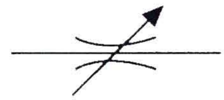
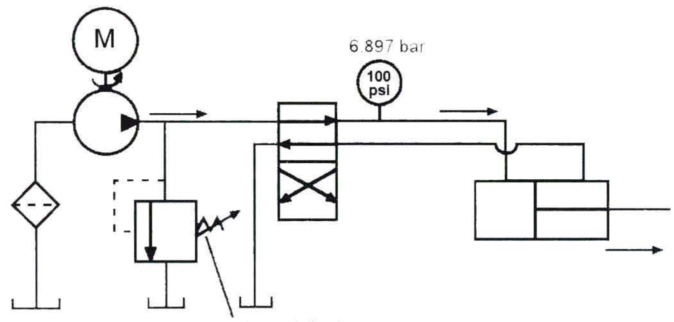
CHAPTER 9

Flow Control Valves

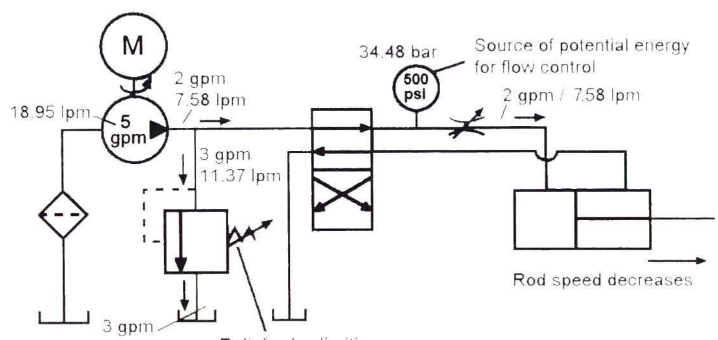
The function of a flow control valve is to reduce a pump's flow rate in its leg of a circuit. It performs its function by being a higher than normal restriction for the system. To overcome the restriction, a positive displacement pump applies a greater pressure to the liquid which causes some of the flow to take another path. This path is usually over a relief valve, but may be to another leg of a system.


Adjustable Flow Control Valve Symbol



In the circuit illustrated, a 5 gpm (18.95 lpm) pump applies to the liquid whatever pressure is necessary to get its flow out into the system. If there is no load at the cylinder, this pressure energy will be changed into heat because of a liquid's viscosity, friction and changing direction.

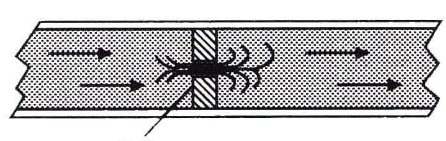
If a flow control valve which restricted pump flow were placed in the circuit, the pump would still attempt to push its total volume through the valve. When the pressure ahead of the valve reached relief valve setting, some flow would be diverted over the relief valve. The rate of flow through the flow control valve at that time will be something less than 5 gpm (18.95 lpm), yet the pressure ahead of the flow control will be up to the relief valve setting. (In the example circuits used in this section, we will assume that the pressure differential through a directional valve and any associated piping is zero.) As far as the flow control valve is concerned, this increased pressure is a source of potential energy which it changes into kinetic energy (rate of flow). The degree to which this happens is dependent on the flow control's orifice.



orifice

An orifice is a relatively small opening in a fluid's flow path. Flow through an orifice is affected by several factors, three of these factors are:

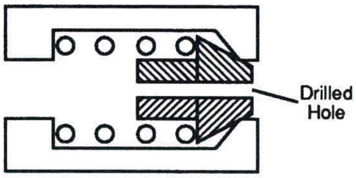
1. size of the orifice
2. pressure differential across the orifice
3. temperature of the fluid




Orifice Symbol

orifice size affects flow

The size of an orifice controls the flow rate through the orifice. A common, everyday example of this is a garden hose which has sprung a leak. If the hole in the hose is small, the leak will be in the form of a drip or spray. But, if the hole is relatively large, the leak will be an stream. In either case, the hole in the hose is an orifice which meters a flow of water to the surrounding outside area. The amount of flow which is metered depends on the size of the opening.



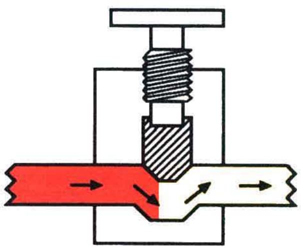
Check Valve

fixed orifice

A fixed orifice is a reduced opening of an unadjustable size. Common examples of fixed orifices used in hydraulics are a pipe plug or check valve with a hole drilled through its center, or a commercial, factory pre-set flow control valve.

variable orifice

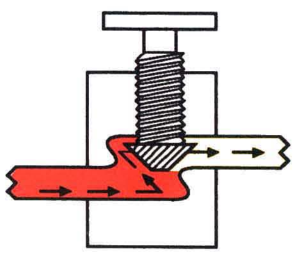
Many times, a variable orifice is more desirable than a fixed orifice because of its degree of flexibility. Gate valves, globe valves and needle valves are examples of variable orifices.


Gate Valve

gate valve

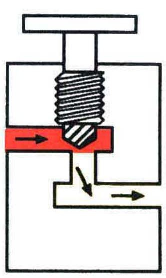
A gate valve has a flow path straight through its center. The size of the orifice is changed by turning the handle which positions a gate or wedge across the fluid path.

Although gate valves are not designed to restrict flow, they are found in some systems where coarse metering is required.


Globe Valve

globe valve

A globe valve does not have a straight-through flow path. Instead, the fluid must bend 90° and pass through an opening which is the seat of a plug or globe. The size of the opening is changed by positioning the globe.


Needle Valve

needle valve

The fluid going through a needle valve must turn 90° and pass through an opening which is the seat for a rod with a cone-shaped tip. The size of the opening is changed by the positioning of the cone in relation to its seat. The orifice size can be changed very gradually because of fine threads on the valve stem and the shape of the cone.

A needle valve is the most frequently used variable orifice in an industrial hydraulic system.

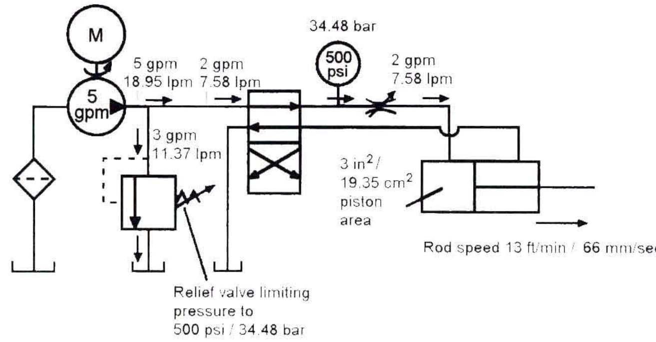
needle valves in a circuit

The circuit illustrated consists of a 5 gpm (18.95 lpm) positive displacement pump, relief valve, directional valve, a adjustable orifice and a cylinder which has a piston area of 3 in² (19.35 cm²).

