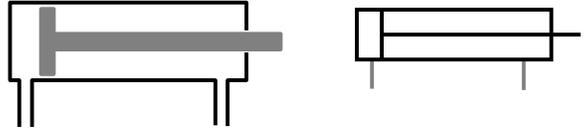


# Energy, Power, Pumps

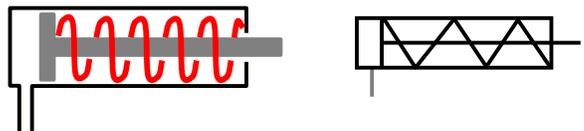
## Diagrams for Lab Reports

We're going to talk about cylinders, valves, pumps, etc. later in the course. You'll be turning in lab reports before we get to all that, so here's some basic information you need to draw the circuit diagrams for the first lab report.

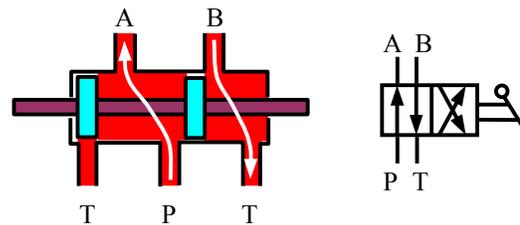
On the hydraulic stand, we use a cylinder that has ports on both ends. When hydraulic fluid flows into the left end of the cylinder, the piston & rod move to the right. That means the fluid on the right side of the cylinder has to flow out...through the port on the right. The symbol of this cylinder also shows two ports.



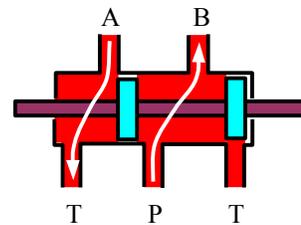
On the pneumatic stand, we use a cylinder that has one inlet port and a spring return. When air flows into the cylinder, the rod extends. When the air pressure is released, a spring returns the rod to its original position. The symbol of this cylinder shows one port, and a zigzag line represents the internal spring.



This is a four-way directional control valve. It's called 4-way because there are 4 ports: A, B, P (pressure), and T (tank). Even though there are two tank ports shown on the valve cut-away, they're connected, and only count as one.



A shaft runs through the valve (purple). The light blue shapes are cylindrical pistons with seals that prevent leakage between different parts of the valve. When the spool is all the way to the left, fluid flows from port P to port A, and then on to whatever the valve is controlling...a cylinder, a motor, another valve, etc. Exhaust fluid from the system flows through port B to port T.

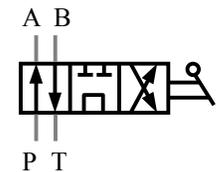


If we shift the spool to the right, then the flow is reversed.

The symbol for this valve shows the four ports, the alternative spool position, and a handle.

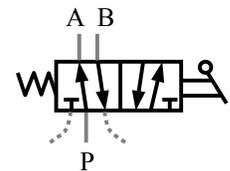
The valve we use in the hydraulic experiment in Lab #1 has a center position. In this neutral position, hydraulic fluid from the pump is returned to tank, so the pump is not working hard. This is a 4-way (4 ports), 3-position directional control valve.

4-way, 3-position, manual control, hydraulic directional control valve



The valve we use in the pneumatic experiment in Lab #1 has no center position. It has a manual control handle, but it also has a spring return. That's the squiggly line on the left side of the valve symbol. With pneumatic valves, since the exhaust ports are visible from the outside, we show all ports. This is a four-way (4 ports), 2-position, spring-returned, directional control valve.

4-way, 2-position, spring-return, pneumatic directional control valve



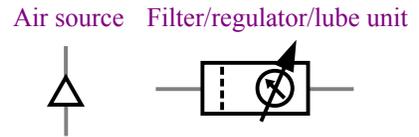
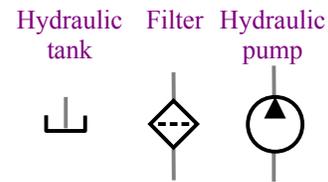
We use a few other symbols in Lab #1. The tank symbol can appear more than once on a diagram...it's understood that all the tank symbols represent the same tank (like the ground symbols in DC electrical diagrams). We draw fluid out of the tank, through the filter and pump, and into the system. We also drain actuators and valves into the tank.

