# Introduction to Fluid Power

## What is Fluid Power?

*Fluid Power* is the application of pressurized oil (hydraulics) or compressed air (pneumatics) to do useful work.
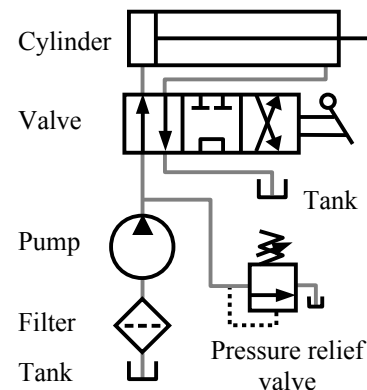
The textbook for this course is *Fluid Power with Applications*. We're going to skip around the book, because in the lab we'll be doing both hydraulic and pneumatic experiments. The textbook covers hydraulics first, then pneumatics later.

Consider the title of the textbook.

- **Fluid:** A liquid or gas. In this course, we'll focus on hydraulic oil and air.
- **Power:** We use a fluid to transmit power from one place to another, or we use a fluid to control something. We transmit electrical power through power lines because it's more efficient than shipping batteries long distances. We transmit mechanical power with connecting rods, cams, gears, bicycle chains, cables (San Francisco cable cars…cables move under the street). We transmit power with fluids to produce linear motion (cylinders) or rotary motion (fluid motors).
- **Applications:** In this class you'll learn useful applications of fluid power...how to design fluid power systems that perform useful work. Application examples from the automotive world include power steering, hydraulic brakes, hydraulic clutch control, and air brakes.

One of the useful things we're going to learn in this class is how to read circuit diagrams, and how to create them. For example, in this circuit diagram, hydraulic fluid is sucked out of a tank and through a filter, to the pump, which pushes it through a directional control valve and into the cap end of a cylinder. The fluid pushes the piston in the cylinder, which pushes the fluid on the rod end of the cylinder through the control valve and back into the tank.

We'll build fluid power circuits in the lab, using a hydraulic test stand and a pneumatic test stand. You'll work together in the lab, and submit individual lab reports. It's okay to discuss your report with other students, but *do not copy other people's work*. Your text, graphs, and circuit diagrams must be your own work.

## Hydraulic Power

Hydraulic power was developed in the 19th century, using water as the working fluid. Water is cheap and widely available, but it can boil or freeze and will corrode many metals. Also, water tends to leak past seals, and does not provide good lubrication between moving metal parts. To avoid these problems, most hydraulic systems today use hydraulic oil. Advantages and disadvantages of hydraulic power include:

- **High pressures and loads**. Since hydraulic oil is almost incompressible, you can raise the pressure without danger of explosion. This is the reason backhoes operate with hydraulic power, not compressed air.
- **Accurate positioning.** Hydraulic oil is nearly incompressible, so you can control the position of a hydraulic implement very closely.
- **Little backlash**. In a mechanical system, *backlash* (also called *lash* or *play*) is clearance between moving parts due to gaps, for example: the gaps between teeth in a gear system. When you reverse motion, the gear teeth are not immediately in contact. Hydraulic systems have very little backlash, so control is much better.
- **Internal lubrication**. Hydraulic oil is a good lubricant, so internal parts are lubricated at all times.
- **Leakage**. If hydraulic fluid leaks, consequences included reduced efficiency, reduced output power, and environmental cleanup.
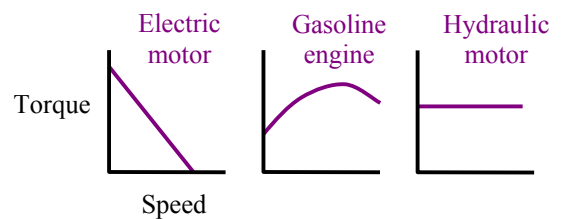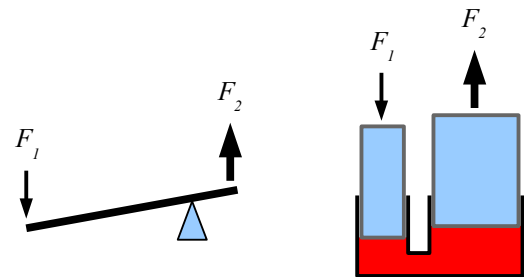
## Pneumatic Power

