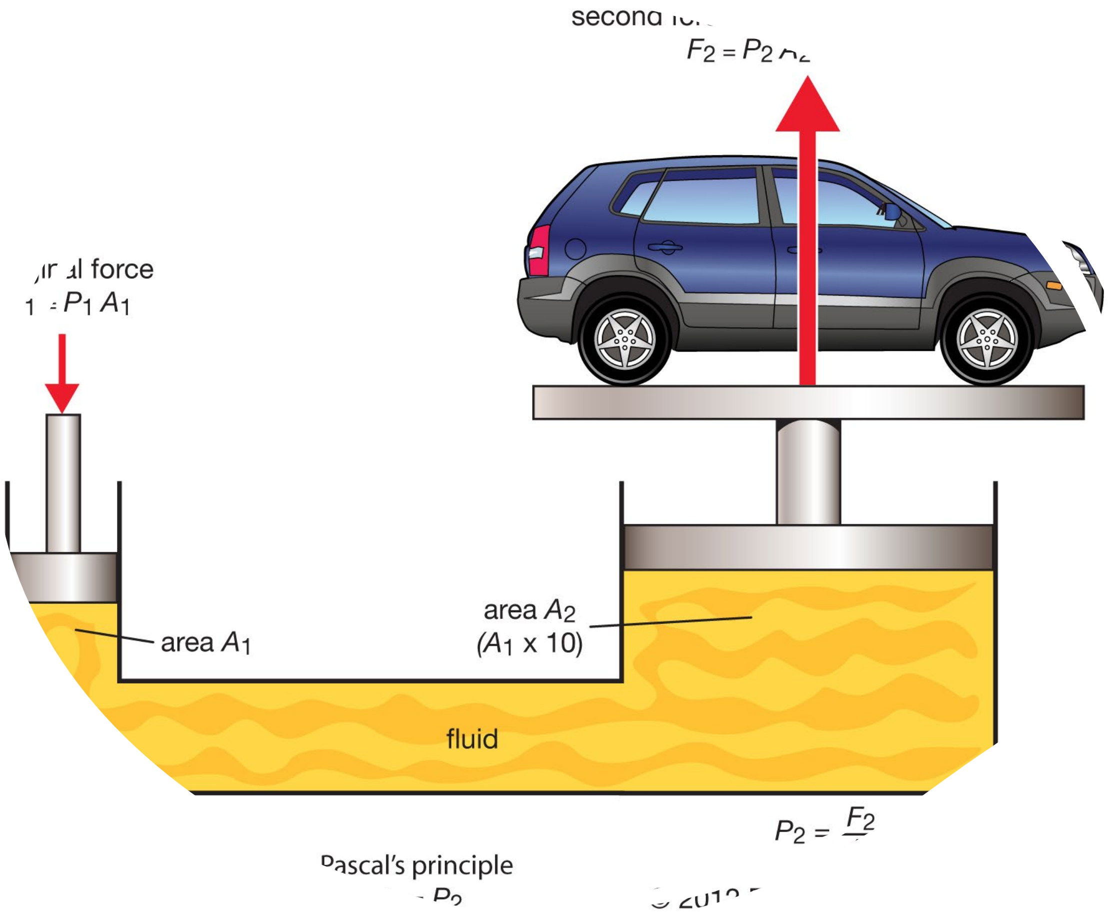


Pneumatics and hydraulics

Energy and Power in Hydraulic Systems

Dr. Ahmad Al-Mahasneh

Outline

- Introduction
- Energy
- Review of mechanics

Introduction

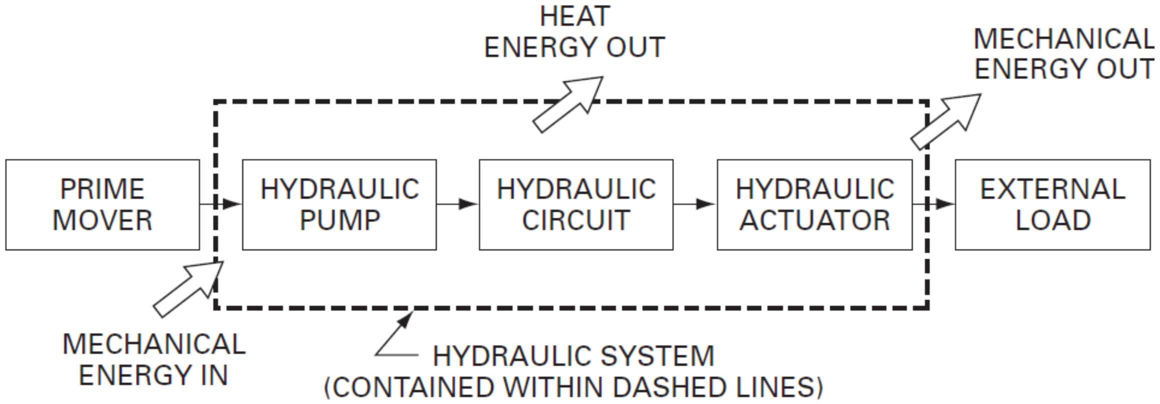


Figure 3-1. Block diagram of hydraulic system showing major components along with energy input and output terms.

Energy is defined as the ability to perform work, and thus the transfer of energy is a key consideration in the operation of hydraulic systems. Figure 3-1 provides a block diagram illustrating how energy is transferred throughout a hydraulic system (contained within the dashed lines).

1. As shown, the prime mover (such as an electric motor or an internal combustion engine) delivers input energy to a pump of the hydraulic system via a rotating shaft.
2. The pump converts this mechanical energy into hydraulic energy by increasing the fluid's pressure and velocity.

Introduction

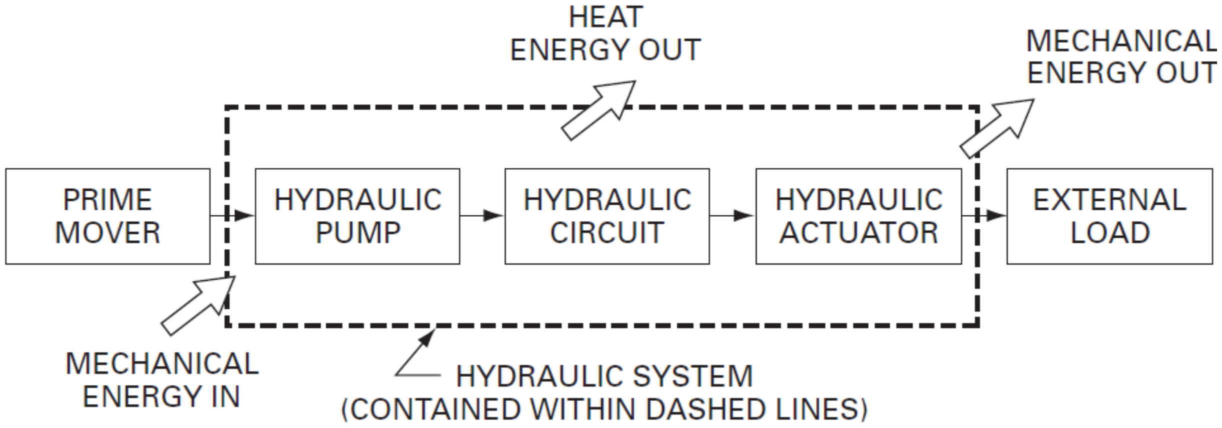


Figure 3-1. Block diagram of hydraulic system showing major components along with energy input and output terms.