The filter symbol is a diamond with a dotted line, representing the screen or filter element.

The pump symbol is a circle with a darkened triangle that points in the direction of flow.

In a pneumatic system, we don't have to draw the compressor and compressed air tank, because they're usually remote from the actual pneumatic machine. Instead, we use an open triangle to indicate a compressed air line, and the triangle's point indicates the direction of flow.

Since air is not a good lubricant, we have to add oil. We also have to screen out any dirt in the line, and we want to regulate the pressure, because line pressure may be too high for the equipment, so we draw a combination filter/lube/regulator symbol. The object of the lab is to connect these symbols to make a circuit that someone else could read, and build a copy of your circuit to make a fluid power system.



## Energy & Power

### Conservation of energy

The Law of Conservation of Energy states that different kinds of energy are equivalent. Some examples include:

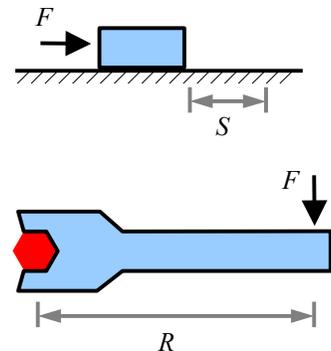
- **Mechanical energy.** The sum of potential energy and kinetic energy.
- **Electromagnetic energy.** Includes magnetic energy and radiant energy (light, in all wavelengths).
- **Thermal energy.** The portion of the energy of an object that results in temperature.
- **Nuclear energy.** Energy released when subatomic particles react.
- **Chemical energy.** Energy released when atoms or molecules react.

The fields of mechanical engineering technology and mechanical engineering are essentially about transforming one type of energy into another to do useful work. Think about a car: chemical energy in liquid fuel is transformed into thermal energy when the fuel ignites, creating mechanical energy in the piston, which is transferred as mechanical energy to the drivetrain and tires, moving the car forward. When a conventional car brakes, mechanical energy is transformed into heat energy as the brake discs or drums heat up. The heat is dissipated into the atmosphere. When a hybrid-electric vehicle brakes, some of the mechanical energy is transformed into electrical energy and sent to the battery, where it is transformed into chemical energy. On start-up, chemical energy is transformed back into electrical energy, starting the electric motors and transforming into mechanical energy.

### Work

The First Law of Thermodynamics, in its simplest form, states "Heat = Work", which, from the Law of Conservation of Energy, is a form of mechanical energy. Work is force times the distance it acts through:  $W = F \cdot S$ . Units of work are in.ilb., ft.ilb., Nim, or J (where 1 J = 1 Nim).

If we have linear motion, then work equals the force times the linear distance it acts through. If we have rotary motion, then work equals the force times the lever arm it acts through:  $W = F \cdot R$ . We call this kind of work *torque*. So when you torque up a bolt, you're performing some work.



## Power

Power is the rate of doing work...it's how fast we're doing the job:  $P = \frac{F \cdot S}{t}$ , where  $P$  is power and  $t$  is time. The first person to define power in this way was James Watt. In 1806, he defined 1 hp = 550 ft.lb./s. Other units of power are in.lb./s, ft.lb./s, and of course, W (defined as 1 W = 1 J/s = 1 Nm/s).

For rotary motion, power equals the torque times the rotational speed:  $P = T \cdot N$ . In the book, the equation is given as

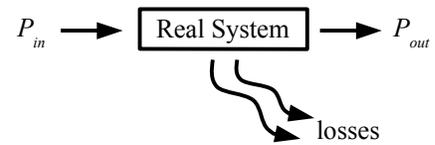
$$P = \frac{T \cdot N}{63,000}$$

with torque in in.lb., rotational speed in rpm, and power in hp. I don't like equations to be written this way,

because if the units are not clearly spelled out, you can calculate the wrong result. The previous equations work in any unit system, but once you throw a constant in, you're in trouble.