With the relief valve set a 500 psi (34.48 bar), the pump attempts to push its 5 gpm (18.95 lpm) flow through the orifice. Because of the size of the orifice opening, only 2 gpm (7.58 lpm) passes through the orifice before the pressure reaches the relief valve setting of 500 psi (34.48 bar). (This, of course, happens instantly.) 2 gpm passes through the orifice and out to the actuator. 3 gpm (11.37 lpm) goes over the relief valve. The piston rod moves at the rate of 13 ft/min. (3.96 m/min).

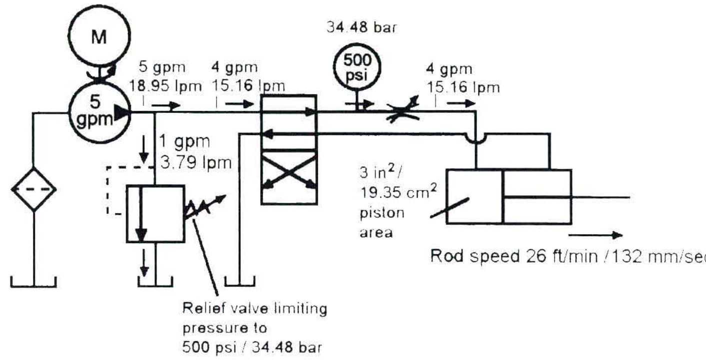
$$\underset{(ft/min)}{\text{rod speed}} = \frac{\text{gpm} \times 231\ (\text{in}^3/\text{gal})}{\text{piston area}\ (\text{in}^2)\ \ (12\ \text{in/ft})}$$

$$\underset{(m/min)}{\text{rod speed}} = \frac{\text{lpm} \times 10}{\text{piston area}\ (\text{cm}^2)}$$



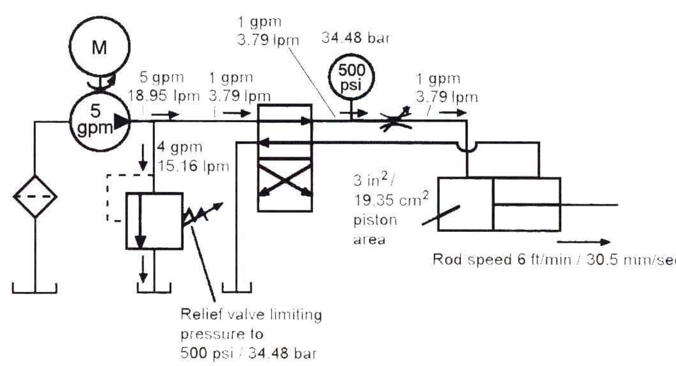
needle valve orifice increased

Turning the knob out and opening the needle valve orifice allows more flow to pass through the valve and out to the cylinder before the relief valve setting is reached. Rod speed increases.



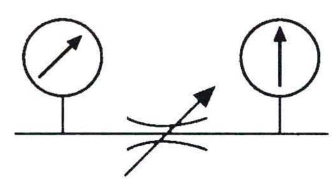
needle valve orifice decreases

Turning the knob in and decreasing the needle valve orifice allows less flow to pass through the needle valve before the 500 psi (34.48 bar) relief setting is reached. Rod speed decreases since the cylinder receives less flow.



pressure differential affects flow

Flow through an orifice is affected by pressure differential. Since pressure in a hydraulic system is potential energy, the greater the difference in pressure across an orifice, the more flow will be developed.



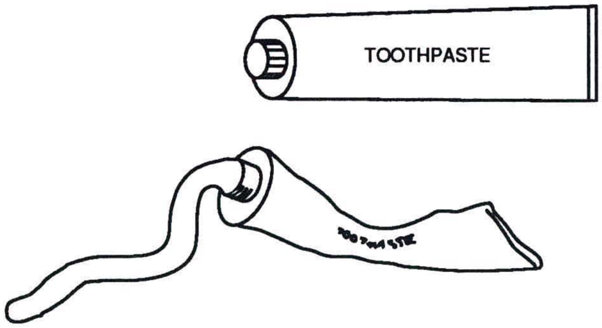
examples from everyday life

After a day at the beach or camping in the woods, a plug is removed from an air mattress so air can escape.

If air is allowed to escape by itself, the mattress takes a while to collapse because the pressure differential is small.

If the mattress were squeezed, air comes rushing out. Squeezing results in the development of a higher pressure inside the mattress. Pressure

differential from within the mattress to the atmosphere has increased. The harder the mattress is squeezed, the more pressure is developed, and the larger the rate of air flow.

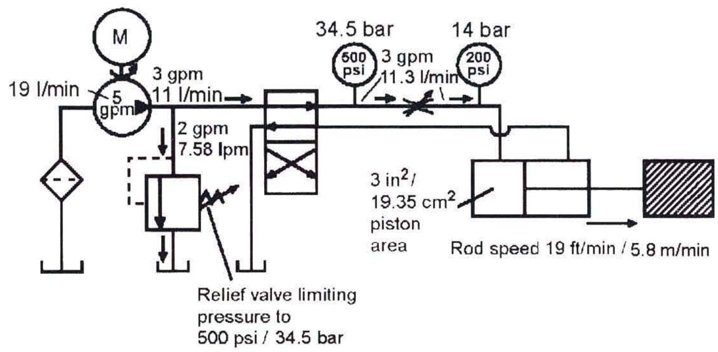


Gently squeezing a full tube of toothpaste results in a small amount of toothpaste on the toothbrush.

If a full tube of toothpaste were squeezed with more force, a large amount of toothpaste would be on the floor. Pressure differential from within the tube to the atmosphere is greater when the tube is stepped on than when it is squeezed.

flow through needle valves in a circuit affected by pressure differential

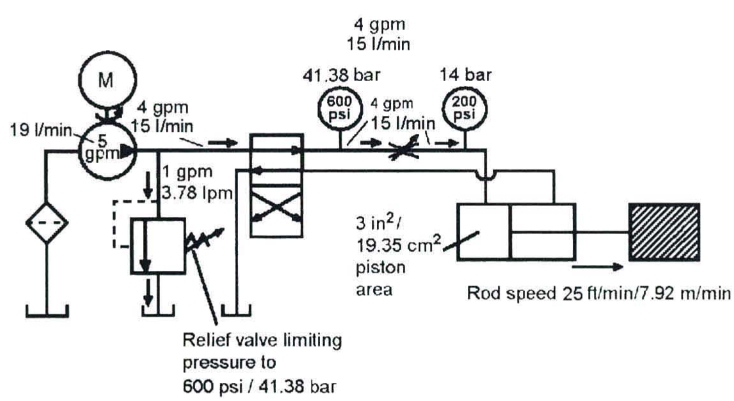
In the circuit illustrated, the needle valve is adjusted to restrict the 5 gpm (19 l/min) pump flow. Relief valve is set at 500 psi (34.5 bar). Pressure ahead of the needle valve is the 500 psi (34.5 bar) relief valve setting. The pressure required to overcome the resistance of the work load is 200 psi (14 bar). 200 psi (14 bar) of the 500 psi (34.5 bar) ahead of the needle valve is used to overcome the resistance of the load. The remaining 300 psi (21 bar) is used to develop a fluid flow through the needle valve. In this particular instance, the 300 psi (21 bar) pressure differential across the needle valve results in a flow of 3 gpm (11.3 lpm) and a rod speed of 19.25 ft/min (5.87 m/min). 2 gpm (7.58 lpm) returns to tank through the relief valve.