3. The fluid flows to an actuator via a hydraulic circuit that consists of pipelines containing valves and other control components.
4. The hydraulic circuit controls the pressures and flow rates throughout the hydraulic system.
5. The actuator (either a hydraulic cylinder or motor) converts the hydraulic energy from the fluid into mechanical energy to drive the external load via a force or torque in an output shaft.

Some of the hydraulic energy of the fluid is lost due to friction as the fluid flows through pipes, valves, fittings, and other control components.

Energy

All these forms of energy are accounted for by the conservation of energy law, which states that energy can be neither created nor destroyed. This is expressed by the following equation for the system of Figure 3-1:

$$\text{Input } ME - \text{Lost } HE = \text{Output } ME$$

where ME = mechanical energy,
HE = heat energy.

Power is defined as the rate of doing work or expending energy. Thus the rate at which the prime mover adds energy to the pump equals the power input to the hydraulic system. Likewise, the rate at which the actuator delivers energy to the external load equals the power output of the hydraulic system. The power output is determined by the requirements of the external load. The greater the force or torque required to move the external load and the faster this work must be done, the greater must be the power output of the hydraulic system.

Energy

A hydraulic system is not a source of energy. The energy source is the prime mover, which drives the pump. Thus, in reality, a hydraulic system is merely an energy transfer system. Why not, then, eliminate hydraulics and simply couple the load directly to the prime mover? The answer is that a hydraulic system is much more versatile in its ability to transmit power. This versatility includes advantages of variable speed, reversibility, overload protection, high power-to-weight ratio, and immunity to damage under stalled conditions.

REVIEW OF MECHANICS

Introduction

Since fluid power deals with the generation of forces to accomplish useful work, it is essential that the basic laws of mechanics be clearly understood. Let's, therefore, have a brief review of mechanics as it relates to fluid power systems.

Forces are essential to the production of work. No motion can be generated and hence no power can be transmitted without the application of some force. It was in the late seventeenth century when Sir Isaac Newton formulated the three laws of motion dealing with the effect a force has on a body:

1. A force is required to change the motion of a body.
2. If a body is acted on by a force, the body will have an acceleration proportional to the magnitude of the force and inverse to the mass of the body.
3. If one body exerts a force on a second body, the second body must exert an equal but opposite force on the first body.

REVIEW OF MECHANICS

The motion of a body can be either linear or angular depending on whether the body travels along a straight line or rotates about a fixed point.

Linear Motion

If a body experiences linear motion, it has a *linear velocity* (or simply *velocity*), which is defined as the distance traveled divided by the corresponding time.

$$v = \frac{s}{t} \tag{3-1}$$

where in the English system of units: s = distance (in or ft),
t = time (s or min),
v = velocity (in/s, in/min, ft/s, or ft/min).

REVIEW OF MECHANICS

If the body's velocity changes, the body has an acceleration, which is defined as the change in velocity divided by the corresponding change in time ($a = \Delta \upsilon / \Delta t$). In accordance with Newton's first law of motion, a force is required to produce this change in velocity. Per Newton's second law, we have

$$F = ma \tag{3-2}$$

where F = force (lb),
a = acceleration (ft/s^2),
m = mass (slugs).

REVIEW OF MECHANICS

This brings us to the concept of energy, which is defined as the ability to perform work. Let's assume that a force acts on a body and moves the body through a specified distance in the direction of the applied force. Then, by definition, work has been done on the body. The amount of this work equals the product of the force and distance where both the force and distance are measured in the same direction:

$$W = FS \tag{3-3}$$

where F = force (lb),
S = distance (in or ft),
W = work (in · lb or ft · lb).

This leads us to a discussion of power, which is defined as the rate of doing work or expending energy. Thus, power equals work divided by time:

$$power = \frac{FS}{t}$$

But since S/t equals υ we can rewrite the power equation as follows:

$$power = F\upsilon \tag{3-4}$$

REVIEW OF MECHANICS

Power is a measure of how fast work is done and (in the English system of units) is usually measured in units of horsepower (hp). By definition, 1 hp equals 550 ft · lb/s or 33,000 ft · lb/min. Thus, we have

$$\text{horsepower} = \text{HP} = \frac{F(\text{lb}) \times v(\text{ft/s})}{550} = \frac{F(\text{lb}) \times v(\text{ft/min})}{33{,}000} \qquad \textbf{(3-5)}$$

The unit of horsepower was created by James Watt at the end of the nineteenth century, when he attempted to compare the rate of doing work by a horse in comparison with a steam engine. During a test he showed that a horse could raise a 150-lb weight (using a block-and-tackle) at an average velocity of 3.67 ft/s. This rate of doing work equals 150 lb × 3.67 ft/s or 550 ft · lb/s, which he defined as 1 horsepower.

REVIEW OF MECHANICS

EXAMPLE 3-1

A person exerts a 30-lb force to move a hand truck 100 ft in 60 s.

a. How much work is done?

b. What is the power delivered by the person?

Solution

a.

$$W = FS = (30\text{ lb})(100\text{ ft}) = 3000\text{ ft}\cdot\text{lb}$$

b.

$$\text{power} = \frac{FS}{t} = \frac{(30\text{ lb})(100\text{ ft})}{60\text{ s}} = 50\text{ ft}\cdot\text{lb/s}$$

$$\text{HP} = \frac{50\text{ ft}\cdot\text{lb/s}}{(550\text{ ft}\cdot\text{lb/s})/\text{hp}} = 0.091\text{ hp}$$

REVIEW OF MECHANICS

Angular Motion

Just as in the case of linear motion, angular motion is caused by the application of a force. Consider, for example, a force F applied to a wrench to tighten a bolt as shown in Figure 3-3. The force F has a moment arm R relative to the center of the bolt. Thus, the force F creates a torque T about the center of the bolt. It is the torque T that causes the wrench to rotate the bolt through a given angle until it is tightened. Note that the moment arm is measured from the center of the bolt (center of rotation) perpendicularly to the line of action of the force. The resulting torque is a clockwise torque because it rotates the bolt clockwise as shown. The magnitude of the torque equals the product of the applied force F and its moment arm R.

$$T = FR \tag{3-6}$$

where F = force (lb),
R = moment arm (in or ft),
T = torque (in · lb or ft · lb).