## Efficiency

In any real system, some losses occur. We use the Greek letter eta to measure efficiency:  $\eta = \frac{\text{Output power}}{\text{Input power}}$ . If  $\eta=1$  (or 100%), then you get everything out that you put in, the system has no losses, and you've invented perpetual motion.



In a fluid power system, losses include mechanical friction between solid parts, fluid friction, leaks, and heat. The definition of efficiency in the cartoon is *power efficiency*. We can also measure the efficiency of other things...

- **Volume.** The volumetric efficiency of a pump is the flow rate produced divided by the flow rate that it theoretically could produce, if there were no internal or external leaks.
- **Energy.** The energy delivered to the wheels of a car divided by chemical energy in a gallon of gasoline is about 20%...a little better for diesel.
- **Studying.** Divide grades by study time, and you've got the efficiency of a student.
- **Money.** ROI is a measure of the efficiency of money invested in a business. Divide profit by investment, and you get Return on Investment.

## Pascal's Law

In 1652, Blaise Pascal found that an incompressible fluid transmits pressure in all directions, and the pressure acts perpendicularly to the walls of the vessel. In the cartoon, push down on piston #1 with force  $F_1$ , and you generate pressure  $p_1$ . At the other end, pressure  $p_2$  pushes on piston #2 to generate force  $F_2$ .

What Pascal said is that both pressures  $p_1$  and  $p_2$  are the same. Since

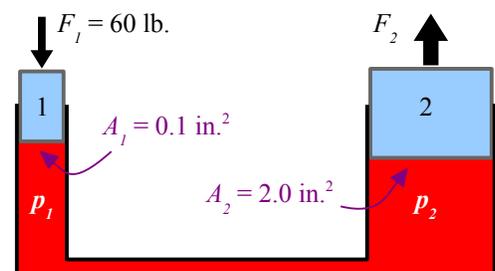
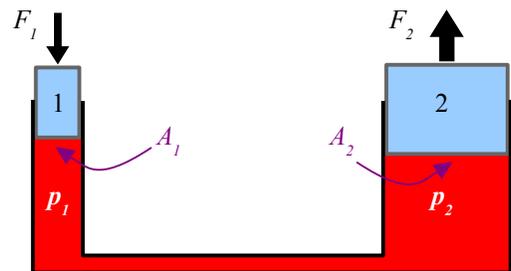
$$p = \frac{F}{A}, \text{ we can write } \frac{F_1}{A_1} = \frac{F_2}{A_2}.$$

Calculate the output force  $F_2$  based on

the areas of the pistons and the input force:  $F_2 = F_1 \frac{A_2}{A_1}$ .

Pascal's Law applies as long as the fluid is not moving (or moving very slowly), and as long as the elevation is the same (the weight of the fluid is insignificant).

For example, let  $A_1 = 0.1 \text{ in.}^2$ ,  $A_2 = 2.0 \text{ in.}^2$ , and  $F_1 = 60 \text{ lb.}$ . The resulting force in piston #2 is  $F_2 = F_1 \frac{A_2}{A_1} = 60 \text{ lb.} \frac{2 \text{ in.}^2}{0.1 \text{ in.}^2} = 1200 \text{ lb.}$  This is the advantage of hydraulic power...you can get tremendous increases in force with two moving parts that are self-lubricated. By selecting two different size cylinders, we increased the force by a factor of 20.



How far does the piston travel? The volume of oil displaced by piston #1 equals the volume of oil displaced by piston #2. A cylindrical volume is the cross sectional area times the distance traveled, so  $V = A \cdot S$  and  $A_1 \cdot S_1 = A_2 \cdot S_2$ .

We can write an algebraic equation for the distance traveled by

piston #2:  $S_2 = S_1 \frac{A_1}{A_2}$ . For example, let  $A_1 = 0.1 \text{ in.}^2$ ,

$A_2 = 2.0 \text{ in.}^2$ , and  $S_1 = 1 \text{ in.}$ . The resulting stroke for piston #2 is  $S_2 = S_1 \frac{A_1}{A_2} = 1 \text{ in.} \frac{0.1 \text{ in.}^2}{2.0 \text{ in.}^2} = 0.050 \text{ in.}$

