MENG2520 Pneumatics and Hydraulics

Module 4 – Hydraulic System Design

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Hydraulic System Design

The design of Hydraulic Systems includes the study of the function, safety and performance of the circuit. This Module will study several examples of Hydraulic Circuits.

In this Module we will study

- **Hydraulic Circuit Design**
- **Safety of Operation**
- **Performance of Desired Function**
- **Efficiency of Operation**

Further Self-Study in this Module includes

- **Chapter 10: Hydraulic Conductors and Fittings**
- **Chapter 11: Ancillary Hydraulic Devices**

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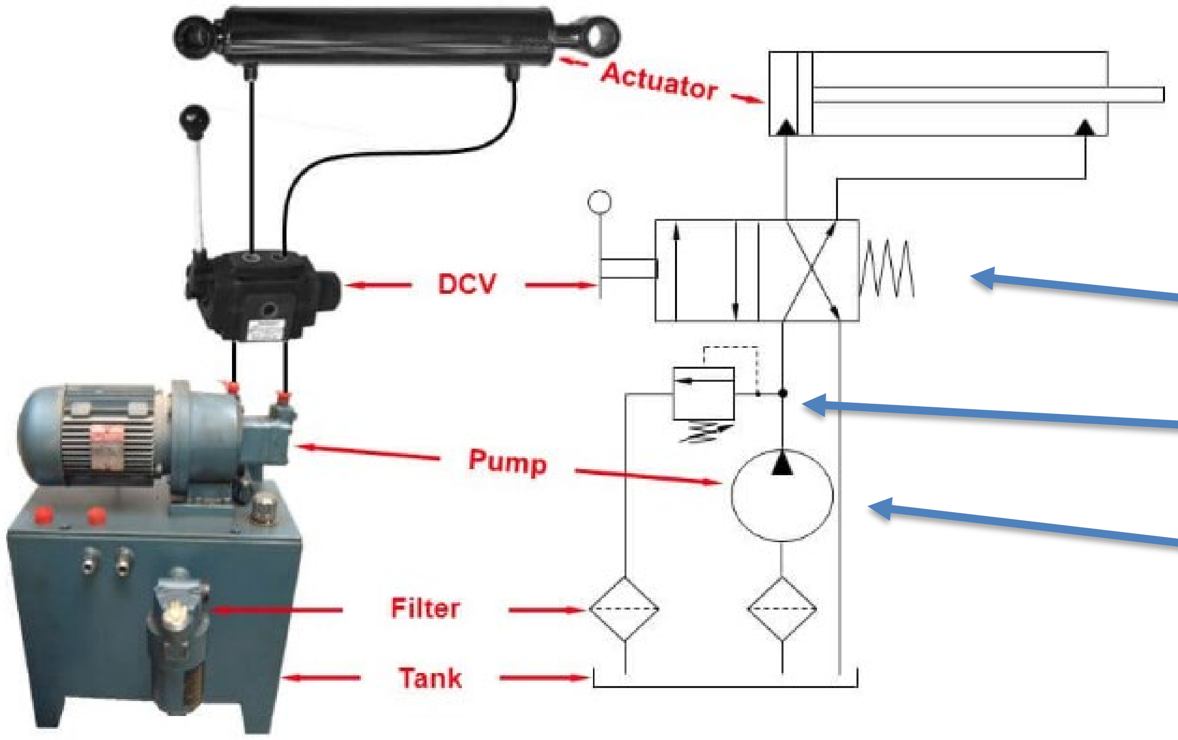
Hydraulic Circuit Design

Hydraulic circuit design involves various considerations achieve a design that meets the **basic functional requirements**, **performs effectively**, **efficiently**, and **safely**.

Simulation tools, like **Automation Studio**, help with hydraulic circuit design providing simulation and mathematical modeling of the system.



How fast?
How much force?

How is operated?

How is it safe?

What are the losses?
How much HP from pump?

https://www.target-hydraulics.com/hydraulic-calculations/

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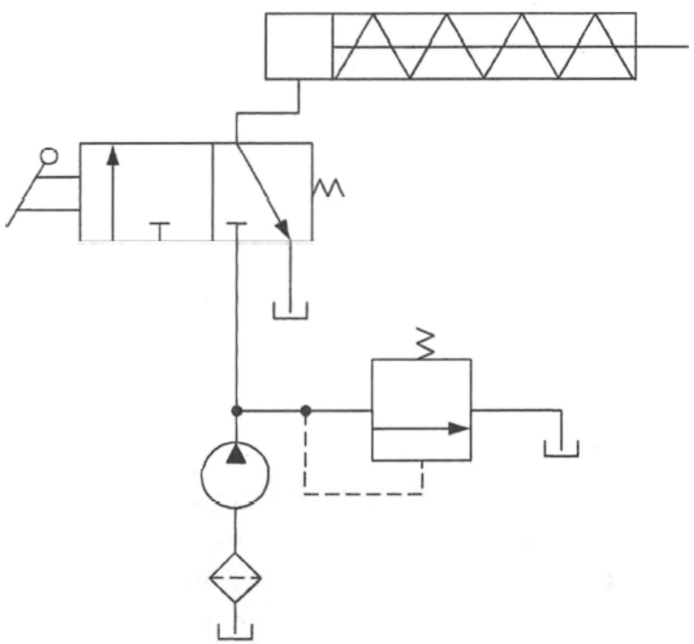
9.2 Basic Cylinder Circuit



Hand lever operated single acting cylinder.

Function: cylinder extends when DCV actuated

Safety: PRV limits system pressure

Performance: analysis required to ensure required force and speed of cylinder achieved

Efficiency: pump is always operating at maximum power

Application: hand operated hatch

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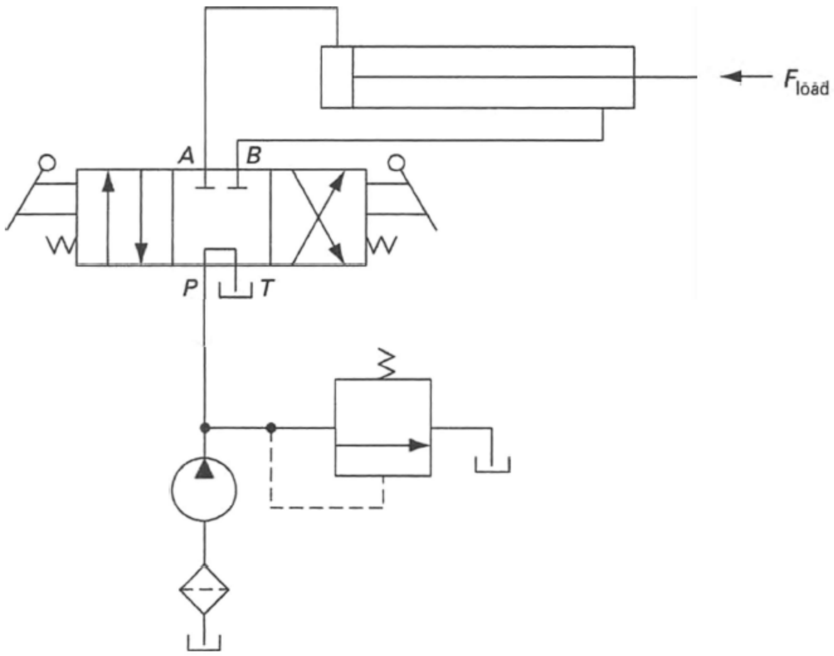
9.3 Basic Cylinder Circuit



Hand lever operated double acting cylinder.

