What is Fluid Power?

A fluid is a theoretical state of matter. It is characterized by its internal cohesive force. A fluid cannot support a shear force and deforms continuously under shear loading.

Two thermodynamic states are described by the fluid model: liquids and gases.

Liquids have a higher internal cohesive bonding than a gas and maintain a definite volume. A gas will expand to fill any volume.

The important mechanical difference between liquids and gases is that liquids are treated as “incompressible” whereas gases are “compressible.

The study of Liquid Fluid Power is called “Hydraulics,” after the Greek hydros**, meaning “water.”**

The study of Gaseous Fluid Power is called “Pneumatics,” after the Greek pneumon**, meaning “lung.”**

Because of the amorphous volume property, fluids can transfer forces more flexibly and with lower losses than mechanical linkages.

Concepts and Units

Pressure is the negative average of the normal stress components in the fluid, $p = -\frac{\tau_{11} + \tau_{22} + \tau_{33}}{3}$**.**

Note that pressure is always greater than 0. This is the "you can't push on a rope" principle.

Pressure is measured in units of force divided by length squared ($\frac{F}{L^2}$**). Conventional units are Pascals (Pa), pounds per square inch (psi), pounds per square feet (psf), among others.**

Density is $\rho = \frac{m}{V}$**. For a continuum, at a point, this would be the ratio of an infinitesimal mass contained in an infinitesimal volume.**

Density is measured in units of mass divided by length cubed ($\frac{M}{L^3}$**). Conventional units are kilograms per liter (kg/L), pounds per cubic inch, and pounds per cubic foot. Note that these pounds are pound-mass.**

Specific Weight is the density of a substance multiplied by the acceleration due to gravity, $\gamma = \rho g$**. Units are force divided by length cubed (**$\frac{F}{L^3}$**). Conventional units are Newtons per Liter (N/L), pounds per cubic inch, or pounds per cubic foot. Note that in the English system of units, the numerical value of density and specific weight will be the same (if expressed in pounds per cubic whatever)!**

Dimensionless Constants

There are two important dimensionless numbers which help characterize a fluid's behavior, the Reynolds number and the Mach Number.

$$Re = \frac{\rho u d}{\mu}$$

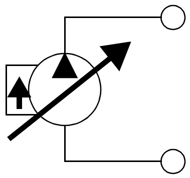
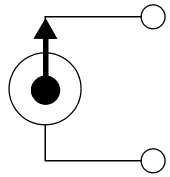
and

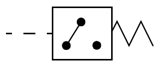
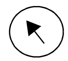
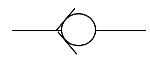
$$M = \frac{u}{a}$$

where u is the average cross-sectional fluid velocity, d is the diameter of the pipe, μ is the fluid viscosity, and a is the speed of sound in the medium. (Note that in acoustics, 'c' represents the speed of sound.)

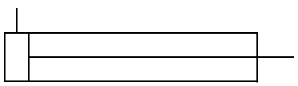
Viscosity represents the internal friction forces in the fluid. In gases, viscosities are very small, especially relative to liquids, however, they are never identically zero. Units of viscosity are $\frac{FT}{L^2}$. In the cgs system of units, viscosity has the units of Poise, which is one dyne-cm/sec^2.

Components in a Pneumatic System

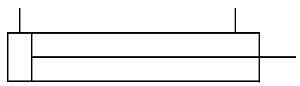
Compressor  **or Air Tank**  **- source of compressed air**