Pneumatic power normally uses air as a working fluid because it is cheaper than other gases. Advantages and disadvantages of pneumatic power include:

- **Low cost**. Since air is available almost everywhere we would use pneumatics, the working fluid is free.
- **Exhausts to atmosphere.** No return lines are needed; a pneumatic system has only one set of hoses or pipes to deliver compressed air.
- **Too compressible for accurate positioning**. Compressed air tries to expand...it acts like a compressed spring...which makes positioning difficult.
- **Must add lubrication**. Unless the pneumatic actuators are self-lubricated, you must add oil to a compressed air system within about 20 line feet of the actuators.
- **Normally limited to 250 psi**. Pressures above 250 psi are an explosion hazard, therefore pneumatic systems under higher pressures are rare. One example is the catapult on an aircraft carrier.
- **Lighter actuators**. Because the pressures are relatively low, you can use thinner walls and lighter materials such as aluminum.

## Reasons for Using Fluid Power

We use Fluid Power for several reasons:

- **Control.** Fluid power systems are easy to control, using valves to direct the flow.
- **Force multiplication**. We can multiply the force by using different size cylinders. A mechanical lever arm multiplies force proportional to the length of the lever…think about a see-saw. A pulley system multiplies force by using multiple pulleys (and lots of cable). A fluid power system multiplies force proportional to the difference in piston diameters.
- **Fewer parts**. There aren't as many parts to break as there are in electrical or mechanical systems…saves on maintenance costs and reduces spare part inventories.
- **More power per unit weight**. You get more power per pound compared with electrical and mechanical power systems. This one of the reasons why hydraulic systems are used to move control surfaces on aircraft. If there was a lighter, reliable alternative, then aircraft wouldn't use hydraulics.
- **Constant force**. We can get a constant force, regardless of speed changes…force is proportional to the fluid pressure, not the speed. With a hydraulic motor, we get a constant torque, regardless of speed changes.
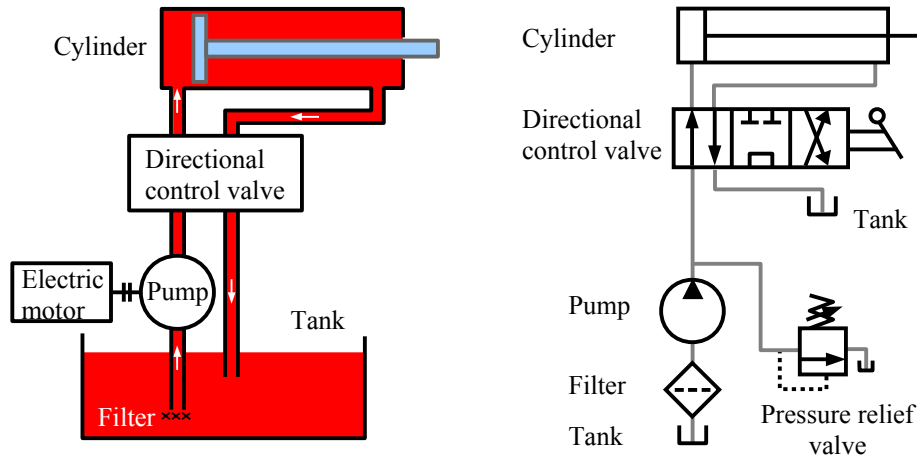
## Fluid Power Diagrams