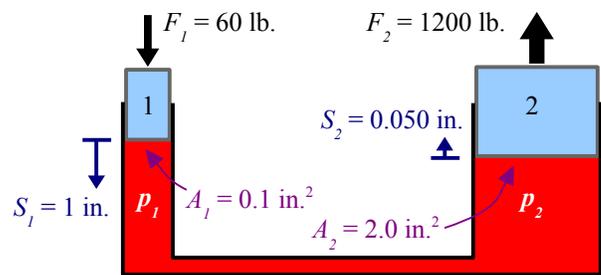
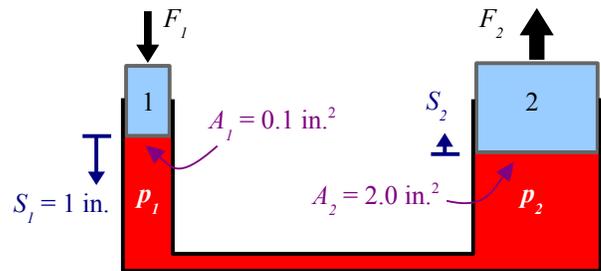
We get a lot of force out of piston #2, but not much stroke. This is a design issue: if piston #1 is too big, then you don't get enough *force* out of piston #2. If piston #1 is too small, then you don't get enough *stroke* out of piston #2. The job of the engineer is to find the happy medium.

How much *work* goes into this hydraulic system? Using the input data,  $W_{in} = F_1 \cdot S_1 = 60 \text{ lb.} \cdot 1 \text{ in.} = 60 \text{ ft.} \cdot \text{lb.}$

Alternatively, you can calculate work from the output data:

$W_{out} = F_2 \cdot S_2 = 1200 \text{ lb.} \cdot 0.050 \text{ in.} = 60 \text{ ft.} \cdot \text{lb.}$

If the system is 100% efficient (no leaks, no heat generated), then  $W_{in} = W_{out}$ .



How much power is consumed by this hydraulic system? Power is the time rate of doing work. Let's say the 1 inch input stroke takes 1 second. Power  $P = \frac{F \cdot S}{t} = \frac{W}{t} = \frac{60 \text{ in.} \cdot \text{lb.}}{1 \text{ s}} \left| \frac{\text{ft.}}{12 \text{ in.}} \right| \frac{\text{hp}}{550 \text{ ft.} \cdot \text{lb.}} = 0.0091 \text{ hp}$ . The gasoline engine of a small car has 10,000 times the power of this hydraulic system.

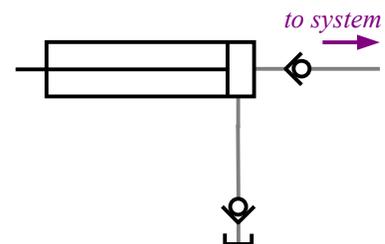
How efficient is this system? Let's say we run an experiment and find  $P_{out} = 0.008 \text{ hp}$ , which is less than  $P_{in}$  because of frictional losses and leakage. The efficiency is  $\eta = \frac{P_{out}}{P_{in}} = \frac{0.008 \text{ hp}}{0.0091 \text{ hp}} = 0.88 = 88\%$ .

### Hydraulic Pumps

Hydraulic pumps are categorized as either *dynamic* or *positive displacement*. Dynamic pumps are used to move fluid from one place to another, where there isn't much pressure. Examples include a squirrel-cage fan (bathroom exhaust fan) a propeller (ceiling fan), or an impeller (automotive water pump). We don't use dynamic pumps in pressurized hydraulic systems.

The second category of hydraulic pumps is *positive displacement* pumps. The simplest type of positive displacement pump can be made with a piston, a cylinder, and a pair of check valves. When the piston moves to the left, it sucks fluid out of the tank. The upper check valve prevents fluid from leaking back into the cylinder from the hydraulic system downstream. When the piston moves to the right, it pushes fluid into the hydraulic system through the upper check valve. The lower check valve prevents fluid from going back into the tank.

We call it a *positive displacement* because the amount of fluid that's pumped is fixed for every stroke.



In practice, most positive displacement pumps are rotary, not linear, so the amount of fluid that's pumped is constant for every rotation of the pump shaft.