Pressure Switches  **, Pressure Gages**  **, Check Valves** 

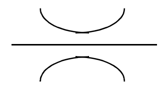
Cylinders

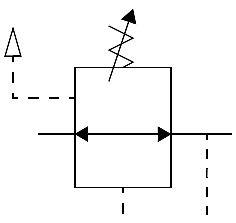


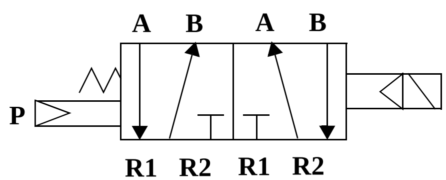
Single Acting



Double Acting

and Orifices 

Regulators  **, Control Valves**



Single Solenoid Valve

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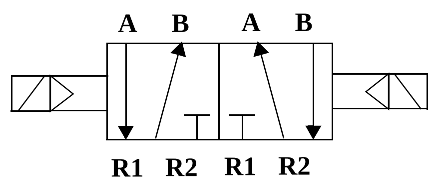
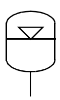
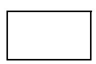
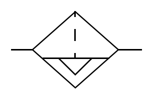
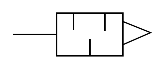
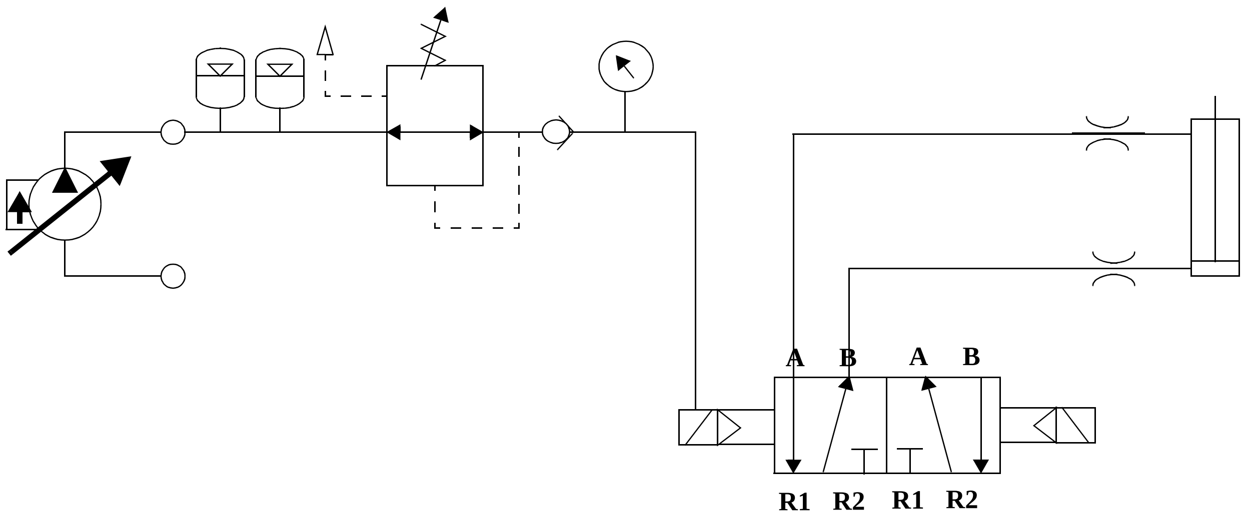


Double Solenoid Valve

Accumulators  **, Reservoirs**  **, Lines, Filters, Lubricators**  **, Silencers**  **, Dryers**

Sample Pneumatic System Set Up



Pneumatic-Electrical Analogy

Designing pneumatic circuits is usually done by electrical analogy. Current is analogous to mass flow. Voltage is analogous to Pressure. For a compressible fluid in a nozzle or orifice,

$$Q = CYA_o\left[\frac{2g(P_1 - P_2)}{\gamma_1}\right]^{\frac{1}{2}}.$$

Q = Volume Flow Rate

Ao = cross-sectional orifice or nozzle outlet area

This equation limps out of Bernoulli's Equation, with two fudge factors to account for flow losses (C) and compressibility (Y). However, it is suitable for design.

If $\frac{D_o}{D_P} < 0.4$ **and** $Re < 10^4$**, then C=0.6 and is independent of** $\frac{D_o}{D_P}$**. (experimental)**

Y varies with pressure drop between 0.86 and 1.0. (experimental)

The mass flow, I, equals $I = \gamma_1 Q = CYA_o[2g\gamma_1(P_1 - P_2)]^{\frac{1}{2}}$

Nozzle as a Resistor

It is convenient to replace the upstream specific gravity, which is unknown, with the upstream pressure, by using conservation of mass:

$$\gamma_1 = \gamma_0 \frac{P_1}{P_0}$$

to yield:

$$I = CYA_o\left[2g\gamma_0\frac{P_1}{P_0}(P_1 - P_2)\right]^{\frac{1}{2}} = R(\Delta P)^{\frac{1}{2}} \approx R\Delta P$$

Alternately, the resistance can be phrased in terms of the flow rate, $Q = R\Delta P$

There are two limiting conditions in a nozzle: no flow and choked (critical) flow.