Function: cylinder extends/retracts when DCV actuated and is hydraulicly locked in center position

Safety: PRV limits system pressure

Performance: analysis required to ensure required force and speed of cylinder achieved

Efficiency: pump is unloaded with tandem center DCV allowing pump to idle saving power

Application: scissor lift

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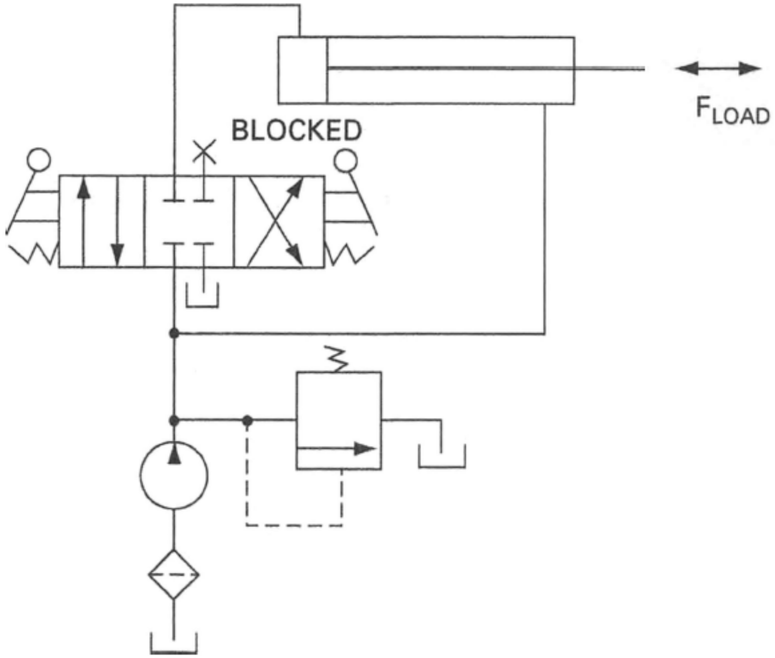
9.4 Regenerative Cylinder Circuit



Hand lever operated double acting cylinder regenerative circuit.

Function: cylinder extends/retracts when DCV actuated and is hydraulicly locked in center position

Safety: PRV limits system pressure

Performance: Extension speed is increased using the retraction flow regeneratively for extension

Efficiency: a lower flow pump can be used to achieve same speed on retraction

Application: long stroke press with low flow pump

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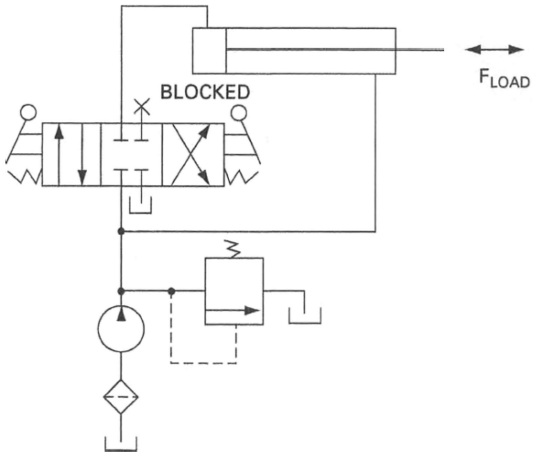
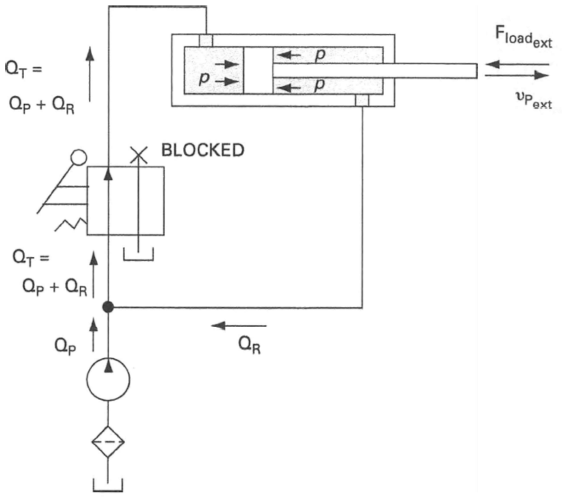
9.4 Regenerative Cylinder Circuit



Complete Regenerative Circuit



Regenerative Circuit During Extension

During retraction, cylinder retracts normally under pump flow once DCV is shifted to right position.

During Extension, oil flow from the rod side of the cylinder is added to the pump flow to speed up the cylinder.

$$Q_T = Q_P + Q_R$$

If we solve for Q_P and substitute for speed and area

$$Q_P = A_P v_{P_{ext}} - (A_P - A_r) v_{P_{ext}}$$

Which reduces to

$$v_{P_{ext}} = \frac{Q_P}{A_r}$$

Speed for extension and retraction as a ratio:

$$\frac{v_{P_{ext}}}{v_{P_{ret}}} = \frac{Q_P/A_r}{Q_P/(A_P - A_r)} = \frac{A_P - A_r}{A_r} = \frac{A_P}{A_r} - 1$$

Force during extension is less than a normal cylinder

$$F_{load_{ext}} = pA_r$$

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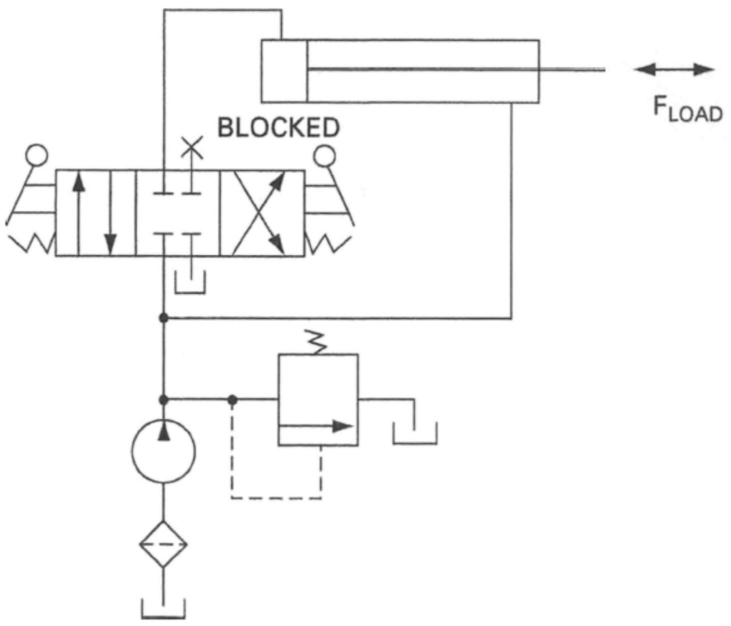
9.4 Regenerative Cylinder Circuit



Example: A double-acting cylinder is hooked up in the regenerative circuit shown. The cracking pressure for the relief valve is 1000 psi. The piston area is 25 in^2 and the rod area is 7 in^2. The pump flow is 20 gpm.

Find:

i) the cylinder speed

ii) load-carrying capacity

iii) power delivered to the load (assuming the load equals the cylinder load-carrying capacity)

during the

a) Extending stroke

and

b) Retracting stroke

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9.4 Regenerative Cylinder Circuit

a. $$v_{P_{ext}} = \frac{Q_P}{A_r} = \frac{(20\ \text{gpm})(231\ \text{in}^3/1\ \text{gal})(1\ \text{min}/60\ \text{s})}{7\ \text{in}^2} = 11.0\ \text{in/s}$$

$$F_{load_{ext}} = pA_r = 1000\ \text{lb/in}^2 \times 7\ \text{in}^2 = 7000\ \text{lb}$$

$$\text{Power}_{ext} = F_{load_{ext}} v_{p_{ext}} = 7000\ \text{lb} \times 11.0\ \text{in/s} = 77{,}000\ \text{in} \cdot \text{lb/s} = 11.7\ \text{hp}$$

b. $$v_{p_{ret}} = \frac{Q_P}{A_p - A_r} = \frac{20 \times \frac{231}{60}}{25 - 7} = 4.28\ \text{in/s}$$

$$F_{load_{ret}} = p(A_P - A_r) = 1000\ \text{lb/in}^2 \times (25 - 7)\ \text{in}^2 = 18{,}000\ \text{lb}$$

$$\text{Power}_{ret} = F_{load_{ret}} v_{p_{ret}} = 18{,}000\ \text{lb} \times 4.28\ \text{in/s} = 77{,}000\ \text{in} \cdot \text{lb/s} = 11.7\ \text{hp}$$

Note that the hydraulic horsepower delivered by the pump during both the extending and retracting strokes can be found as follows, and this equals the power delivered to the loads during both extension and retraction:

$$HP_{pump} = \frac{p(\text{psi}) \times Q_{pump}(\text{gpm})}{1714} = \frac{1000\ \text{psi} \times 20\ \text{gpm}}{1714} = 11.7\ \text{hp}$$