### Hydraulic Diagrams

Every hydraulic system has a similar set of components: hydraulic fluid; a tank to contain it; a filter or screen to remove particles from the oil; a pump to pressurize the fluid; an electric motor to run the pump; valves to control pressure, direction, and flow rate of fluid; actuators to convert pressure to useful motion (linear or rotary); and piping to carry pressurized oil to actuators, and return back to tank (zero pressure).
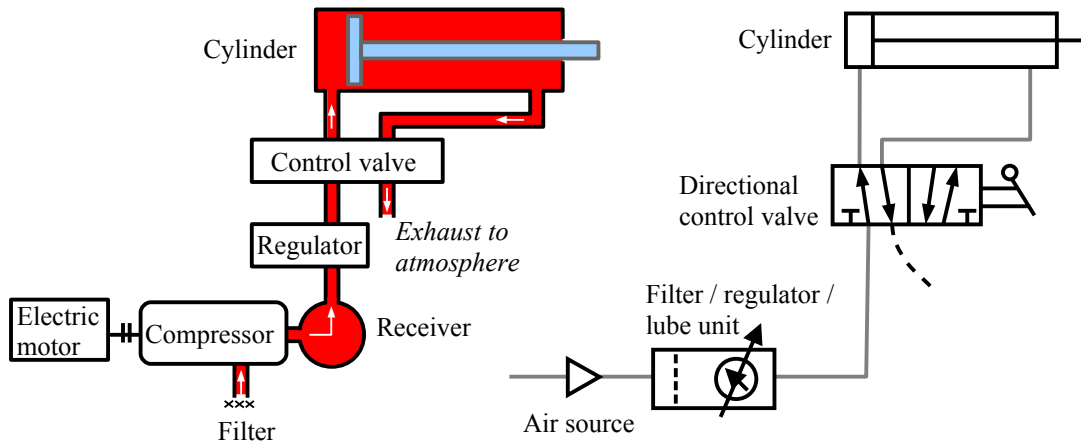
The cartoon on the left shows all of these components, but we can save a lot of ink by drawing pressure and return pipes as individual lines, and by representing motors, cylinders, tanks, etc. with ANSI fluid power symbols, as shown at the right. You have symbols in the back of the book, and also in the lab manual.

## Pneumatic Diagrams

A pneumatic system has many similar components to a hydraulic system: pneumatic fluid (usually air); a filter to remove particles from the air; a compressor to pressurize the fluid; an electric motor to run the compressor; a receiver tank to serve as a reservoir of compressed air; valves to control pressure, direction, & flow rate of fluid; actuators to convert pressure to useful motion (linear or rotary); and piping to carry pressurized air to actuators.

The cartoon at the left shows all of these components; in a pneumatic diagram we don't show the filter, compressor, or receiver because they are often separated from the actuator by some distance. Instead, they are shown as an air source.

## Fluid Properties

Chapter 2 discusses the properties of hydraulic fluids. First, let's think about what hydraulic fluids actually do in a hydraulic system. The main purpose of the fluid is to transmit power from one place to another. You step on the brake pedal in your car, and the force from your foot is transmitted to the brakes, slowing the car down. Second, the fluid lubricates moving parts. Every time you push the brake pedal down, brake fluid moves in the brake system and lubricates the moving parts. If you don't use your brakes for a long time, then some parts could stick together. Third, the fluid seals clearances between moving parts. There's always a little space between moving parts, and the surface tension of the fluid enables the fluid to

seal the gap. If this didn't happen, you would lose brake fluid every time you applied the brakes, and you would have to refill your brake fluid every week. Finally, fluids can dissipate heat generated by the system, and carry it away by convection.

Some of the properties we need to consider include lubricity, fire resistance, chemical stability, low density, foaming resistance, toxicity, and incompressibility.

### Weight, Specific Weight, and Mass Density

From Newton's First Law, the *weight* of a solid object or quantity of fluid is its mass times the acceleration of gravity: $W = mg$ .

The *specific weight* of a solid object or quantity of fluid is its weight divided by its volume: $\gamma = \dfrac{W}{V}$ . The symbol is the lower-case Greek letter gamma. In U.S. Customary units, specific weight is given in lb./ft.$^3$ or lb./gal. In SI units, it is given in N/m$^3$ because the SI unit of weight is the newton.