relief valve setting increased

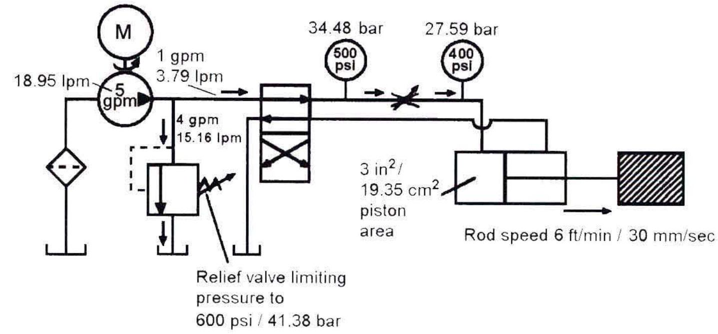
With the work-load pressure and the setting of the needle valve remaining the same, relief valve setting is increased to 600 psi (41.38 bar).

Now 600 psi (41.38 bar) is the pressure ahead of the needle valve. 200 psi (14 bar) of the 600 psi (41.38 bar) is used to overcome the resistance of the load. The resulting 400 psi (28 bar) pressure differential develops a flow of 4 gpm (15 l/min) through the needle valve. 1 gpm (3.79 lpm) passes over the relief valve. Rod speed increases to 26 ft/min (7.92 m/min).



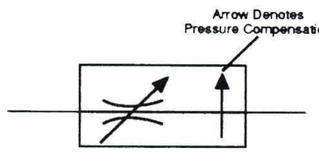
work-load pressure increased

With the relief valve setting again at 500 psi (34.5 bar) and with the same needle valve adjustment, work-load pressure has increased to 400 psi (28 bar) because of a larger load. 500 psi (34.5 bar) is the pressure ahead of the needle valve. 400 psi (28 bar) of the 500 psi (34.5 bar) is used to overcome the resistance of the load. The remaining 100 psi (6.9 bar) develops a 1 gpm (3.79 l/min) flow through the needle valve. 4 gpm (15 l/min) is dumped over the relief valve. Rod speed decreases to 6 ft/min (30 mm/sec).



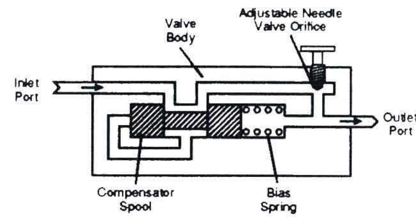
pressure compensated flow control valves

As can be seen from the previous examples, any change in pressure ahead of or after a metering orifice affects the flow through the orifice resulting in a change of actuator speed. These pressure changes must be neutralized, or compensated for, before an orifice can precisely meter fluid.



Pressure Compensated
Flow Control Valve Symbol

Needle valves are designated non-compensated flow control valves. They are good metering devices as long as pressure differential across the valve remains constant and the needle stays centered. If more precise metering is required, a pressure compensated flow control valve is used; that is, a flow control which makes allowances for pressure changes ahead or after the orifice.



Pressure Compensated Flow
Control Valve — Restricted Type

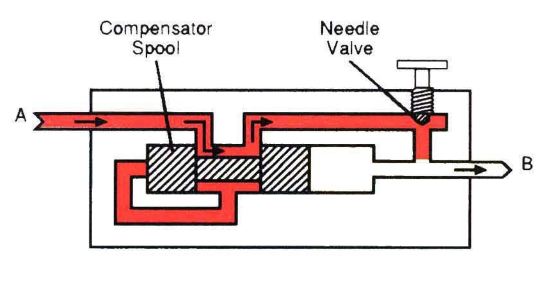
Pressure compensated flow control valves are classified as either restrictor or bypass types.

what a restrictor type pressure compensated flow control valve consists of

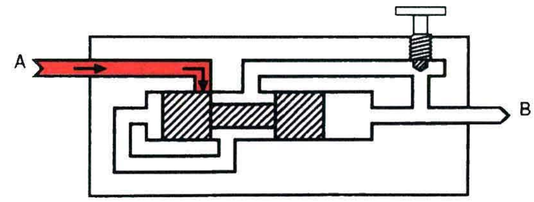
A restrictor type pressure compensated flow control valve consists of a valve body with inlet and outlet ports, a needle valve, a compensator spool and a spring which biases the spool.

how a restrictor type pressure compensated flow control valve works

To determine how a restrictor type valve works, we will examine its operation step by step.



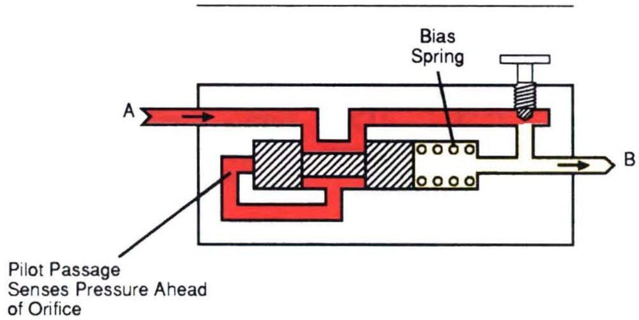
With the compensator spool fully shifted toward side A, any pressurized fluid flow entering the inlet port will arrive at the needle valve.

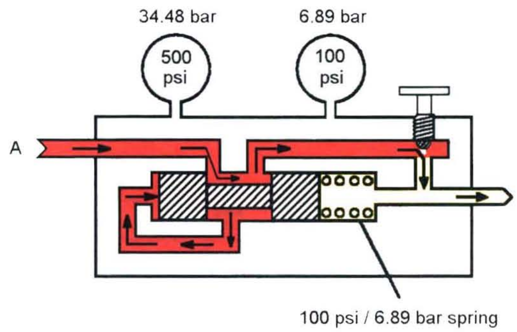


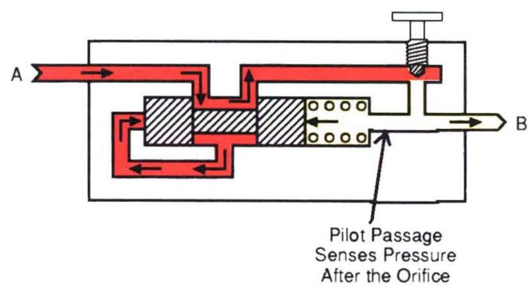
With the spool shifted slightly toward side B, pressurized fluid flow is blocked through the valve.