No flow occurs when the pressure differential across the nozzle is zero.

Choked flow occurs when the flow velocity reaches the speed of sound. At this speed, without a shock wave, the velocity cannot increase further. Hence, any larger pressure drop yields no increase in flow.

Perfect Gas Law

Under many conditions, air acts as a perfect gas. This means its thermodynamic properties follow the relation:

$$PV = RT$$

where P is pressure, V is volume, T is the absolute temperature, and R is the gas constant for air, $0.28700\frac{kJ}{kg\ K}$**.**

If there are two states where this relation is applied,

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} = R$$

or

$$V_1 = \frac{P_2}{P_1}\frac{T_2}{T_1}V_2$$

For steady conditions,

$$Q_1 = \frac{P_2}{P_1}\frac{T_2}{T_1}Q_2$$

Pneumatic Actuators

Pneumatic cylinders function on the principle that a pressure differential across an area generates a force according to: $F = (P_s - P_a) = (\Delta P)A$**. Substantial forces can be generated.**

For example, a 30 psi source venting to atmosphere (14 psi) acting on a cylinder with a 1 inch diameter piston would exert a force of $(30 - 14)psi*3.14*\frac{(1inch)^2}{4} = 12.5lb$**.**

The rate at which the volume in the piston changes is $Q_s = A\dot{x}$**.**

If the piston is being opposed by the force, F_L**, then, its rate of extension would be determined from Newton's 2nd Law (assuming an infinite reservoir and steady conditions)** $M\ddot{x} = (\Delta P)A - F_L = 0$ **or** $P_sA = F_L + P_aA$**.**

Assuming an isothermal process to fill the cylinder from the reservoir $P_sA = P_r\frac{Q_r}{Q_s}A = \frac{P_rQ_r}{\dot{x}}$ **where** P_rQ_r **is constant.**

Combining yields $\dot{x} = \frac{P_rQ_r}{F_L + P_aA}$**.**

Air Cylinder with a Flow Restriction

If the cylinder in the previous example had a flow restriction (usually an orifice) in line with the cylinder, the relation $Q_r = R\Delta P = R(P_r - P_s)$ **would apply.**

Since $P_s = P_r\frac{Q_r}{Q_s}$**,** $P_s = \frac{R(P_r - P_s)P_r}{Q_s} = \frac{(RP_r^2)}{Q_s} - \frac{RP_rP_s}{Q_s}$**. Solving for** P_s**,** $P_s = \frac{RP_r^2}{Q_s + RP_r}$**.**

Recalling that $Q_s = A\dot{x}$ **and** $P_s = \frac{F_L}{A} + P_a$**, then** $\frac{RP_r^2}{Q_s + RP_r} = \frac{F_L}{A} + P_a$ **and**

$$\dot{x} = \frac{RP_r^2}{(F_L + AP_a)} - \frac{RP_r}{A} \quad .$$

This last result is hurried and severely non-validated as yet.

Consider a bore diameter of $A = 1.5\text{in}^2$**, reservoir pressure of** $P_r = 60\text{psi}$**, a load of** $F_L = 25\text{lb}$**, and a resistance of** $R = 1\frac{\text{in}^5}{\text{lb} \cdot \text{sec}}$**, the extension rate is** $\dot{x} = \left(1\frac{\text{in}^5}{\text{lb} \cdot \text{sec}}\right)(60\text{psi})\left(\frac{60\text{psi}}{25\text{lb} + (1.5\text{in}^2)(14\text{psi})} - \frac{1}{1.5\text{in}^2}\right) = 38.3\frac{\text{in}}{\text{sec}}$**, which is a pretty furious rate of extension.**