REVIEW OF MECHANICS

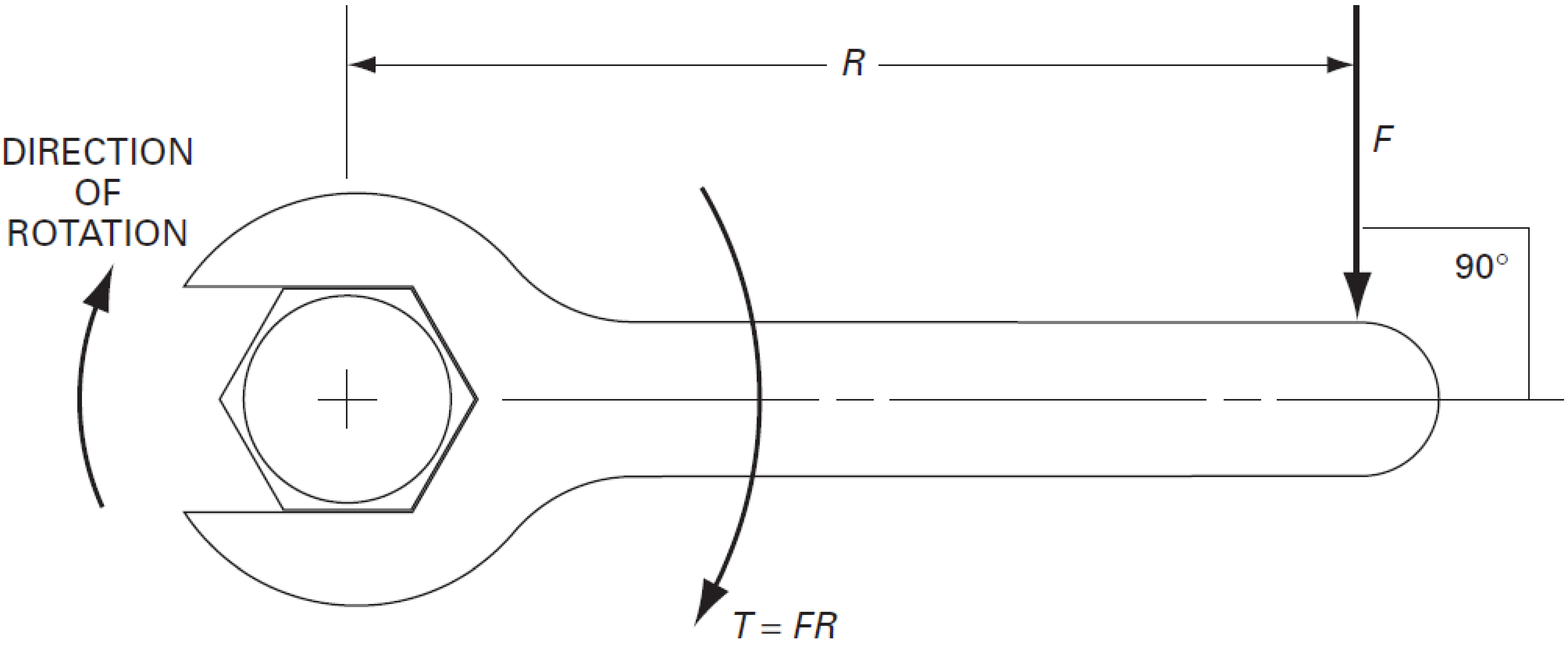


Figure 3-3. Force F applied to wrench creates torque T to tighten bolt.

REVIEW OF MECHANICS

$$\text{HP} = \frac{TN}{63{,}000}$$

where T = torque (in · lb),
N = rotational speed (rpm),
HP = torque horsepower or brake horsepower.

EXAMPLE 3-2

How much torque is delivered by a 2-hp, 1800-rpm hydraulic motor?

Solution

$$\text{HP} = \frac{TN}{63{,}000}$$

Substituting known values, we have

$$2 = \frac{T(1800)}{63{,}000}$$

$$T = 70 \text{ in} \cdot \text{lb}$$

REVIEW OF MECHANICS

Efficiency

Efficiency is defined as output power divided by input power. Mathematically we have

$$\eta = \frac{\text{output power}}{\text{input power}} \tag{3-8}$$

where η = Greek letter eta = efficiency.

The efficiency of any system or component is always less than 100% and is calculated to determine power losses. In hydraulic systems these losses are due to fluid leakage past close-fitting parts, fluid friction due to fluid movement, and mechanical friction due to the rubbing of mating parts. Efficiency determines the amount of power that is actually delivered in comparison to the power received. The power difference (input power – output power) represents loss power since it is transformed into heat due to frictional effects and thus is not available to perform useful work. The output power is usually computed from force and linear velocity (or torque and angular velocity) associated with the load. The input power is normally computed from the same parameters associated with the prime mover.

REVIEW OF MECHANICS

EXAMPLE 3-3

An elevator raises a 3000-lb load through a distance of 50 ft in 10 s. If the efficiency of the entire system is 80% (0.80 in decimal fraction form for use in equations), how much input horsepower is required by the elevator hoist motor?

Solution

$$\text{output power} = \frac{FS}{t} = \frac{(3000\ \text{lb})(50\ \text{ft})}{(10\ \text{s})} = 15{,}000\ \text{ft} \cdot \text{lb/s}$$

$$\text{output HP} = \frac{15{,}000}{550} = 27.3\ \text{hp}$$

$$\eta = \frac{\text{output power}}{\text{input power}}$$

$$0.80 = \frac{27.3\ \text{hp}}{\text{input power}}$$

$$\text{input power} = 34.1\ \text{hp}$$

REVIEW OF MECHANICS

3.3 MULTIPLICATION OF FORCE (PASCAL'S LAW)

Introduction

Pascal's law reveals the basic principle of how fluid power systems perform useful work. This law can be stated as follows: *Pressure applied to a confined fluid is transmitted undiminished in all directions throughout the fluid and acts perpendicular to the surfaces in contact with the fluid*. Pascal's law explains why a glass bottle, filled with a liquid, can break if a stopper is forced into its open end. The liquid transmits the pressure, created by the force of the stopper, throughout the container, as illustrated in Figure 3-5. Let's assume that the area of the stopper is 1 in^2 and that the area of the bottom is 20 in^2. Then a 10-lb force applied to the stopper produces a pressure of 10 psi. This pressure is transmitted undiminished to the bottom of the bottle, acting on the full 20-in^2 area and producing a 200-lb force. Therefore, it is possible to break out the bottom by pushing on the stopper with a moderate force.