Density is mass per unit volume: $\rho = \dfrac{m}{V}$ . U.S. Customary units are slugs/ft.$^3$; SI units are kg/m$^3$.

For example, let's calculate the density of water in slugs/ft.$^3$; knowing the specific weight of water is 62.4 lb./ft.$^3$.

$$\rho_{water} = \frac{m_{water}}{V_{water}} = \frac{W_{water}/g}{V_{water}} = \frac{W_{water}/V_{water}}{g} = \frac{\gamma_{water}}{g} = \frac{62.4\,\text{lb.}}{\text{ft.}^3} \left.\frac{s^2}{32.2\,\text{ft.}}\right|\frac{\text{slug ft. s}^2}{\text{lb.}} = 1.9\,\text{slug/ft.}^3$$

### Pressure

Pressure in a fluid is like stress in a solid: divide force by area. In a fluid power cylinder, $p = \dfrac{F}{A}$ , so the larger the the the area the force acts upon, the lower the pressure. The larger the area that a pressure acts on, the larger the force.

Units are pounds per square inch (psi) in the U.S. Customary system; pascals (Pa) in the SI system, where $\text{Pa} = \dfrac{\text{N}}{\text{m}^2}$ .



Consider a cubical container measuring 1 foot along each edge. If you fill the cube with water, what is the pressure at the bottom of the cube?

Water has a specific weight $\gamma = 62.4\,\text{lb./ft.}^3$ . The force acting on the bottom of the container is the weight of the water, $W = \gamma V$ . Pressure $p = \dfrac{F}{A} = \dfrac{\gamma V}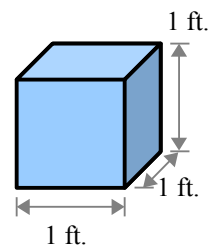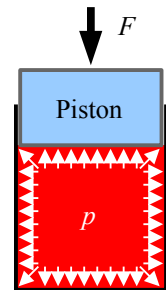{A}$ . If we call the length of each side of the cube $h$, then the volume of the cube is $h^3$ and the area of the base is $h^2$. Therefore, $p = \dfrac{\gamma V}{A} = \dfrac{\gamma h^3}{h^2} = \gamma h$ .



The pressure at the base of the cube is $p = \dfrac{62.4\,\text{lb.}}{\text{ft.}^3} \dfrac{1\,\text{ft.}}{} \left.\dfrac{\text{ft.}^2}{(12\,\text{in.})^2}\right| = 0.43\,\text{psi}$ . Notice that the base area doesn't matter...only the depth does.

If we have a stack of 10 cubes of water, pressure at the base is $p = \dfrac{62.4\,\text{lb.}}{\text{ft.}^3} \dfrac{10\,\text{ft.}}{} \left.\dfrac{\text{ft.}^2}{(12\,\text{in.})^2}\right| = 4.3\,\text{psi}$  The height of a liquid column is called the *head*, and the pressure generated by the weight of the liquid is called *head pressure*.

If we have a stack of 10 cubes of mercury, pressure at the base is greater because mercury has a higher specific weight. In this case, $p = \dfrac{850\,\text{lb.}}{\text{ft.}^3} \dfrac{10\,\text{ft.}}{} \left.\dfrac{\text{ft.}^2}{(12\,\text{in.})^2}\right| = 59\,\text{psi}$ .

Look at the algebraic equation…it's only the specific weight and the depth. The cross-sectional area of the column doesn't

matter…it could be 1 ft.², or 1 in.², or 1 mi.²…the pressure at the bottom will be the same. The pressure at the bottom of a tank doesn't depend on its shape, only its depth. The pressure 2 feet below the surface of a hot tub is the same as the pressure 2 feet below the surface of a swimming pool, or 2 feet below the surface of the Maumee River.

The atmospheric pressure in Fort Wayne is equal to the weight of the air in an imaginary column that extends to outer space, divided by the area of the base of the column. Since air is compressible, we can't use the same formula as for liquids. However, the weight of a column of air sitting above 1 in.² area is about 14.7 lb. Therefore, the atmospheric pressure is 14.7 psia…short for "psi absolute".