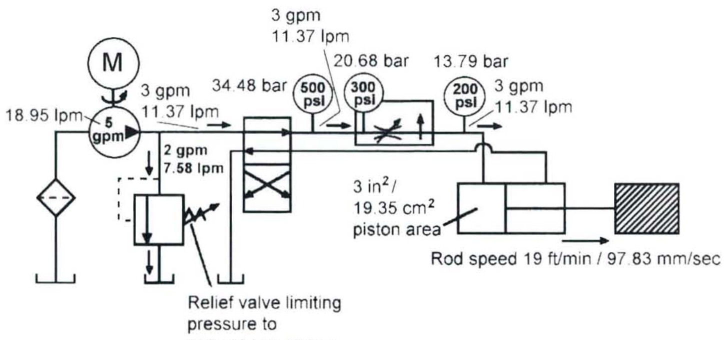
To keep the flow path through the valve open, a spring biases the compensator spool toward side A.

Pressure ahead of the needle valve is sensed at the A side of the spool by means of an internal pilot









passage. When fluid pressure at this point tries to become more than the pressure of the spring, the spool will move toward side B.

With the needle valve orifice adjusted for something less than pump flow, pressure ahead of the needle valve wants to climb to the relief valve setting. When the pressure attempts to rise above the value of the compensator spring, the spool moves and restricts flow to the needle valve. As the fluid passes over this restriction, all of the pressure energy in excess of the value of the spring is turned into heat. For example, if the spring had a value of 100 psi (6.89 bar) and the relief valve were set at 500 psi (34.48 bar), fluid pressure at the valve's inlet will be 500 psi (34.48 bar). But, the compensator spool reduces the pressure before it gets to the needle valve by transforming 400 psi (27.59 bar) into heat energy as the fluid passes through the restriction. This means that regardless of what the pressure is at the flow control inlet, the pressure ahead of the needle valve to develop flow will always be 100 psi (6.89 bar).

As we have seen from previous circuits using needle valves, controlling the pressure ahead of the orifice is only half the battle. A fluctuation in pressure after the orifice must also be compensated for. In other words, a constant pressure differential is required. To accomplish this, a pilot passage which senses pressure downstream from the needle valve is directed to the bias spring chamber. Now two pressures bias the spool toward side A—spring pressure and fluid pressure after the needle valve.

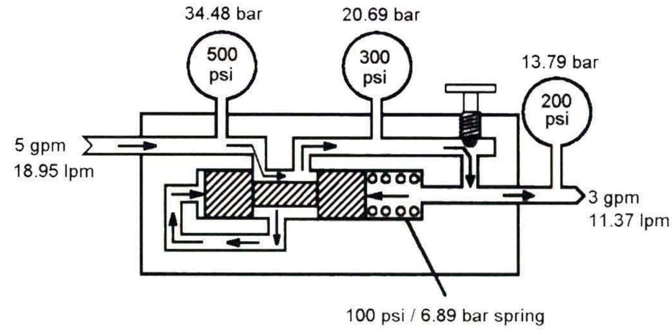
If the spring has a value of 100 psi (6.89 bar), fluid pressure ahead of the orifice would be limited to 100 psi (6.89 bar) above the pressure after the orifice. As long as the relief valve is set high enough, the pressure differential across the needle valve orifice will always be the value of the spring which in this case is 100 psi (6.89 bar). In this way, the same amount of pressure is available to develop a flow through the orifice regardless of pressure fluctuations.

restrictor type pressure compensated flow control valves in a circuit

In the circuit illustrated, the restrictor type pressure compensated flow control valve is set for 3 gpm (11.37 lpm). Relief valve setting is 500 psi (34.48 bar). Work-load pressure is 200 psi (13.79 bar). The spring biasing the compensator spool has a value of 100 psi (6.89 bar).

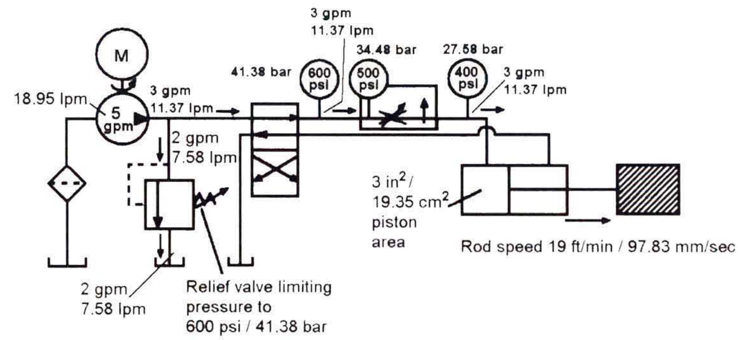
During system operation, the workload pressure of 200 psi (13.79 bar), plus the 100 psi (6.89 bar) spring, bias the compensator spool.

The pump attempts to push its total flow of 5 gpm (18.95 lpm) through the needle valve orifice. When pressure ahead of the needle valve reaches 300 psi (20.69 bar), the compensator spool moves and causes a restriction for the incoming fluid. The pressure at the flow control inlet rises to the relief valve setting of 500 psi (34.48 bar). As the fluid passes over the restriction made by the compensator spool, 200 psi (13.79 bar) of the 500 psi (34.48 bar) is transformed into heat. The pressure ahead of the needle valve is limited to 300 psi (20.69 bar). Of this 300 psi (20.69 bar), 200 psi (13.79 bar) is used to overcome the resistance of the load; 100 psi (6.89 bar) is used to develop a flow rate through the needle valve orifice. The flow rate in this case is 3 gpm (11.37 lpm). The remaining 2 gpm (7.58 lpm) is dumped over the relief valve. See Appendix B-18.



workload pressure and relief valve setting increased

If the workload pressure were increased to 400 psi (27.58 bar), or if the relief valve setting were re-set to 600 psi (41.38 bar), 100 psi (6.89 bar) would still be available to develop a flow rate through the needle valve. As long as the relief valve setting is 100 psi (6.89 bar) higher than the workload pressure, or in other words high enough to operate the compensator spool, a constant rate of flow of 3 gpm (11.37 lpm) will be delivered to the cylinder.



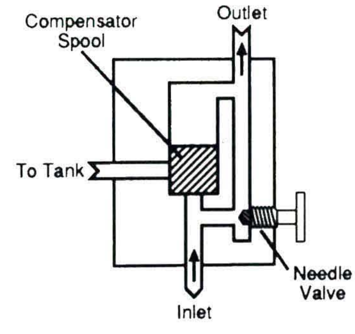
what a bypass type pressure compensated flow control valve consists of

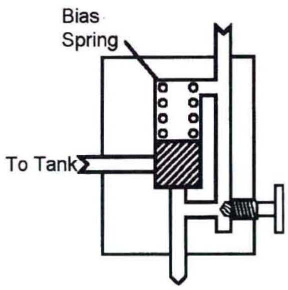
A bypass type pressure compensated flow control valve consists of a valve body with inlet, outlet and tank ports; a needle valve; a compensator spool; and a spring which biases the spool.