## External Gear Pump

An *external* gear has teeth on the outside (what most of us call a gear). An external gear pump uses a pair of external gears, which pump fluid between the moving gear teeth and the housing. One example is the oil pump on an automobile engine. It actually produces more pressure than the lubrication system needs, so the excess pressure is bled off through a pressure relief valve. Sometimes, when an oil filter on a car explodes, it's because the pressure relief valve in the engine failed.

Efficiency losses occur as a result of leakage past the gears, leakage around the shaft seals (input power has to come from outside the pump housing), and frictional heat.

## Lobe Pump

A lobe pump works like an external gear pump, but instead of gears, we have interlocking cams. It's got a higher displacement because each of the two gears has only three "teeth", and there's a lot more fluid moving for each tooth. This type of pump is useful if there are contaminants in the fluid, because particles won't get stuck between small teeth. Pressure capacity is pretty low compared with other hydraulic pumps, and the flow tends to pulsate. This pump is also useful if there are bubbles in the fluid, or if the fluid is sensitive to shear (might break down...)

## Internal Gear Pump

The teeth of an external gear mesh with the internal teeth of a larger gear. Pumping chambers are formed between the gear teeth. The crescent-shaped seal is machined into the pump body, sealing between the inlet and outlet ports.

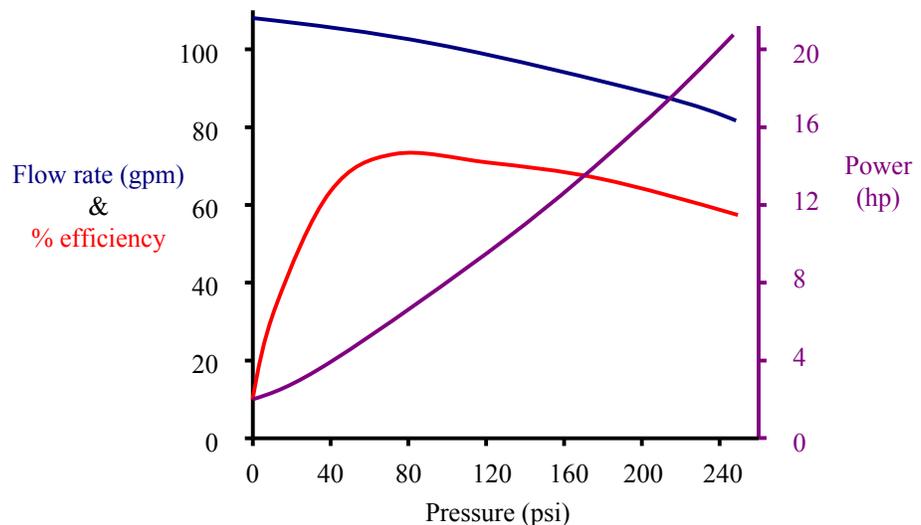
## Gerotor Pump

An external gear rotates at the center, turning a larger internal gear. The external gear has one less tooth than the internal gear, so the internal gear rotates slower. As the oil enters on the right, spaces between the rotating teeth increase. During the second half of each turn, spaces between the rotating teeth decrease, which forces the fluid out through the discharge port on the left.

## Vane Pump

Vanes are fitted into slots in the rotor. Once the pump gets up to about 600 rpm, centrifugal forces pushes the vanes out to the housing, and you get a good seal. Pumping chambers are formed between the vanes, rotor, and housing. One advantage of this type of pump is that there's almost no load on the motor when it first starts up, so you don't have to add a pump unloading circuit, and you could use a smaller motor. In this sense, it combines the advantages of a dynamic pump at low speeds with the advantages of a positive displacement pump at high speeds.

Why do we need different kinds of pumps? Because they have different performance. The graph shows a set of performance curves for a rotary pump. The flow rate at the lowest power usage is about 110 gpm. This pump runs at its maximum efficiency at around 100 gpm, producing a pressure of around 80 psi, consuming about 8 hp. If you need a pump that's efficient at a different pressure or flow rate, you may need a different type of pump.



*Dr. Barry Dupen, Indiana University-Purdue University Fort Wayne. Revised May 2014. This document was created with Apache Software Foundation's OpenOffice software v.4.1.0.*

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