REVIEW OF MECHANICS

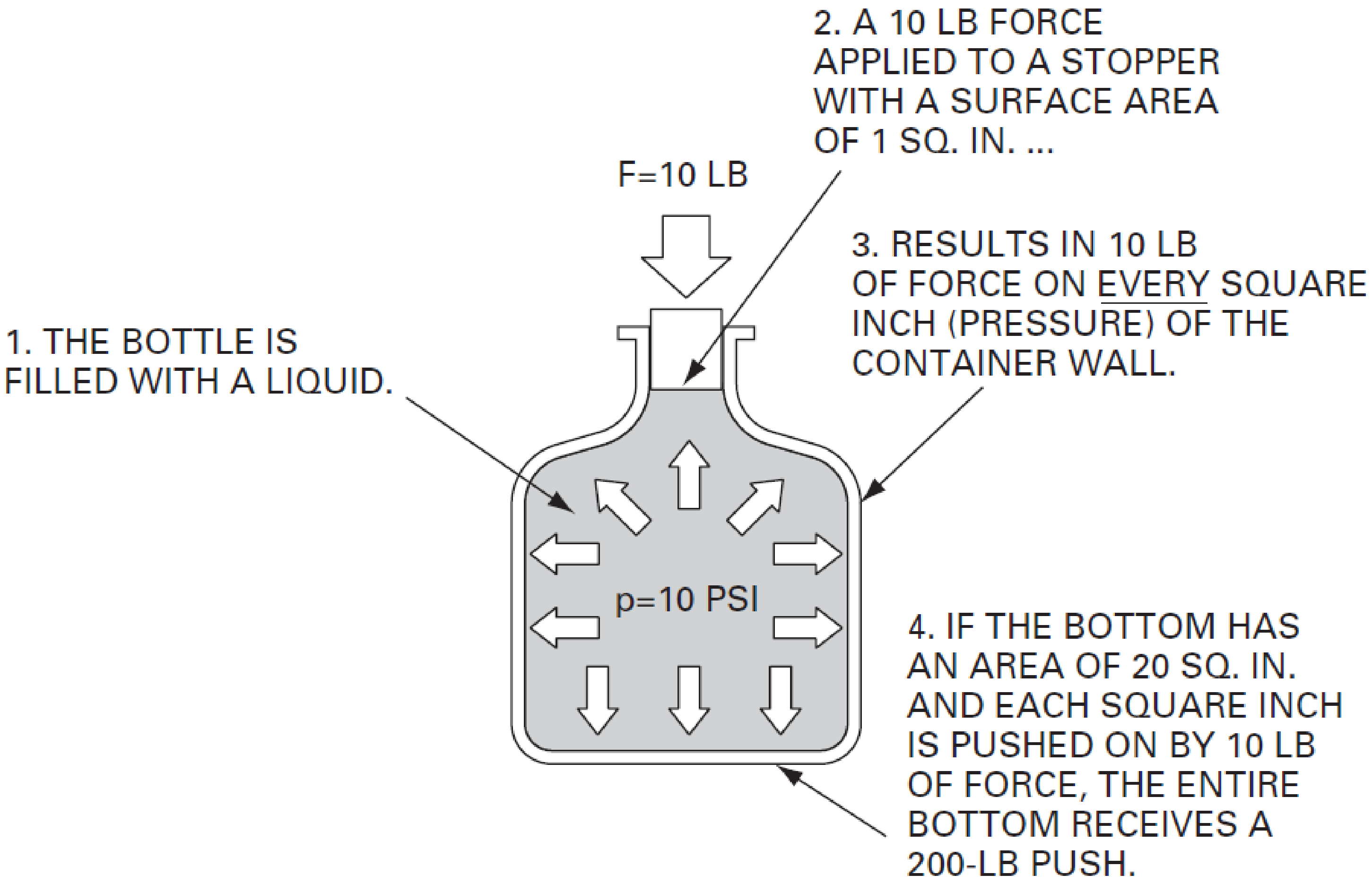


Figure 3-5. Demonstration of Pascal's law. *(Courtesy of Sperry Vickers, Sperry Rand Corp., Troy, Michigan.)*

REVIEW OF MECHANICS

Analysis of Simple Hydraulic Jack

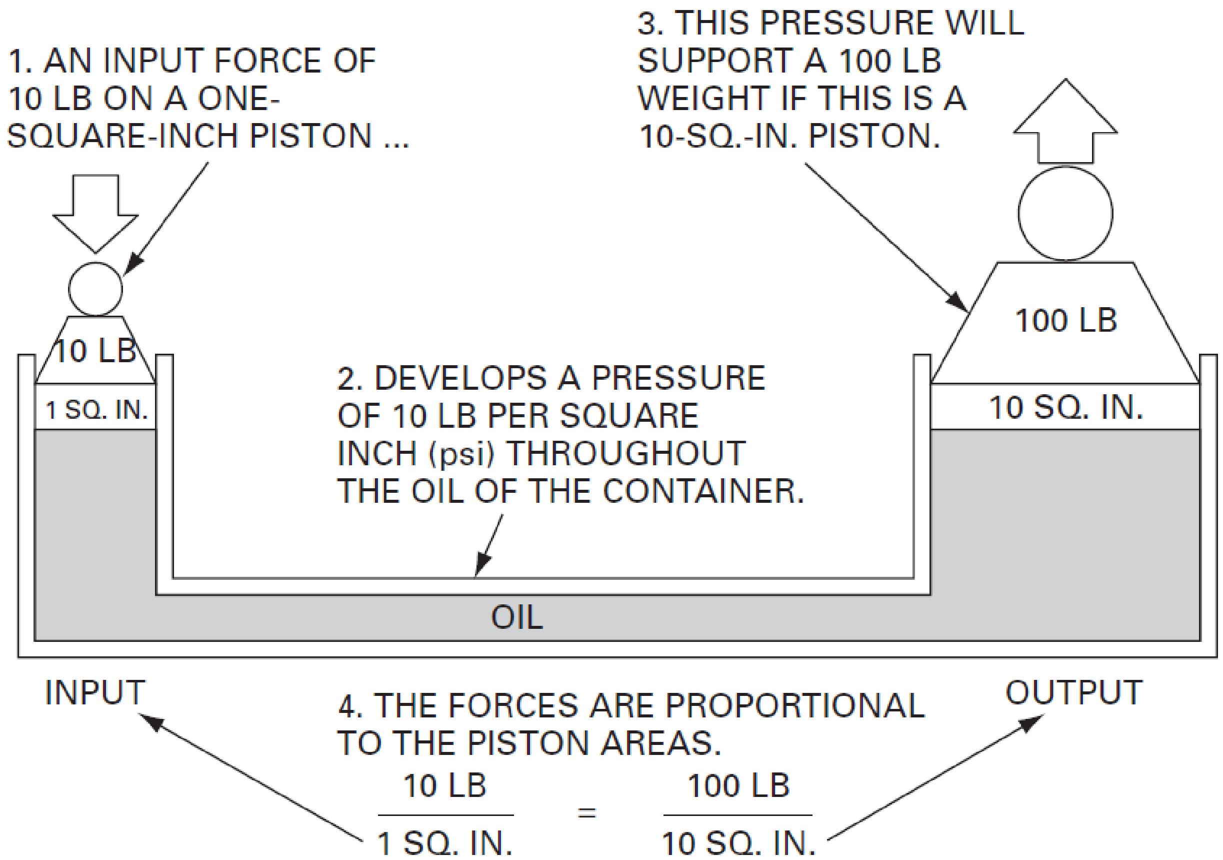
An interesting question relative to the hydraulic jack of Figure 3-6(a) is, Are we getting something for nothing? That is to say, does a hydraulic jack produce more energy than it receives? A fluid power system (like any other power system) cannot create energy. This is in accordance with the conservation of energy law presented in Section 3.6. To answer this question, let's analyze the hydraulic jack illustrated in Figure 3-7.

As shown, a downward input force F_1 is applied to the small-diameter piston 1, which has an area A_1. This produces an oil pressure p_1 at the bottom of piston 1. This pressure is transmitted through the oil to the large-diameter piston 2, which has an area A_2. The pressure p_2 at piston 2 pushes up on the piston to create an output force F_2.