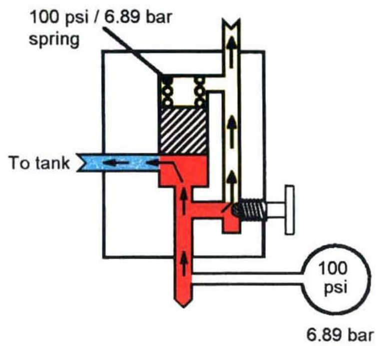
how a bypass type pressure compensated flow control valve works

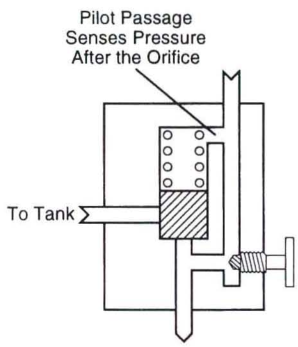
To determine how a bypass type valve works, we will examine its operation step by step.

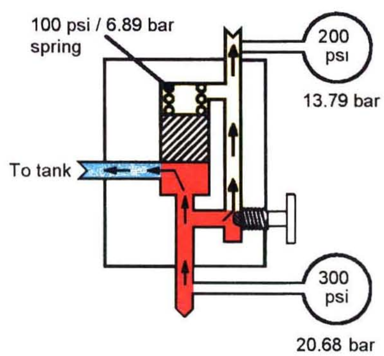
The compensator spool in this valve develops a constant pressure differential across a needle valve orifice by opening and closing a passage to tank.

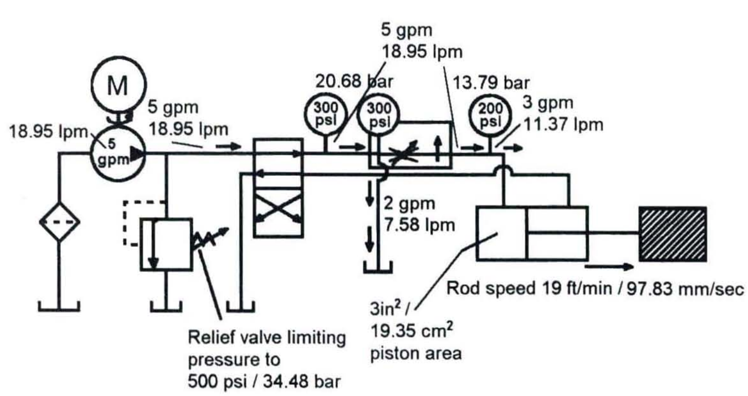












With the compensator spool fully seated in the down position, the passage to tank is blocked. With the compensator spool in the up position, the passage to tank is open.

In this condition, any flow coming into the valve will return to tank. In its normal condition, the compensator spool is biased in the closed position by a spring. If the spring as assembled has a value of 100 psi (6.89 bar), the pressure ahead of the needle valve will be limited to 100 psi (6.89 bar).

During system operation, the pressure ahead of the needle valve attempts to rise to the relief valve setting. When the pressure reaches 100 psi (6.89 bar), the spool uncovers the passage to tank thus limiting the pressure ahead of the needle valve to 100 psi (6.89 bar). A constant pressure ahead of the needle valve orifice does not necessarily guarantee a constant flow rate. If the pressure after the orifice changes, the pressure differential across the orifice changes and consequently so does the flow.

To compensate for this situation, pressure after the needle valve orifice is added to the top of the piston by means of a pilot passage. Two pressures now bias the spool spring pressure and fluid pressure after the needle valve.

If the spring had a value of 100 psi (6.89 bar), fluid pressure ahead of the needle valve orifice would be limited to 100 psi (6.89 bar) above the pressure after the orifice. As long as the relief valve setting is high enough, pressure differential across the needle valve will always be the value of the spring which in this example is 100 psi (6.89 bar). In this way, the same amount of pressure is available to develop a flow through the orifice regardless of changes in pressure.

bypass type pressure compensated flow control valves in a circuit

In the circuit illustrated, the bypass type pressure compensated flow control valve is set for 3 gpm (11.37 l/min). Relief valve setting is 500 psi (34.48 bar). Workload pressure is 200 psi (13.79 bar). The spring biasing the compensator spool has a value of 100 psi (6.89 bar).

During system operation, the workload pressure of 200 psi (13.79 bar), plus the 100 psi (6.89 bar) spring, bias the compensator spool. The pump attempts to push its total flow of 5 gpm (18.95 l/min) through the needle valve orifice. When pressure ahead of the needle valve reaches 300 psi (20.68 bar), the compensator spool uncovers the passage to tank. Pressure ahead of the needle valve is therefore limited to 300 psi (20.68 bar). Of this 300 psi (20.68 bar), 200 psi (13.79 bar) is used to overcome the resistance of the load; 100 psi (6.89 bar) is used to develop a flow rate through the needle valve. The flow rate in this case is 3 gpm (11.37 lpm).

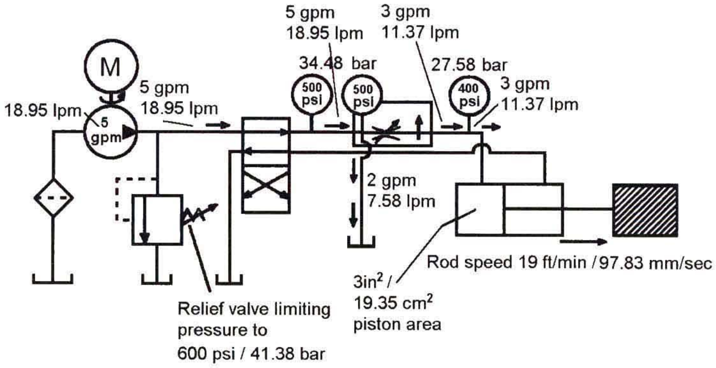
The remaining 2 gpm (7.58 lpm) is bypassed to tank through the passage in the valve.

workload pressure and relief valve setting increased

If the workload pressure were increased to 400 psi (27.59 bar), pressure ahead of the needle valve orifice would then be limited to 500 psi (34.48 bar). 100 psi (6.89 bar) would still be available ahead of the orifice to develop the 3 gpm (11.37 lpm) flow rate.

Note that when a bypass type pressure compensated flow control valve is used in a circuit, excess flow is not diverted over the relief valve. The operating pressure for the flow control is 100 psi (6.89 bar) above the workload pressure.

Since excess flow does not return to tank over the relief valve, a higher setting has no effect on the operation of the flow control. However, if the relief valve were not set at least 100 psi (6.89 bar) above the workload pressure, the compensator spool in the flow control would not operate. Flow through the needle valve would not be pressure compensated.