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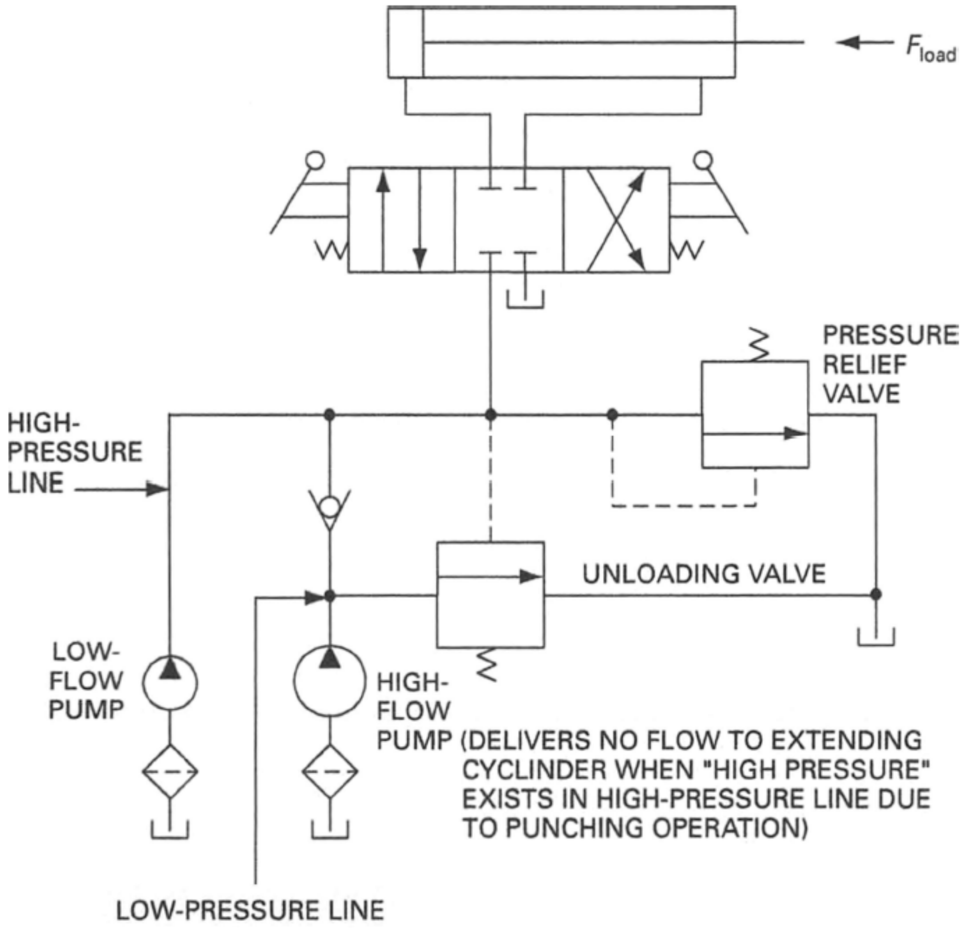
9.6 Double Pump Hydraulic System



Hand lever operated double acting cylinder dual pump circuit.

Function: cylinder extends quickly under low pressure, then completes extension performing desired function (e.g. punch) under high pressure

Safety: PRV limits system pressure

Performance: Extension speed is increased using the retraction flow regeneratively for extension

Efficiency: a *high flow low pressure* pump is used in combination with a *low flow high pressure* pump to achieve desired function, instead of a more expensive *high flow high pressure pump*

Application: large stroke punching press with force required only at end of stroke

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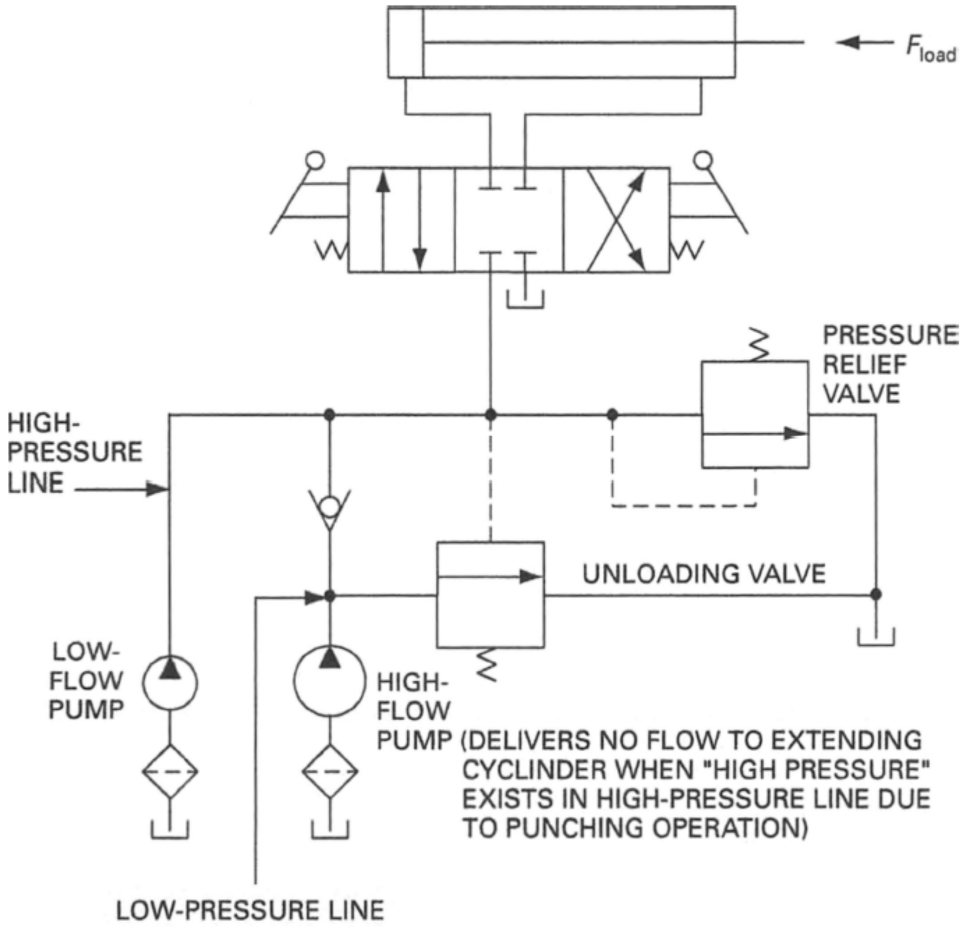
9.6 Double Pump Hydraulic System



Example: For the double-pump system shown, what should be the pressure settings of the unloading valve and pressure relief valve under the following conditions?

a. Sheet metal punching operation requires a force of 2000 lb.
b. Hydraulic cylinder has a 1.5-in-diameter piston and 0.5-in-diameter rod.
c. During rapid extension of the cylinder, a frictional pressure loss of 100 psi occurs in the line from the high-flow pump to the blank end of the cylinder. During the same time a 50-psi pressure loss occurs in the return line from the rod end of the cylinder to the oil tank. Frictional pressure losses in these lines are negligibly small during the punching operation.
d. Assume that the unloading valve and pressure relief valve pressure settings (for their full pump flow requirements) should be 50% higher than the pressure required to overcome frictional pressure losses and the cylinder punching load, respectively.