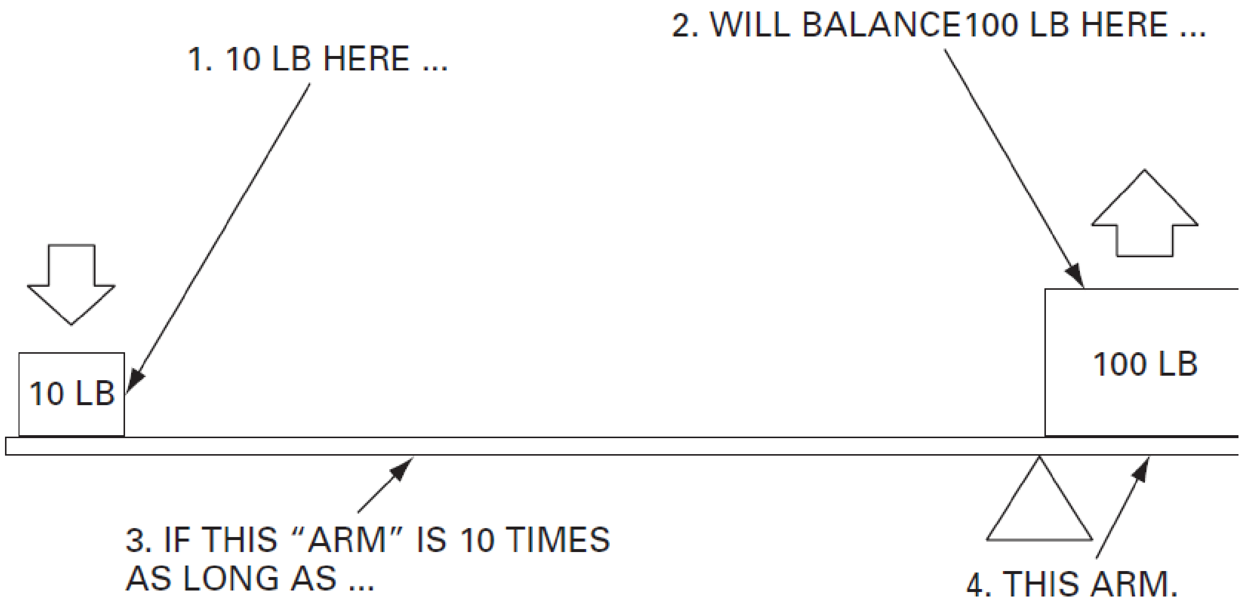
By Pascal's law, $p_1 = p_2$. Since pressure equals force divided by area, we have

$$\frac{F_1}{A_1} = \frac{F_2}{A_2}$$

REVIEW OF MECHANICS



(a) SIMPLE HYDRAULIC JACK



(b) MECHANICAL LEVER SYSTEM

REVIEW OF MECHANICS

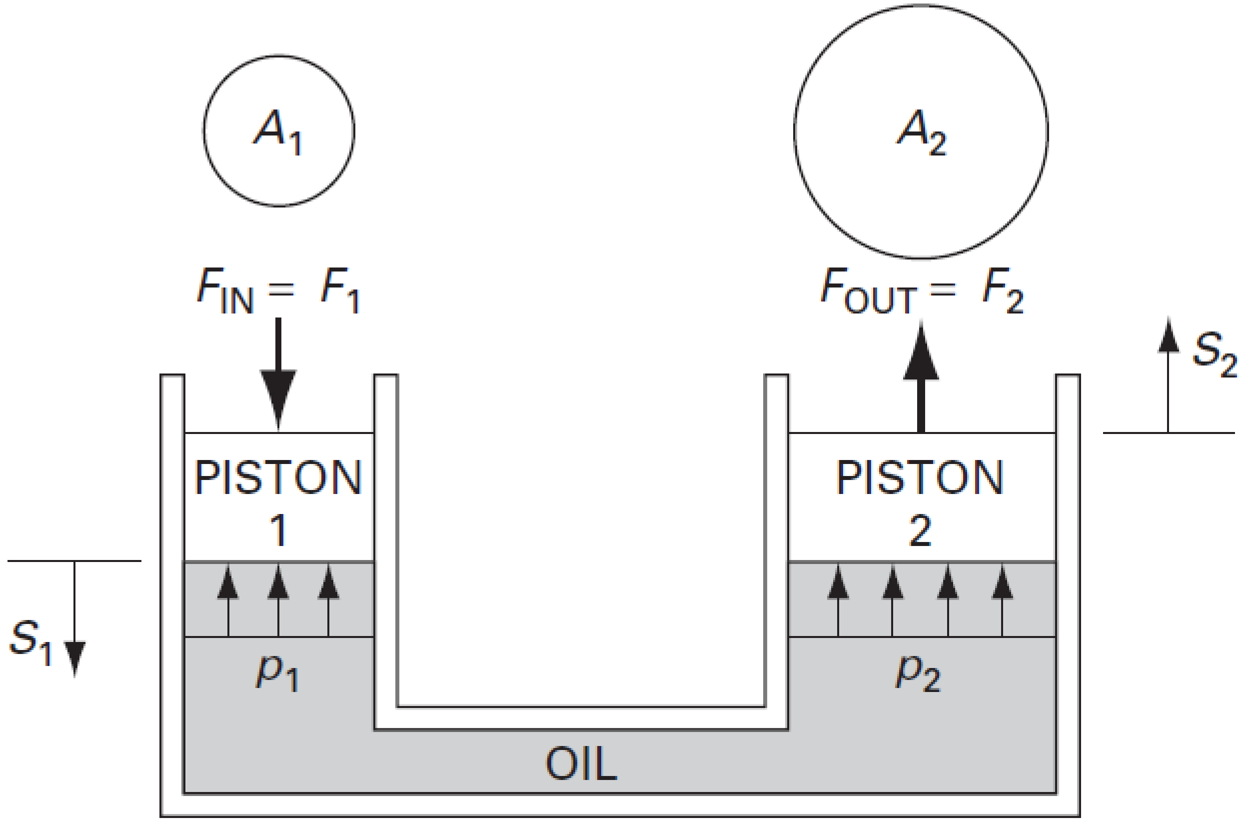


Figure 3-7. Operation of simple hydraulic jack.

cylindrical volume of oil displaced by the input piston equals the cylindrical volume displaced by the output piston:

$$V_1 = V_2$$

Since the volume of a cylinder equals the product of its cross-sectional area and its height we have

$$A_1S_1 = A_2S_2$$

where S_1 = the downward movement of piston 1,
S_2 = the upward movement of piston 2.

Thus,

$$\frac{S_2}{S_1} = \frac{A_1}{A_2} \qquad \textbf{(3-10)}$$

REVIEW OF MECHANICS

EXAMPLE 3-4

For the hydraulic jack of Figure 3-7, the following data are given:

$$A_1 = 2 \text{ in}^2 \quad A_2 = 20 \text{ in}^2$$

$$S_1 = 1 \text{ in}$$

$$F_1 = 100 \text{ lb}$$

Determine each of the following.

- **a.** F_2
- **b.** S_2
- **c.** The energy input
- **d.** The energy output

Solution

a. From Eq. (3-9) we have

$$F_2 = \frac{A_2}{A_1} \times F_1 = \frac{20}{2} \times 100 = 1000 \text{ lb}$$

REVIEW OF MECHANICS

b. From Eq. (3-10) we have

$$S_2 = \frac{A_1}{A_2} \times S_1 = \frac{2}{20} \times 1 = 0.1 \text{ in}$$

c. Energy input $= F_1S_1 = (100 \text{ lb}) \times (1 \text{ in}) = 100 \text{ in} \cdot \text{lb}$

d. Energy output $= F_2S_2 = (1000 \text{ lb}) \times (0.1 \text{ in}) = 100 \text{ in} \cdot \text{lb}$