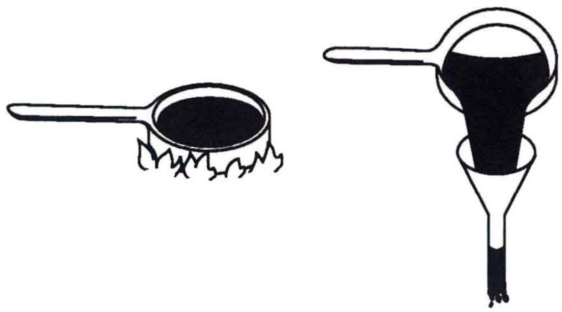


Even though a restrictor type valve generates more heat, it is the more popular type of pressure compensated flow control in an industrial hydraulic system. This popularity is probably the result of its accuracy and its flexibility in controlling flow in any part of a system. (A bypass flow control can only control flow to an actuator.)

temperature affects flow

So far, it has been shown that flow through an orifice is affected by the size of the orifice and the pressure differential across the orifice. Flow through an orifice is also affected by temperature which changes a liquid's viscosity.

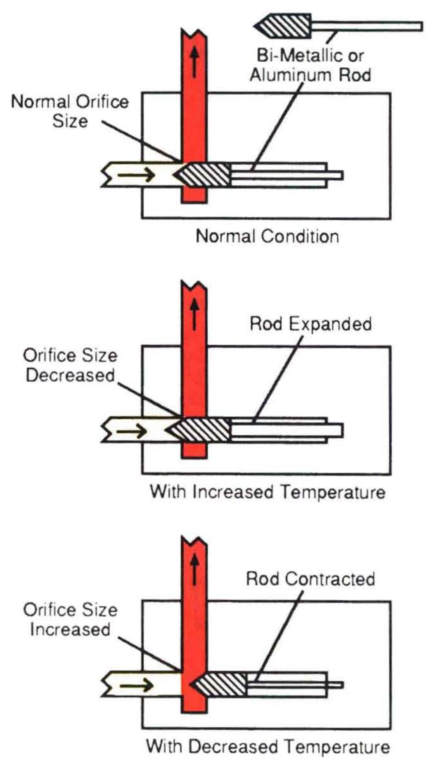
For example, pouring a viscous liquid like cold molasses from a sauce pan, through a funnel is a time-consuming job. Heating the sauce pan results in the molasses flowing readily through the funnel. Rate of flow through the funnel increases because heating reduces a liquid's viscosity.



Just like any mechanical, electrical or pneumatic system, hydraulic systems are not 100% efficient. While in operation this inefficiency shows up in the form of heat which reduces a liquid's viscosity. Like heated molasses, the warmed fluid flows more readily through an orifice. If the pressure differential across a metering orifice and the size of an orifice are kept constant, the flow rate through the orifice and to the actuator will increase with a rise in temperature. If precise actuator speed is necessary, a change in fluid temperature must be compensated for.

temperature compensation with a metal rod

One method of temperature compensation is the use of an aluminum rod. The rod is attached to the movable section of a variable orifice and controls the size of the orifice with a change in temperature.



how temperature compensation with a metal rod works

The flow rate through an orifice tends to become greater as temperature increases. The heat expands the rod which pushes the movable section of the orifice toward its seat, decreasing the opening. The flow rate for the heated fluid through the smaller orifice is the same as the flow rate through the normal orifice before heating. Consequently, flow rate is not affected by an increase in temperature.

If temperature is decreased, flow rate tends to become less. The decreased temperature causes the rod to contract which pulls the movable section away from its seat, increasing the opening.

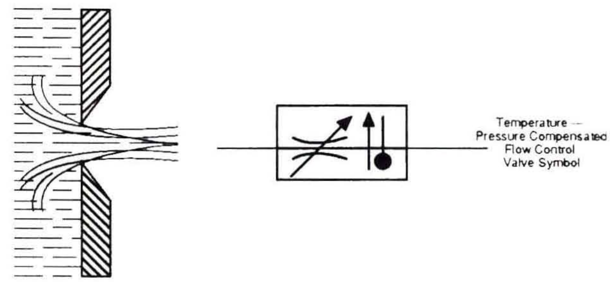
The flow rate for the cooled fluid with the larger orifice is the same as the flow rate through the normal orifice before it was cooled. Therefore, flow is not affected by a decrease in temperature.

temperature compensation with a sharp edge orifice

Laboratory experiments have shown that when liquid passes through a properly shaped orifice with a sharp edge, rate of flow is not affected by temperature. The manner in which liquid is sheared, while moving across a sharp edge, is of such a character that it actually cancels out or neutralizes the effect of a fluid's viscosity. The reason this occurs is not clearly understood, but its effect results in very accurate control.

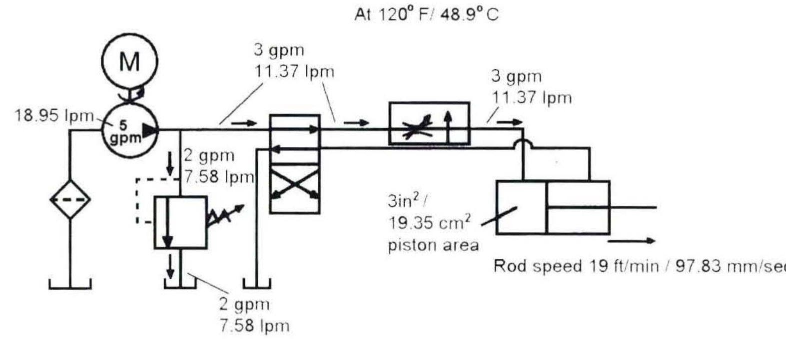
temperature-pressure compensated flow control valve

Temperature compensation using a sharp edge orifice is a non-moving type compensation which disregards the effects of temperature over a given range. It is very difficult to design and manufacture an orifice of this type because the characteristics of the orifice must fall within certain mathematical boundaries and the orifice must be precision machined and held to very close tolerances. Some manufacturers still use the aluminum or bi-metallic rod method of temperature compensation because of this difficulty.



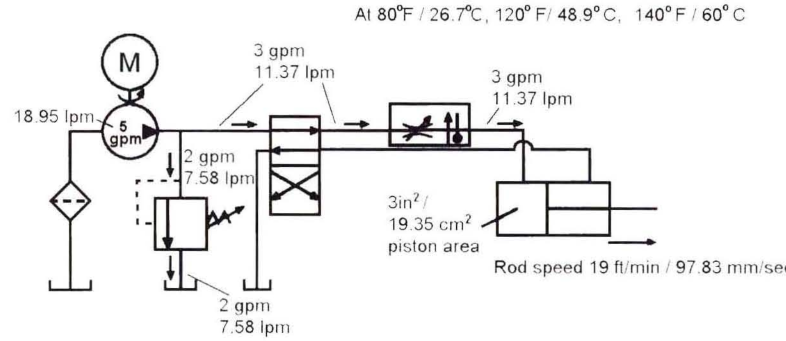
temperature-pressure compensated flow control valve in a circuit

In the circuit illustrated, a pressure compensated flow control valve will control the operating speed of the cylinder effectively as long as the temperature remains at a constant 120°F (48.9°C).