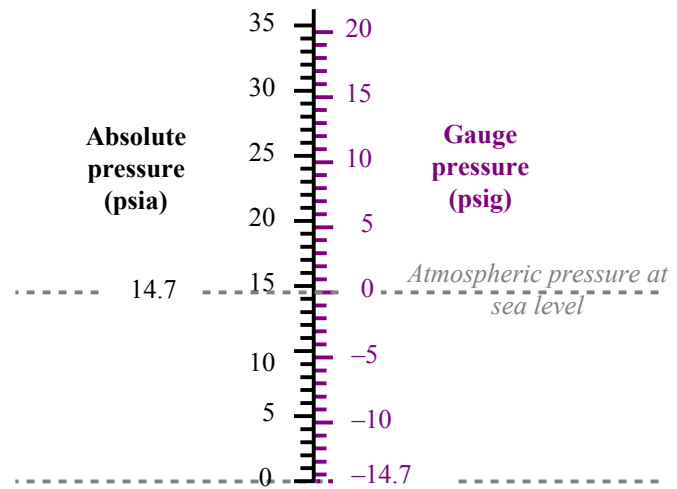In the SI system, this pressure is called 1 atm, or 101 kPa. The "abs" stands for "absolute".

$$p_{atm} = 14.7\,\text{psia} = 30\,\text{in. mercury} = 1\,\text{atm} = 101.3\,\text{kPa\_abs} = 1\,\text{bar}$$

We don't use absolute pressure for everything…because the easiest way to build a pressure gauge is to show the *difference* in pressure between one thing and another. When you measure the air pressure in the tires on your car, you're actually measuring the *difference* between the pressure inside the tire and the ambient atmospheric pressure around the tire gauge.

If you pump up your car tire to 30 psi, that's 30 psi gauge, or 30 + 14.7 = 44.7 psi absolute.

Take the tire to the moon, and measure the pressure, the gauge will read 44.7 psi, because the gauge measures the difference between the pressure in the tire and the pressure outside the tire…which in space is zero absolute.

Sometimes, you can read a negative gauge pressure; this means the pressure is below atmospheric pressure. The lowest gauge pressure you can measure is – 14.7 psig.

**Absolute pressure (psia)**

**Gauge pressure (psig)**

*Atmospheric pressure at sea level*

Absolute and gauge pressures are a lot like temperature scales…we measure Celsius with respect to the freezing point of water, so there are positive and negative temperatures. But there's an absolute lower limit…-273°C is the same as 0 Kelvins. So Kelvin is an absolute temperature scale, just like psia is an absolute pressure scale.
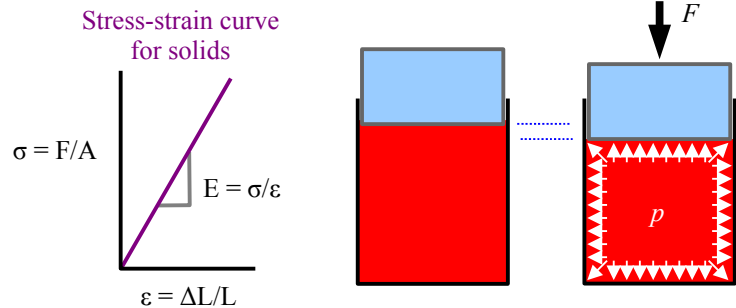
## Bulk Modulus

With solids, we measure the elastic modulus, or Young's modulus, by compressing or stretching a test specimen in a tensile testing machine. Young's modulus is the ratio of stress over strain: $E = \dfrac{\sigma}{\Delta L/L}$ . In liquids, we can do a similar experiment: compress a liquid, and its volume changes a little. The *bulk modulus* is the ratio of the pressure change over the change in volume divided by the original volume: $\beta = \dfrac{p}{\Delta V/V}$ .