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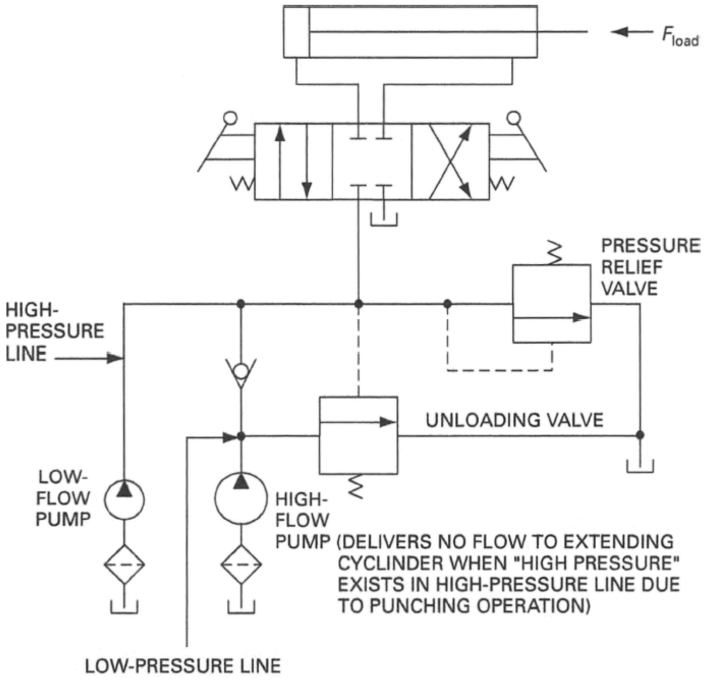
9.6 Double Pump Hydraulic System



Unloading Valve:

Back-pressure force on the cylinder equals the product of the pressure loss in the return line and the effective area of the cylinder $(A_p - A_r)$.

$$F_{\text{back pressure}} = 50\,\frac{\text{lb}}{\text{in}^2} \times \frac{\pi}{4}(1.5^2 - 0.5^2)\text{in}^2 = 78.5\text{ lb}$$

Pressure at the blank end of the cylinder required to overcome back-pressure force equals the back-pressure force divided by the area of the cylinder piston.

$$p_{\text{cyl blank end}} = \frac{78.5\text{ lb}}{\frac{\pi}{4}(1.5\text{ in})^2} = 44.4\text{ psi}$$

Thus, the pressure setting of the unloading valve should be 1.50(100 + 44.4)psi = 217 psi.

Pressure Relief Valve:

The pressure required to overcome the punching operation equals the punching load divided by the area of the cylinder piston.

$$p_{\text{punching}} = \frac{2000\text{ lb}}{\frac{\pi}{4}(1.5\text{ in})^2} = 1132\text{ psi}$$

Thus, the pressure setting of the pressure relief valve should be 1.50 × 1132 psi = 1698 psi.

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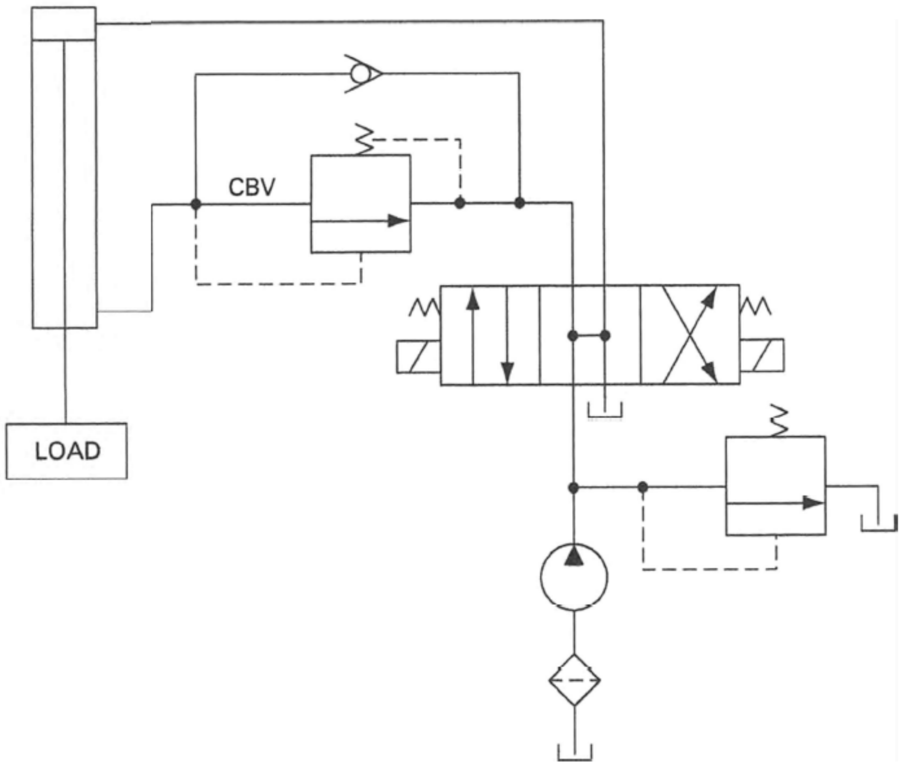
9.7 Counterbalance Valve Circuit



Solenoid operated double acting cylinder with a suspended load

Function: Counterbalance valve hold cylinder in position with suspended load until DCV commands extension.

Safety: counterbalance valve prevents runaway of the suspended load. PRV limits system pressure

Performance: additional pressure is required to overcome the counterbalance function

Efficiency: pump is unloaded through open-center DCV

Application: a punch operation with a heavy punch tool

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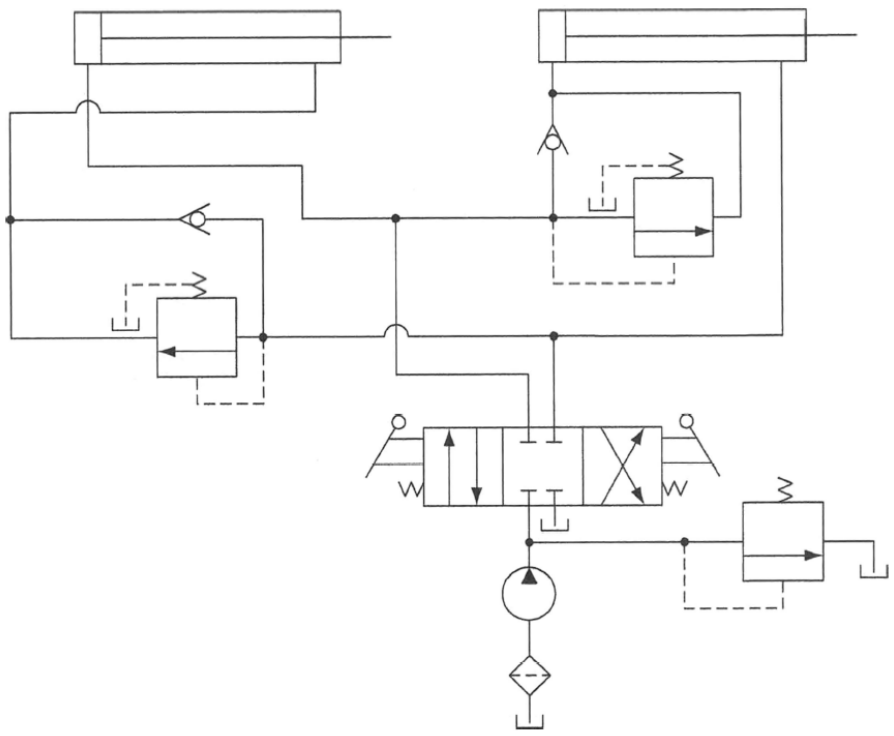
9.8 Hydraulic Cylinder Sequencing Circuit



Hand lever operated double acting cylinders, sequential operation

Function: on extension, cylinder Left extends, and once complete cylinder Right then extends. On retraction, Right cylinder retracts then Left cylinder retracts.