The operating temperature of industrial hydraulic systems may range from 80°F (26.7°C) in the morning to 140°F (60°C) in the afternoon. As a result the operating speed of the actuator changes over the course of the day.

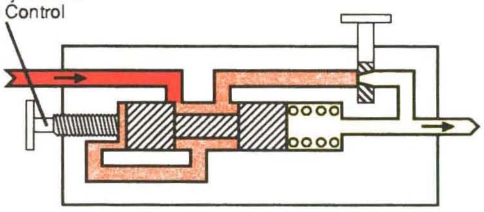
If the speed of an actuator must be precise throughout the workday, a temperature-pressure compensated flow control could be used.



lunge control

The proper operation of a pressure compensated or temperature-pressure compensated flow control valve depends on the compensator spool partially restricting flow to the orifice and transforming excess pressure energy into heat. This was pointed out previously in the description of a restrictor type flow control.

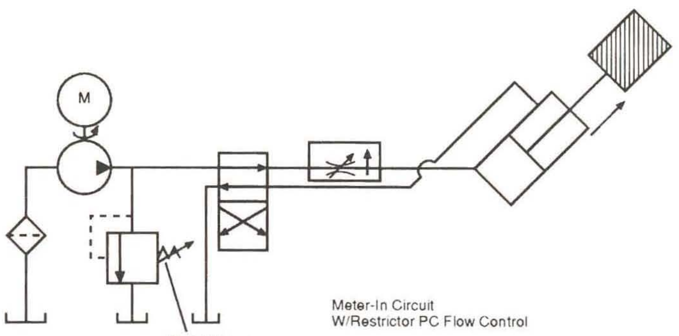
When flow is not being metered through the valve, the compensator spool is fully seated toward side A and the path to the orifice is completely opened. When it comes time for the valve to operate, the orifice is directly subjected to the pump's pressurized flow for an instant before the compensator can react. This causes a burst of fluid to be pushed through the orifice and results in a jump or lunge at the actuator. In some precision applications, this jump or lunge may damage the machine, the tools, or the product being machined. To avoid this situation, a pressure compensated or temperature-pressure compensated flow control valve can be equipped with a lunge control.



A lunge control is a screw adjustment which prepositions the compensator spool at the A side of the valve. While the valve is operating, the screw is turned in until it contacts the compensator spool, and then is backed off slightly. When the valve is not functioning, the spool does not reseat, but remains near its compensating position. Now when flow through the valve resumes, the spool compensates immediately and does not allow the actuator to jump. Lunge controls should be used only in circuits in which the load pressure remains relatively constant.

flow control valves in a circuit

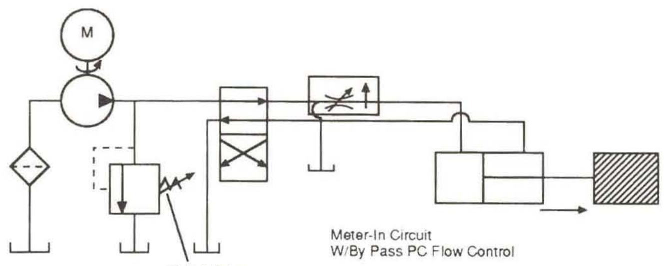
Up to this time, when the operation of a particular flow control was described in a circuit, the flow control was positioned in the circuit directly before the actuator whose speed it was controlling. In this arrangement, all the flow is measured as it enters the actuator. This is termed a meter-in circuit.



Meter-In Circuit
W/Restrictor PC Flow Control

meter-in circuit

A meter-in circuit is used to control the speed of an actuator which works against a positive load. In other words, while the orifice is metering fluid to an actuator, the workload pressure is continuously a positive value. An example of a constant load would be any load which is vertically lifted.

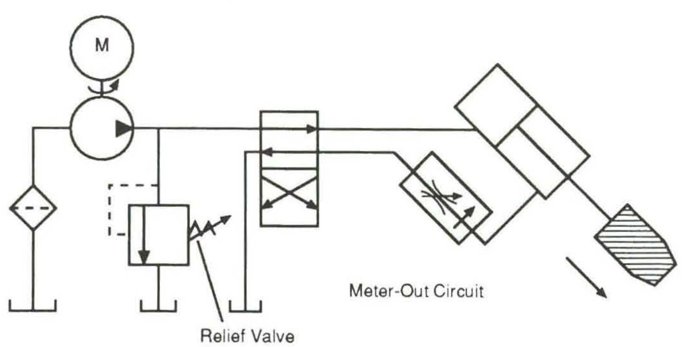


Meter-In Circuit
W/By Pass PC Flow Control

A meter-in circuit is the only type of circuit in which a bypass type PC flow control can be used.

For reasons which will be explained in a later section, a meter-in circuit is not used to accurately control the speed of a hydraulic motor. See Appendix B-18.

meter-out circuit



Meter-Out Circuit

In some cases, the work load changes direction (load passing over the center point of an arc) or the work load pressure suddenly changes from full to zero pressure (drill breaking through stock). This causes the cylinder to run away.

A flow control valve placed at the outlet port of an actuator controls the rate of flow exiting the actuator. This is a meter-out circuit and gives positive speed control to actuators used in drilling, sawing, boring and dumping operations. A meter-out circuit is a very popular industrial hydraulic flow control circuit. See Appendix B-19.

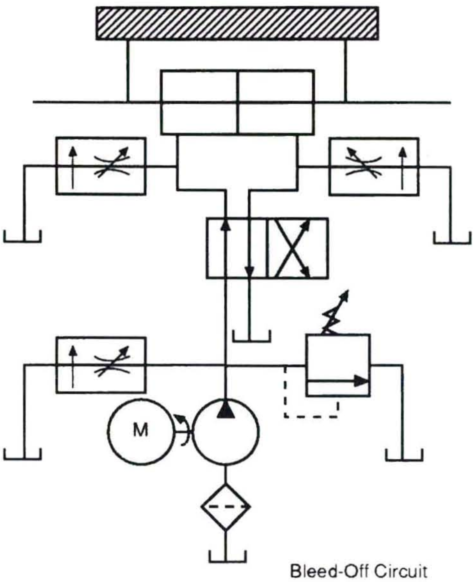
bleed-off circuit

Another type of flow control circuit is the bleed-off circuit. In this circuit, the flow control valve does not cause an additional resistance for the pump. It operates by bleeding-off to tank a portion of the pump's flow at the existing system pressure.