REVIEW OF MECHANICS

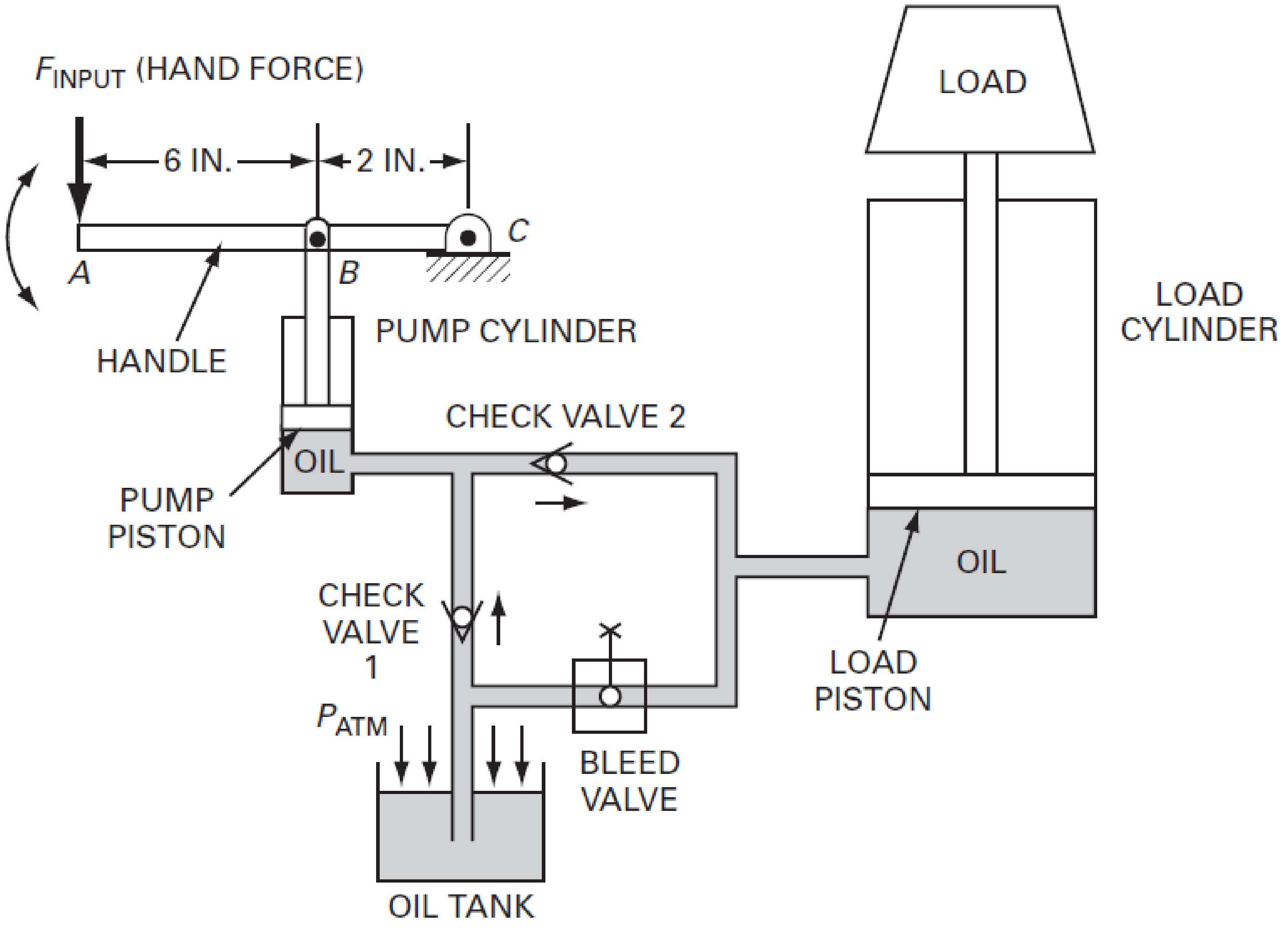


Figure 3-8. Hand-operated hydraulic jack.

REVIEW OF MECHANICS

EXAMPLE 3-5

An operator makes one complete cycle per second interval using the hydraulic jack of Figure 3-8. Each complete cycle consists of two pump cylinder strokes (intake and power). The pump cylinder has a 1-in-diameter piston and the load cylinder has a 3.25-in-diameter piston. If the average hand force is 25 lb during the power stroke,

a. How much load can be lifted?

b. How many cycles are required to lift the load 10 in assuming no oil leakage? The pump piston has a 2-in stroke.

c. What is the output HP assuming 100% efficiency?

d. What is the output HP assuming 80% efficiency?

REVIEW OF MECHANICS

Solution

a. First determine the force acting on the rod of the pump cylinder due to the mechanical advantage of the input handle:

$$F_{\text{rod}} = \frac{8}{2} \times F_{\text{input}} = \frac{8}{2}(25) = 100 \text{ lb}$$

Next, calculate the pump cylinder discharge pressure p:

$$p = \frac{\text{rod force}}{\text{piston area}} = \frac{F_{\text{rod}}}{A_{\text{pump piston}}} = \frac{100 \text{ lb}}{(\pi/4)(1)^2 \text{in}^2} = 127 \text{ psi}$$

Per Pascal's law this is also the same pressure acting on the load piston. We can now calculate the load-carrying capacity:

$$F_{\text{load}} = pA_{\text{load piston}} = (127)\text{lb/in}^2\left[\frac{\pi}{4}(3.25)^2\right]\text{in}^2 = 1055 \text{ lb}$$

REVIEW OF MECHANICS

Solution

a. First determine the force acting on the rod of the pump cylinder due to the mechanical advantage of the input handle:

$$F_{\text{rod}} = \frac{8}{2} \times F_{\text{input}} = \frac{8}{2}(25) = 100 \text{ lb}$$

Next, calculate the pump cylinder discharge pressure p:

$$p = \frac{\text{rod force}}{\text{piston area}} = \frac{F_{\text{rod}}}{A_{\text{pump piston}}} = \frac{100 \text{ lb}}{(\pi/4)(1)^2 \text{in}^2} = 127 \text{ psi}$$

Per Pascal's law this is also the same pressure acting on the load piston. We can now calculate the load-carrying capacity:

$$F_{\text{load}} = pA_{\text{load piston}} = (127)\text{lb/in}^2\left[\frac{\pi}{4}(3.25)^2\right]\text{in}^2 = 1055 \text{ lb}$$

REVIEW OF MECHANICS

b. To find the load displacement, assume the oil to be incompressible. Therefore, the total volume of oil ejected from the pump cylinder equals the volume of oil displacing the load cylinder:

$$(A \times S)_{\text{pump piston}} \times (\text{no. of cycles}) = (A \times S)_{\text{load piston}}$$

Substituting, we have

$$\frac{\pi}{4}(1)^2 \text{in}^2 \times 2 \text{ in} \times (\text{no. of cycles}) = \frac{\pi}{4}(3.25)^2 \text{ in}^2 \times 10 \text{ in}$$

$$1.57 \text{ in}^3 \times (\text{no. of cycles}) = 82.7 \text{ in}^3$$

$$\text{no. of cycles} = 52.7$$

REVIEW OF MECHANICS

c.

$$\text{Power} = \frac{FS}{t} = \frac{(1055\ \text{lb})\left(\frac{10}{12}\ \text{ft}\right)}{52.7\ \text{s}} = 16.7\ \text{ft} \cdot \text{lb/s}$$

$$\text{HP} = \frac{16.7}{550} = 0.030\ \text{hp}$$

The HP output value is small, as expected, since the power comes from a human being.

d.

$$\text{HP} = (0.80)(0.03) = 0.024\ \text{hp}$$

REVIEW OF MECHANICS

Air-to-Hydraulic Pressure Booster

This device is used for converting shop air into the higher hydraulic pressure needed for operating hydraulic cylinders requiring small to medium volumes of higher-pressure oil. It consists of a cylinder containing a large-diameter air piston driving a small-diameter hydraulic piston, which is actually a long rod connected to the piston (see Figure 3-11). Any shop equipped with an air line can obtain smooth, efficient hydraulic power from an air-to-hydraulic pressure booster hooked into the air line. The alternative would be a complete hydraulic system including expensive pumps and high-pressure valves. Other benefits include a space savings and a reduction in operating costs and maintenance.