Safety: PRV limits system pressure

Performance: Automatic sequencing is achieved with correct sequence valve settings

Efficiency: sequence operation is achieved with minimal components

Application: clamp and drill operation

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9.12 Fail Safe

Good hydraulic system design considers safety and builds in automatic safeguarding

Fail safe design prevents injury to the operator or damage to equipment

-prevention of inadvertent cylinder movement (loads falling)
-overload protection (ref Section 9.12)
-two-handed operation
-hydraulic fuses (ref Section 8.8)

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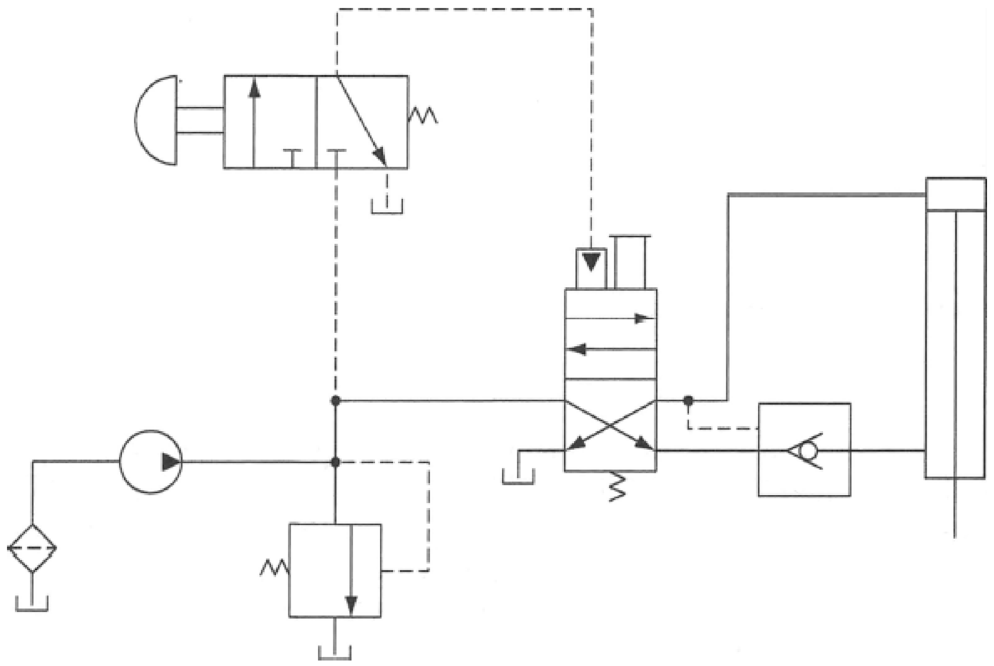
9.12 Inadvertent Cylinder Extension

Prevents the cylinder from accidentally falling in the event a hydraulic line ruptures or a person inadvertently operates the manual override on the pilot actuated directional control valve when the pump is not operating.

To lower the cylinder, pilot pressure from the blank end of the piston must pilot-open the check valve at the rod end to allow oil to return through the DCV to the tank.

This happens when the push-button valve is actuated to permit pilot pressure actuation of the DCV or when the DCV is directly manually actuated while the pump is operating.

The pilot-operated DCV allows free flow in the opposite direction to retract the cylinder when this DCV returns to its spring-offset mode.



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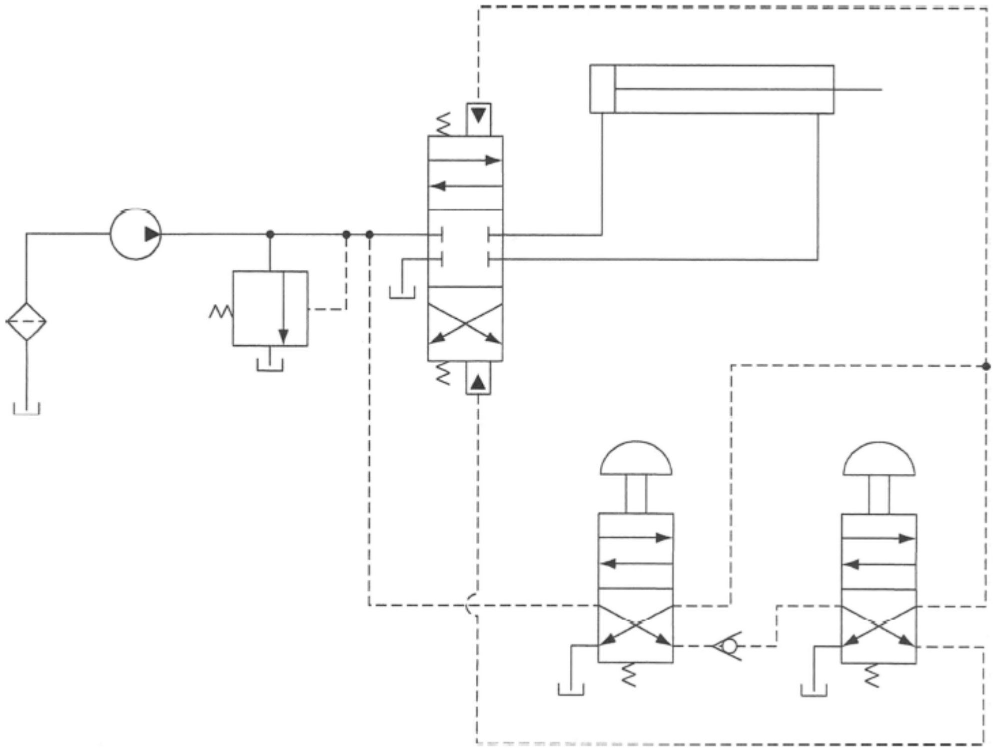
9.12 Two Handed Operation

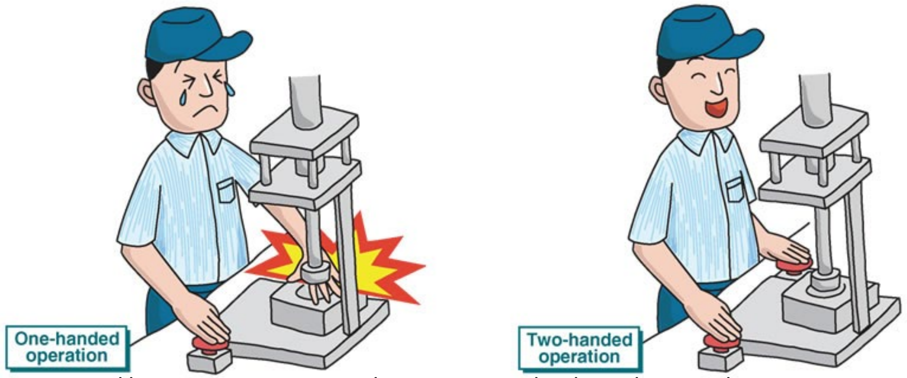
Protects an operator from injury requiring both hands to be free from workspace.

The operator must depress both manually actuated valves via the push buttons.

When the two buttons are depressed, the main three-position DCV is pilot-actuated to extend the cylinder. When both push buttons are released, the cylinder retracts.

The operator cannot circumvent this safety feature by tying down one of the buttons, because it is necessary to release both buttons to retract the cylinder.





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9.13 Speed Control

Speed control of a hydraulic actuator (cylinder or motor) is achieved by using a Flow Control Valve (ref Section 8.4).

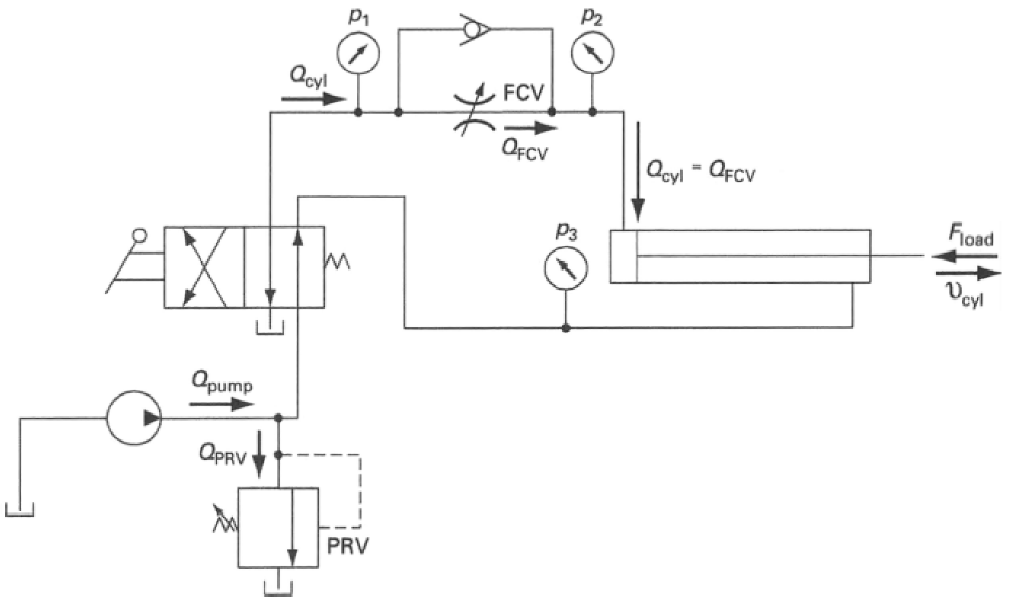
Recall: $v_{cyl} = Q_{cyl}/A_{piston} = Q_{FCV}/A_{piston}$

The FCV meters the flow of the hydraulic fluid either *into* or *out* of the cylinder.