Besides generating less heat, a bleed-off circuit can also be more economical than a meter-in or meter-out circuit. For instance, if a flow rate of 100 gpm (379 lpm) had to be reduced to 90 gpm (341.1 lpm), a 90 gpm (341.1 lpm) flow control valve would be needed in a meter-in circuit and, depending on the size of the cylinder, approximately a 70 gpm (265.3 lpm) flow control in a meter-out circuit. Whereas in a bleed-off circuit, a 10 gpm (37.9 lpm) flow control could be used.

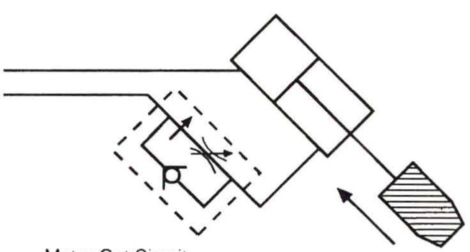
Even with these apparent advantages, a bleed-off circuit is not a very popular flow control circuit. This is because a flow control in a bleed-off arrangement only indirectly controls the speed of an actuator. It can precisely meter flow to the tank, but if leakage through various system components increases, actuator speed will decrease.

A bleed-off circuit can be used in any application where precision flow regulation is not required; and where the load offers a constant resistance as in reciprocating grinding tables, honing operations, and vertically lifting a load. See Appendix B-20.

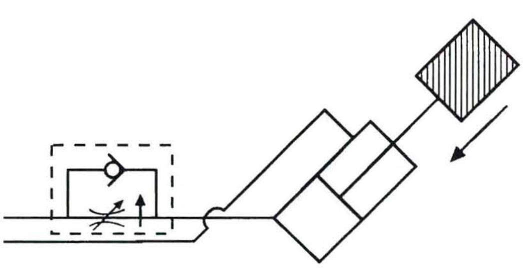


Bleed-Off Circuit

Flow control can be located directly after the pump or in a line to an actuator.



Meter-Out Circuit



Meter-In Circuit

reverse flow through a flow control valve

In the examples seen so far, flow to an actuator was described as being controlled in one direction only. But cylinders and motors usually work in two directions. It is often not required, and even undesirable, to reduce the speed of an actuator in the opposite direction. To bypass a flow control valve when retracting a cylinder or reversing a hydraulic motor, a check valve is used.

terms and idioms associated with flow control valves

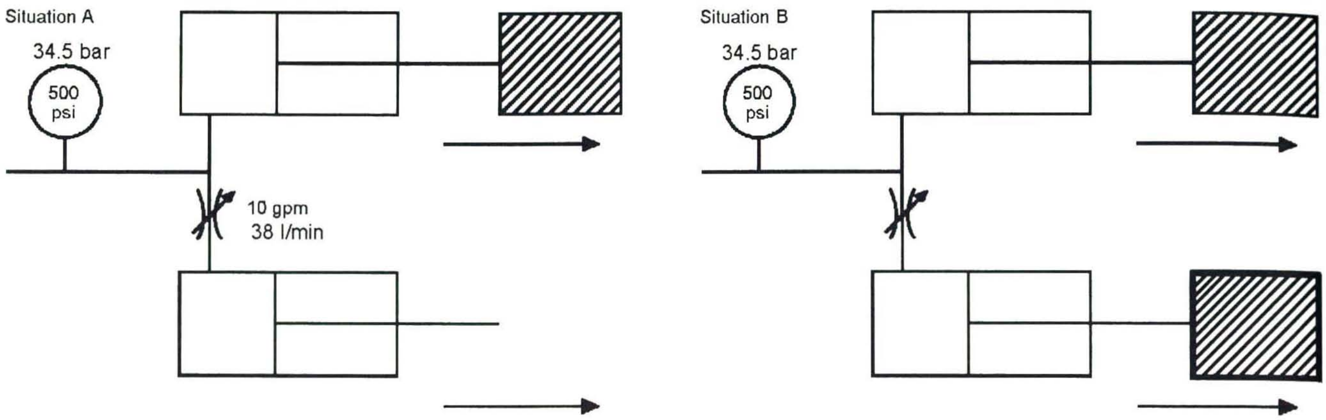
NON-JUMP CONTROL - lunge control.

PRIORITY FLOW DIVIDER - bypass type pressure compensated flow control valve; secondary flow is to an actuator instead of to tank.

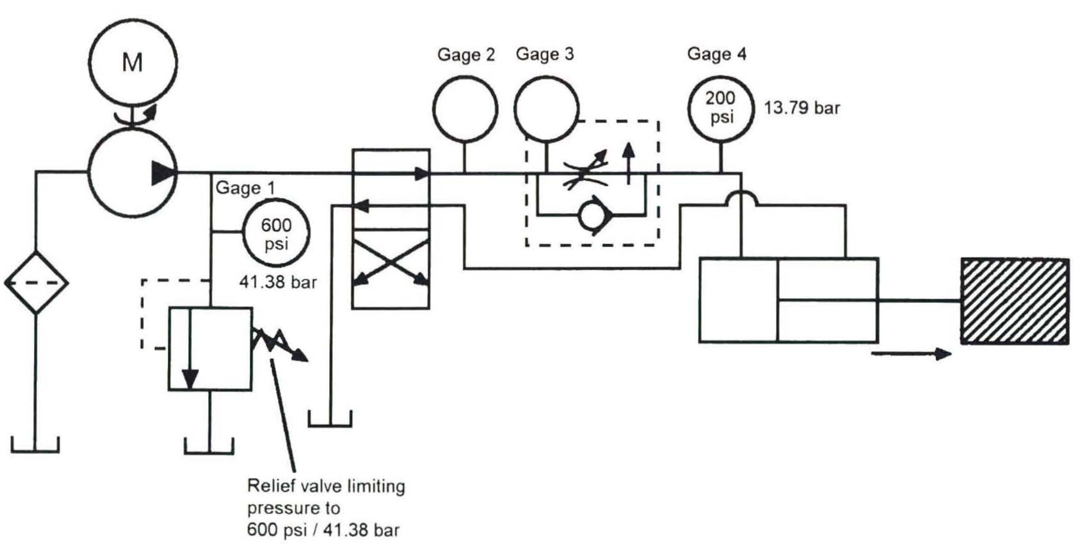
exercise
flow control valves
40 points

Instructions: Answer the following questions or solve the following problems as required.

1. Assuming the cylinders to be the same size and the loads to be equal, how does the flow rate through the needle valve differ from situation A to situation B?
   a. flow remains exactly the same
   b. flow decreases
   c. flow increases



2. Assuming pipe friction to be zero, what do the gages read? (The spring acting on the spool in the pressure compensated flow control has a value of 100 psi/34.5 bar.)



flow control valves (cont.)

3. In situation A, the cylinder rod is pushing out the load. In situation B, there is no load on the cylinder rod.

   The system relief valve is set at 2000 psi (137.9 bar). The flow control valve is metering flow out of the cylinder.

   What do the gages read in each case?