**Stress-strain curve for solids**

$\sigma = F/A$

$E = \sigma/\varepsilon$

$\varepsilon = \Delta L/L$

The higher the bulk modulus, the more incompressible the fluid. The units will be similar: pressure is in kPa, or psi; the change in volume divided by initial volume is unitless; so bulk modulus is in stress or pressure units. A typical value of bulk modulus for a hydraulic fluid is 250,000 psi.

## Absolute and Kinematic Viscosity

Viscosity is probably the most important property of a hydraulic fluid; it is a measure of resistance to flow. If viscosity is too high the system is sluggish, power use increases, pressure drop in the lines increases, and friction causes the hydraulic oil to heat up. If viscosity is too low then the seals will leak, and excessive wear occurs because the lubrication film breaks
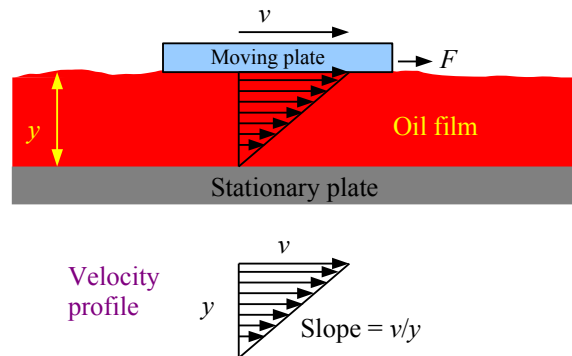
down between moving parts.

We measure Absolute Viscosity by dragging a plate over a film of oil. We can measure the thickness $y$ of the film, the velocity $v$ of the moving plate, and the force $F$ on the plate.

The shear stress between the plate and the oil is $\tau = \frac{F}{A}$ where $A$ is the area of the moving plate that is in contact with the oil.

The slope of the velocity profile is $v/y$.

Absolute viscosity is the shear stress in the oil divided by the slope of the velocity profile: $\mu = \frac{\tau}{v \div y} = \frac{F \div A}{v \div y}$ .

Viscosity was defined when the predominant "metric" unit system was based not on meters, kilograms, and seconds like the current SI system; instead, it was based on centimeters, grams, and seconds (cgs system). In the cgs system, the unit of force is the dyne, defined as $\text{dyne} = \frac{\text{g cm}}{\text{s}^2}$ , where $10^5$ dynes = 1 newton.

The unit of absolute viscosity is therefore $\frac{\text{dyne/cm}^2}{(\text{cm/s}) \text{ cm}} = \frac{\text{dyne} \cdot \text{s}}{\text{cm}^2} = P$ where P is the unit "poise". Unfortunately, the poise is too large for practical use, so we usually measure absolute viscosity of oils in centipoise (1 P = 100 cP).

Divide absolute viscosity by density to obtain *kinematic viscosity*: $\nu = \frac{\mu}{\rho}$ where the units are

$\frac{\text{dyne} \cdot \text{s}}{\text{cm}^2} \frac{\text{cm}^3}{\text{g}} \left| \frac{\text{g cm}}{\text{dyne s}^2} = \frac{\text{cm}^2}{\text{s}} = St \right.$ where St is the unit "stoke". The stoke is too large for practical use, so we usually measure kinematic viscosity of oil in centistokes (1 St = 100 cSt). In the textbook, the author uses "S" for stoke, which is incorrect.

In theory, you can measure viscosity with a stationary plate separated from a moving plate by a film of oil. In practice, this is messy and difficult. Instead, we have more convenient test methods.

- **Saybolt viscometer**. This instrument measures how long it takes for a fixed amount of oil at a given temperature to flow through an orifice of a given size. The time to drain is SUS, Saybolt Universal Seconds.
- **Capillary tube viscometer.** This instrument measures the time to drain a fixed amount of oil through a capillary tube. There's a picture in the textbook.
- **Brookfield viscometer**. A rotating spindle is immersed in the fluid . The instrument measures the torque required to maintain a constant speed. Brookfield viscometers are used for many different fluids, from oils to cake batter to industrial adhesives.

What these methods have in common is that the fluid is moving, either under the force of gravity or due to a rotating spindle. We measure the resistance of the fluid to this motion, in time or torque.