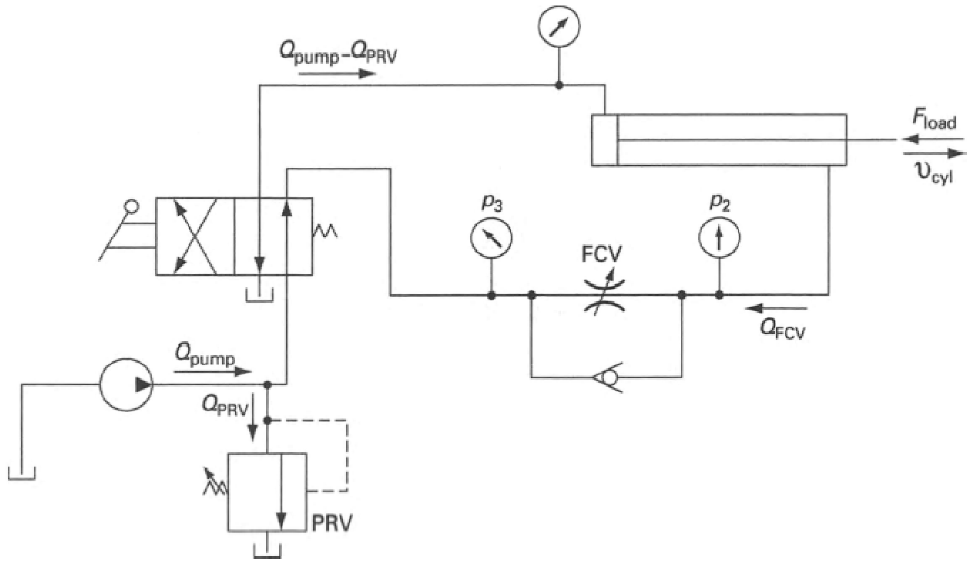
Meter-in is used primarily when the F_{load} opposes the motion of the cylinder.

Meter-out is used when the F_{load} is in the direction of the motion of the cylinder, such as a vertically suspended load on extension.

-can cause excessive pressure buildup in the rod end of the cylinder while it is extending due to the magnitude of back pressure that the FCV can create as well as the size of the external load and the piston-to-rod area ratio of the cylinder



Meter-in speed control of extension



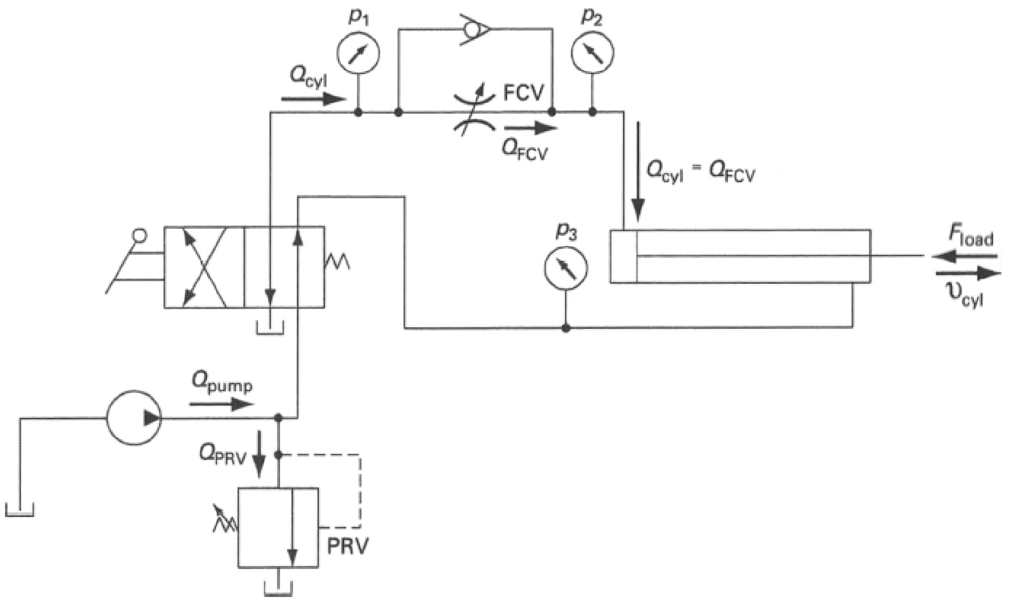
Meter-out speed control of extension

9.13 Speed Control

The flow rate through the flow control valve (FCV) is governed by

$$Q_{FCV} = C_v\sqrt{\frac{\Delta p}{SG}} = C_v\sqrt{\frac{p_1 - p_2}{SG}}$$

where Δp = pressure drop across FCV,
Cv = capacity coefficient of FCV,
SG = specific gravity of oil,
Pressure $p_1 = p_{PRV}$=PRV setting.



Meter-in speed control of extension

Pressure $p_2 = F_{load}/A_{piston}$

Cylinder speed $v_{cyl} = Q_{cyl}/A_{piston} = Q_{FCV}/A_{piston}$

Combining these equations:

$$v_{cyl} = \frac{C_v}{A_{piston}}\sqrt{\frac{p_{PRV} - F_{load}/A_{piston}}{SG}}$$

As can be seen by varying the setting of the FCV, and thus the value of *Cv*, the desired extending speed of the cylinder can be achieved.

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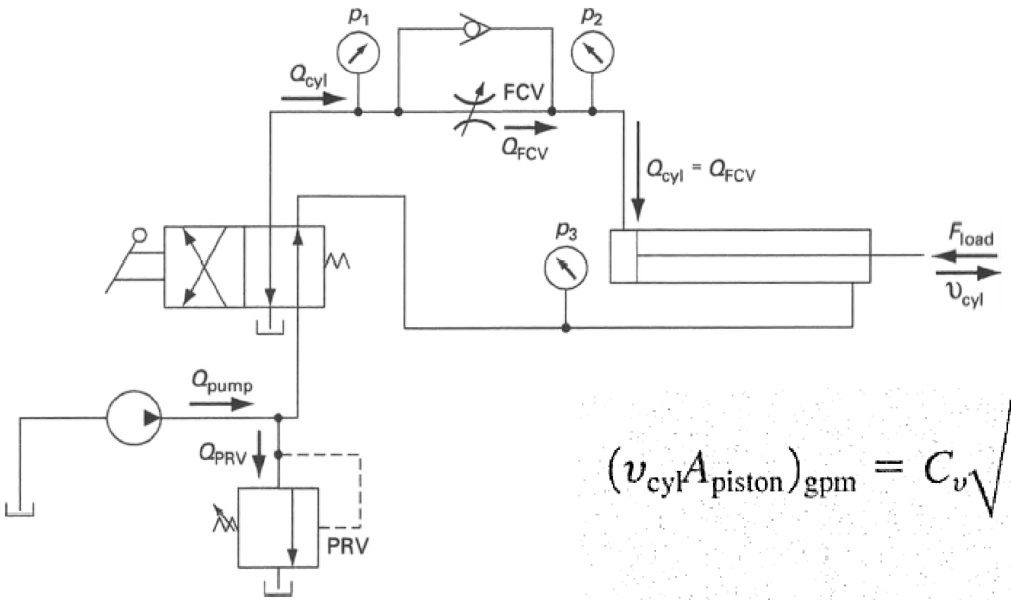
9.13 Speed Control



Example: For the meter-in system shown the following data are given:

Valve capacity coefficient = 1.0 gpm /sqrt(psi)

Cylinder piston diameter = 2 in (area = 3.14 in^2)