REVIEW OF MECHANICS

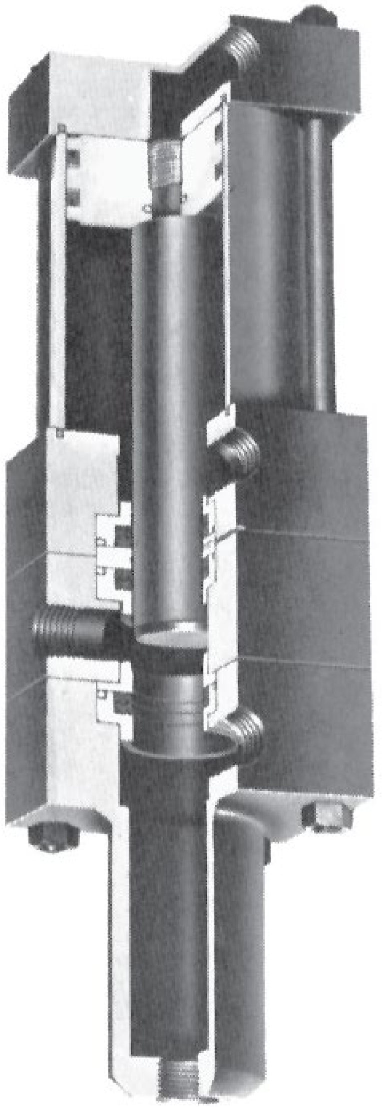


Figure 3-11. Cutaway view of an air-to-hydraulic pressure booster. *(Courtesy of the S-P Manufacturing Corp., Cleveland, Ohio.)*

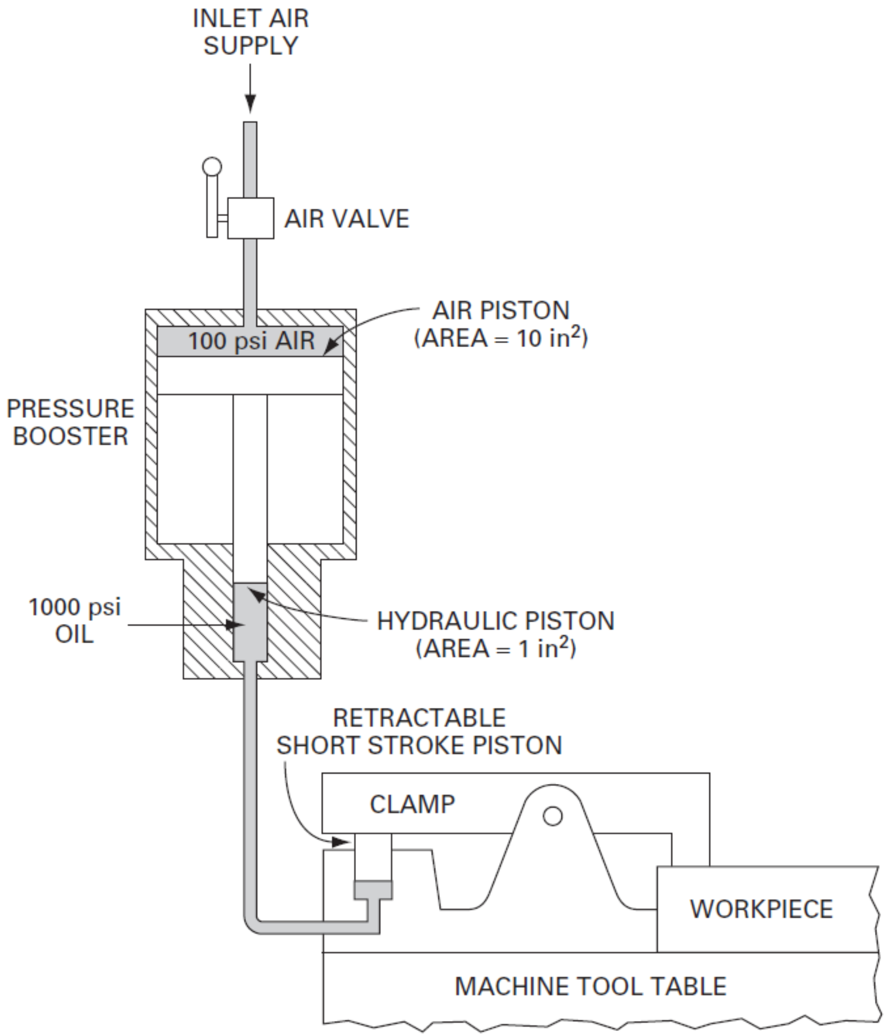


Figure 3-12. Manufacturing application of air-to-hydraulic pressure booster.

REVIEW OF MECHANICS

The air-to-hydraulic pressure booster operates as follows (see Figure 3-12): Let's assume that the air piston has a 10-in^2 area and is subjected to 100-psi air pressure. This produces a 1000-lb force on the booster's hydraulic piston. Thus, if the area of the booster's hydraulic piston is 1 in^2, the hydraulic discharge oil pressure will be 1000 psi. Per Pascal's law, this produces 1000-psi oil at the short stroke piston of the hydraulic clamping cylinder mounted on the machine tool table.

The pressure ratio of an air-to-hydraulic pressure booster can be found by using Eq. (3-12).

$$\text{pressure ratio} = \frac{\text{output oil pressure}}{\text{input air pressure}} = \frac{\text{area of air piston}}{\text{area of hydraulic piston}} \qquad \textbf{(3-12)}$$

Air-to-hydraulic pressure boosters are available in a wide range of pressure ratios and can provide hydraulic pressures up to 15,000 psi using 100-psi shop air.

REVIEW OF MECHANICS

EXAMPLE 3-6

Figure 3-13 shows a pressure booster used to drive a load F via a hydraulic cylinder. The following data are given:

$$\text{inlet air pressure } (p_1) = 100 \text{ psi}$$

$$\text{air piston area } (A_1) = 20 \text{ in}^2$$

$$\text{oil piston area } (A_2) = 1 \text{ in}^2$$

$$\text{load piston area } (A_3) = 25 \text{ in}^2 \text{ (diameter} = 5.64 \text{ in)}$$

Find the load-carrying capacity F of the system.

Solution First, find the booster discharge pressure p_2:

$$\text{booster input force} = \text{booster output force}$$

$$p_1 A_1 = p_2 A_2$$

$$p_2 = \frac{p_1 A_1}{A_2} = (100)\left(\frac{20}{1}\right) = 2000 \text{ psi}$$

REVIEW OF MECHANICS

Example 3-6

Figure 3-13 shows a pressure booster used to drive a load F via a hydraulic cylinder. The following data are given:

$$\text{inlet air pressure } (p_1) = 100 \text{ psi}$$

$$\text{air piston area } (A_1) = 20 \text{ in}^2$$

$$\text{oil piston area } (A_2) = 1 \text{ in}^2$$

$$\text{load piston area } (A_3) = 25 \text{ in}^2 \text{ (diameter} = 5.64 \text{ in)}$$

Find the load-carrying capacity F of the system.

