.3 = 65 \text{ bar}$