Cylinder load = 4000 lb

Specific gravity of oil = 0.90

Pressure relief valve setting = 1400 psi

Determine the cylinder speed.

$$(v_{cyl}A_{piston})_{gpm} = C_v\sqrt{\frac{p_{PRV} - F_{load}/A_{piston}}{SG}} = 1.0\sqrt{\frac{1400 - 4000/3.14}{0.9}} = 11.8 \text{ gpm}$$

$$= 11.8\frac{\text{gal}}{\text{min}} \times \frac{231 \text{ in}^3}{1 \text{ gal}} \times \frac{1 \text{ min}}{60 \text{ s}} = 45.4 \text{ in}^3/\text{s}$$

Solving for the cylinder speed we have

$$v_{cyl} = \frac{45.4 \text{ in}^3/\text{s}}{A_{piston}(\text{in}^2)} = \frac{45.4}{3.14} = 14.5 \text{ in/s}$$

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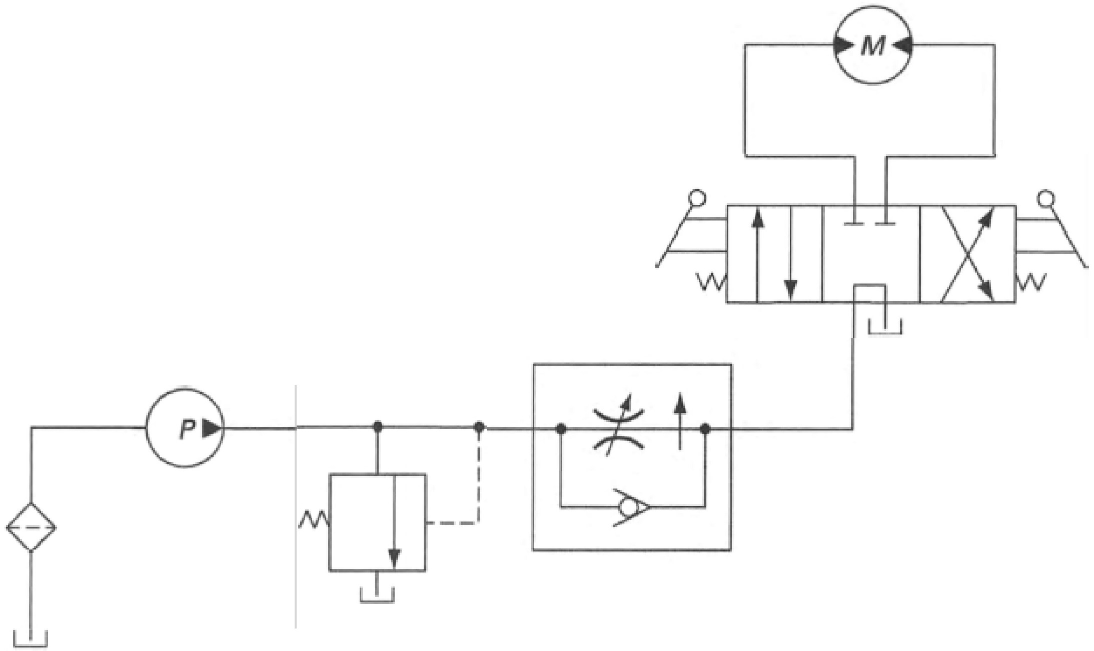
9.14 Motor Speed Control

Sped control of a motor is accomplished through a FCV

In this circuit, a meter-in speed control is employed with a pressure-compensated FCV.

The DCV provides CW/CCW rotation spin control
The tandem center hydraulically locks the motor from spinning when not activated



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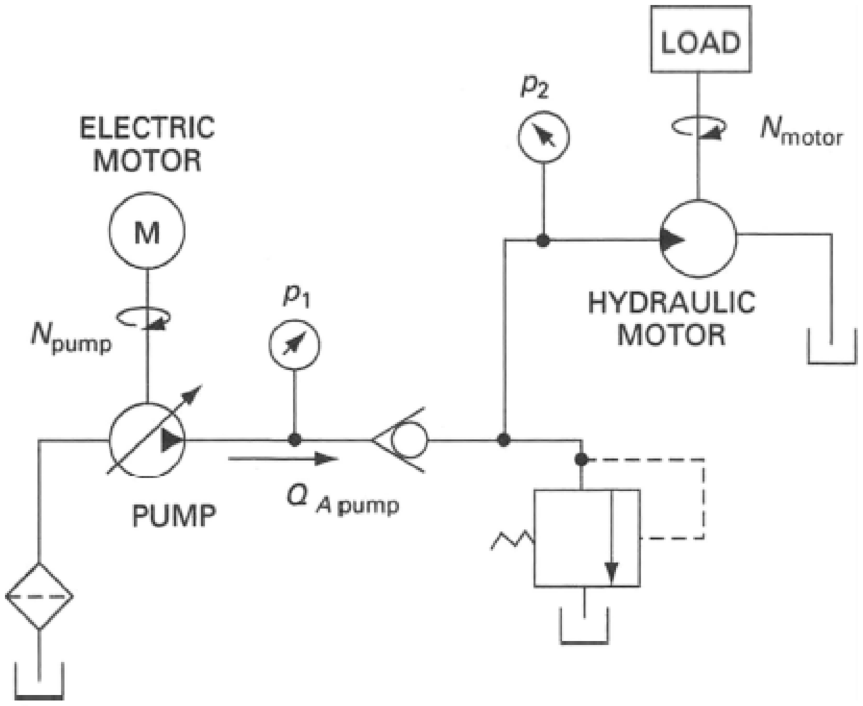
9.18 Hydraulic System Analysis

By example, we will complete an analysis of a complete hydraulic system, taking frictional losses into account.

The system shown contains a pump delivering high-pressure oil to a hydraulic motor, which drives an external load via a rotating shaft.
The following data are given:



Pump:
η_m=94%
η_v =92%
V_D = 10 in^3
N = 1000 rpm
inlet pressure = -4 psi

Hydraulic motor:
η_m = 92%
η_v = 90%
V_D = 8 in^3
inlet pressure p_2 required to drive load = 500 psi
motor discharge pressure = 5 psi

Pump discharge pipeline:
Pipe: 1-in schedule 40, 50 ft long (point 1 to point 2)
Fittings: two 90° elbows (K = 0.75 for each elbow), one check valve (K = 4.0)

Oil:
viscosity = 125 cS
specific gravity = 0.9

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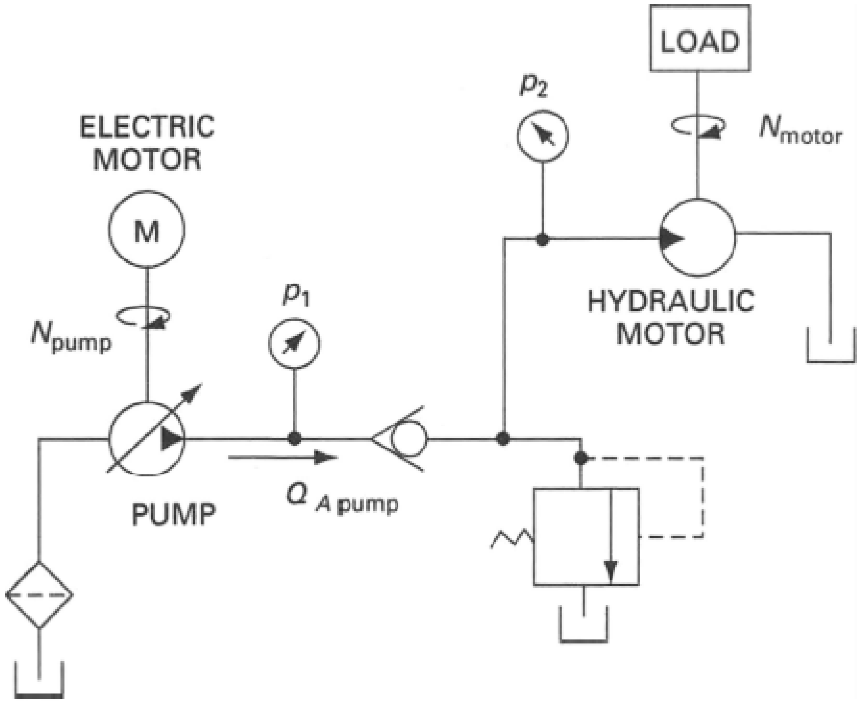
9.18 Hydraulic System Analysis