Solution First, find the booster discharge pressure p_2:

$$\text{booster input force} = \text{booster output force}$$

$$p_1 A_1 = p_2 A_2$$

$$p_2 = \frac{p_1 A_1}{A_2} = (100)\left(\frac{20}{1}\right) = 2000 \text{ psi}$$

REVIEW OF MECHANICS

Per Pascal's law, $p_3 = p_2 = 2000$ psi:

$$F = p_3 A_3 = (2000)(25) = 50{,}000 \text{ lb}$$

To produce this force without the booster would require a 500-in^2-area load piston (diameter = 25.2 in), assuming 100-psi air pressure.

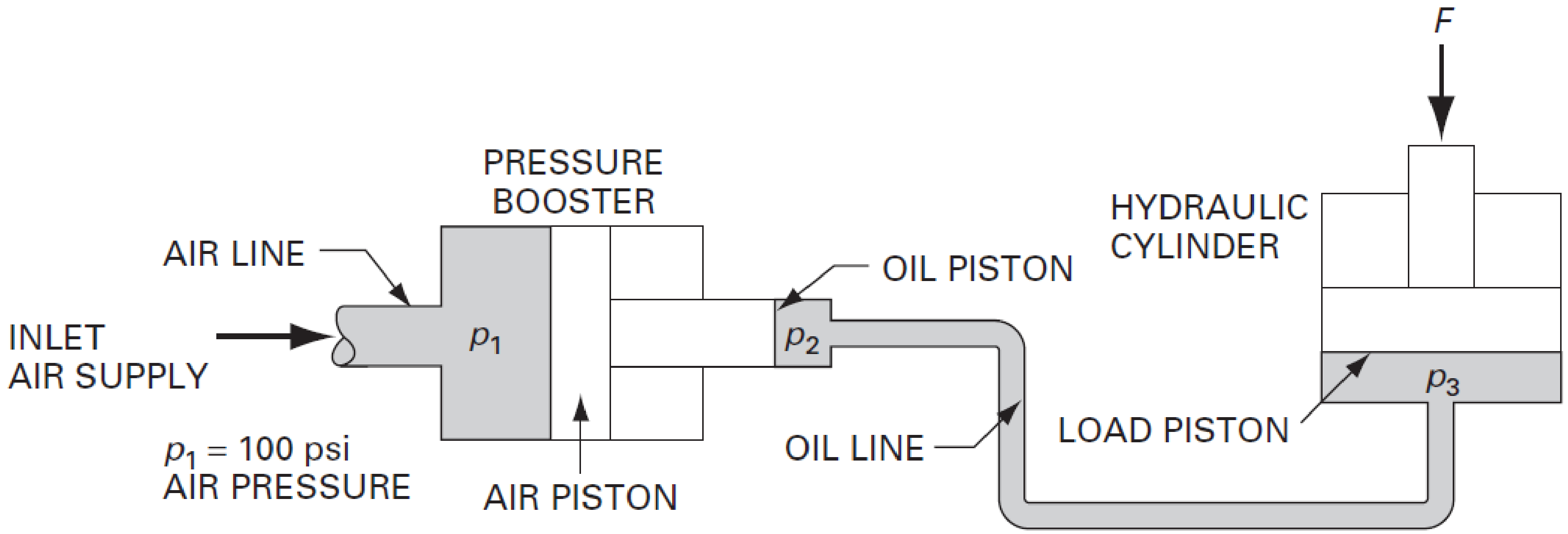


Figure 3-13. An air-to-hydraulic pressure booster system.

REVIEW OF MECHANICS

3.6 CONSERVATION OF ENERGY

The conservation of energy law states that energy can be neither created nor destroyed. This means that the total energy of a system remains constant. The total energy includes potential energy due to elevation and pressure and also kinetic energy due to velocity. Let's examine each of the three types of energy.

1. **Potential energy due to elevation (EPE):** Figure 3-22 shows a chunk of fluid of weight W lb at an elevation Z with respect to a reference plane. The weight has potential energy (EPE) relative to the reference plane because work would have to be done on the fluid to lift it through a distance Z:

$$\text{EPE} = \text{WZ} \tag{3-13}$$

The units of EPE are ft · lb.

REVIEW OF MECHANICS

2. Potential energy due to pressure (PPE): If the W lb of fluid in Figure 3-22 possesses a pressure p, it contains pressure energy as represented by

$$\mathrm{PPE} = W\frac{p}{\gamma} \tag{3-14}$$

where γ is the specific weight of the fluid. PPE has units of ft · lb.

3. Kinetic energy (KE): If the W lb of fluid in Figure 3-22 is moving with a velocity υ, it contains kinetic energy, which can be found using

$$\mathrm{KE} = \frac{1}{2}\frac{W}{g}\upsilon^2 \tag{3-15}$$

where g = acceleration of gravity.

KE has units of ft · lb.

REVIEW OF MECHANICS

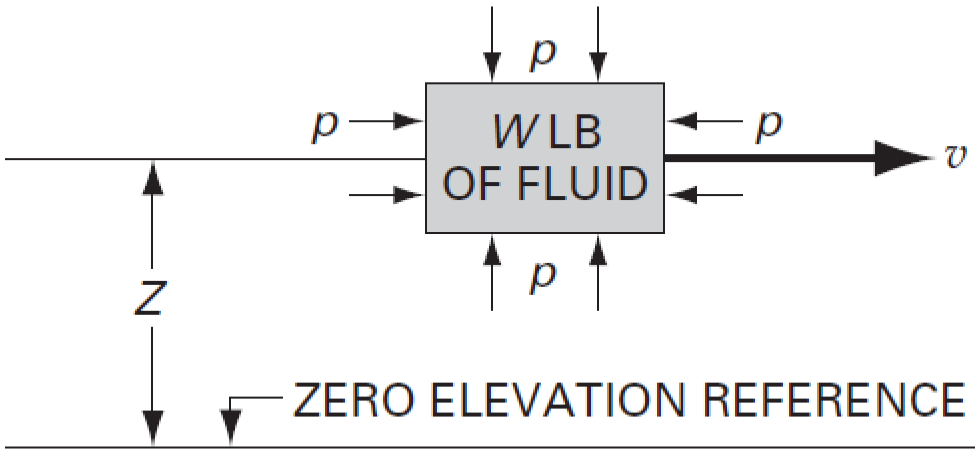


Figure 3-22. The three forms of energy as established by elevation (Z), pressure (p), and velocity (υ).

Per the conservation of energy law we can make the following statement about the W-lb chunk fluid in Figure 3-22: The total energy E_T possessed by the W-lb chunk of fluid remains constant (unless energy is added to the fluid via pumps or removed from the fluid via hydraulic motors or friction) as the W-lb chunk flows through a pipeline of a hydraulic system. Mathematically we have

$$E_T = WZ + W\frac{p}{\gamma} + \frac{1}{2}\frac{W}{g}\upsilon^2 = \text{constant} \tag{3-16}$$