If the hydraulic motor is 20 ft above the pump, determine the

a. Pump flow rate
b. Pump discharge pressure p_1
c. Input hp required to drive the pump
d. Motor speed
e. Motor output hp
f. Motor output torque
g. Overall efficiency of system



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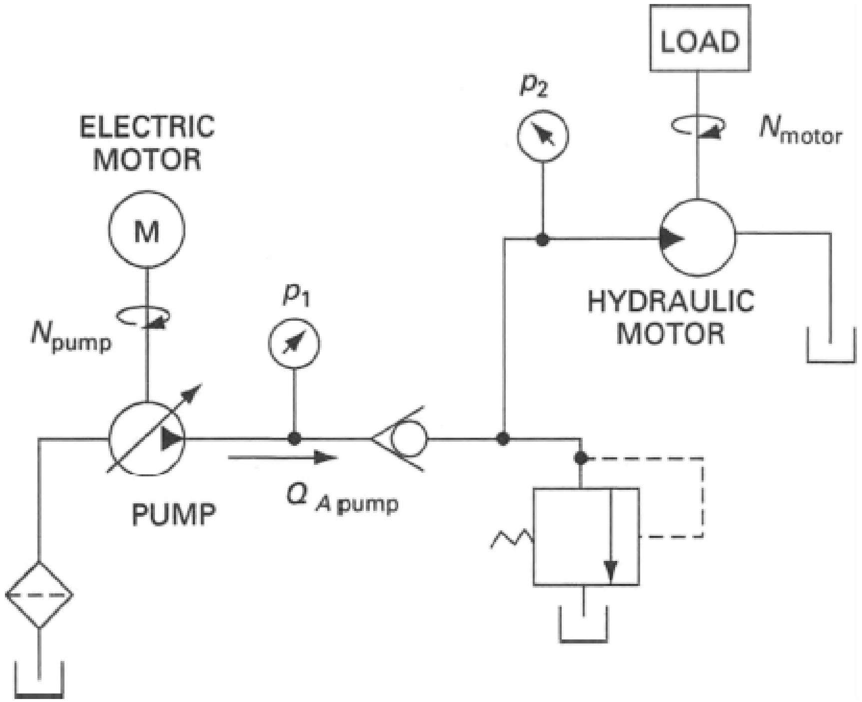
9.18 Hydraulic System Analysis

Solution

a. To determine the pump's actual flow rate, we first calculate the pump's theoretical flow rate.

$$(Q_T)_{\text{pump}} = \frac{(V_D)_{\text{pump}} \times N_p}{231} = \frac{10 \text{ in}^3 \times 1000 \text{ rpm}}{231} = 43.3 \text{ gpm}$$

$$(Q_A)_{\text{pump}} = (Q_T)_{\text{pump}} \times (\eta_v)_{\text{pump}} = 43.3 \times 0.94 = 40.7 \text{ gpm}$$



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9.18 Hydraulic System Analysis

b. To obtain the pump discharge pressure p_1 we need to calculate the frictional pressure loss $(p_1 - p_2)$ in the pump discharge line. Writing the energy equation between points 1 and 2, we have

$$Z_1 + \frac{p_1}{\gamma} + \frac{v_1^2}{2g} + H_p - H_m - H_L = Z_2 + \frac{p_2}{\gamma} + \frac{v_2^2}{2g}$$

Since there is no hydraulic motor or pump between stations 1 and 2, $H_m = H_p = 0$. Also, $v_1 = v_2$ and $Z_2 - Z_1 = 20$ ft. Also, per Figure 10-2 for 1-in schedule 40 pipe, the inside diameter equals 1.040 in. We next solve for the Reynolds number, friction factor, and head loss due to friction.

$$v = \frac{(Q_A)_{\text{pump}}}{A} = \frac{40.7/449\ \text{ft}^3/\text{s}}{\frac{\pi}{4}\left(\frac{1.040}{12}\text{ft}\right)^2} = \frac{0.0908\ \text{ft}^3/\text{s}}{0.00590\ \text{ft}^2} = 15.4\ \text{ft/s}$$

$$N_R = \frac{7740 v(\text{ft/s}) \times D(\text{in})}{\nu(\text{cS})} = \frac{7740 \times 15.4 \times 1.040}{125} = 992$$

Since the flow is laminar, the friction factor can be found directly from the Reynolds number.

$$f = \frac{64}{N_R} = \frac{64}{992} = 0.0645$$

Also,

$$H_L = f\left(\frac{L_{e\text{TOT}}}{D}\right)\frac{v^2}{2g} \qquad \text{where}$$

$$L_{e\text{TOT}} = 50 + 2\left(\frac{KD}{f}\right)_{90^\circ\ \text{elbow}} + \left(\frac{KD}{f}\right)_{\text{check valve}}$$

$$= 50 + \frac{2 \times 0.75 \times 1.040/12}{0.0645} + \frac{4.0 \times 1.040/12}{0.0645} = 50 + 2.02 + 5.37 = 57.39\ \text{ft}$$

Thus,

$$H_L = 0.0645 \times \frac{57.39}{1.040/12} \times \frac{(15.4)^2}{2 \times 32.2} = 157.3\ \text{ft}$$

Next, we substitute into the energy equation to solve for $(p_1 - p_2)/\gamma$.

$$\frac{p_1 - p_2}{\gamma} = (Z_2 - Z_1) + H_L = 20\ \text{ft} + 157.3\ \text{ft} = 177.3\ \text{ft}$$

Hence,

$$p_1 - p_2 = 177.3\ \text{ft} \times \gamma\left(\frac{\text{lb}}{\text{ft}^3}\right) = 177.3\ \text{ft} \times 0.9 \times 62.4\frac{\text{lb}}{\text{ft}^3} = 9960\frac{\text{lb}}{\text{ft}^2} = 69\ \text{psi}$$

$$p_1 = p_2 + 69 = 500 + 69 = 569\ \text{psi}$$

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9.18 Hydraulic System Analysis

c. hp delivered to pump $= \dfrac{\text{pump hydraulic horsepower}}{(\eta_o)_{\text{pump}}}$

$$= \frac{(569 + 4)\text{psi} \times 40.7\ \text{gpm}}{1714 \times 0.94 \times 0.92} = 15.7\ \text{hp}$$

d. To obtain the motor speed we first need to determine the motor theoretical flow rate

$$(Q_T)_{\text{motor}} = (Q_A)_{\text{pump}} \times (\eta_v)_{\text{motor}} = 40.7 \times 0.90 = 36.6\ \text{gpm}$$

$$N_{\text{motor}} = \frac{(Q_T)_{\text{motor}} \times 231}{(V_D)_{\text{motor}}} = \frac{36.6 \times 231}{8} = 1057\ \text{rpm}$$

e. To obtain the motor output hp we first need to determine the motor input hp.

$$\text{motor input hp} = \frac{(500 - 5)\text{psi} \times 40.7\ \text{gpm}}{1714} = 11.8\ \text{hp}$$

Thus,

$$\text{motor output hp} = \text{motor input hp} \times (\eta_o)_{\text{motor}} = 11.8 \times 0.92 \times 0.90 = 9.77\ \text{hp}$$

f. motor output torque $= \dfrac{\text{motor output hp} \times 63{,}000}{N_{\text{motor}}}$

$$= \frac{9.77 \times 63{,}000}{1057} = 582\ \text{in} \cdot \text{lb}$$

g. The overall efficiency of the system is

$$(\eta_o)_{\text{overall}} = \frac{\text{motor output hp}}{\text{pump input hp}} = \frac{9.77}{15.7} = 0.622 = 62.2\%$$

Thus, 62.2% of the power delivered to the pump by the electric motor is delivered to the load by the hydraulic motor.

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Chapter Reading

Chapter 9 - all

Chapter 10 - all

Chapter 11 - all