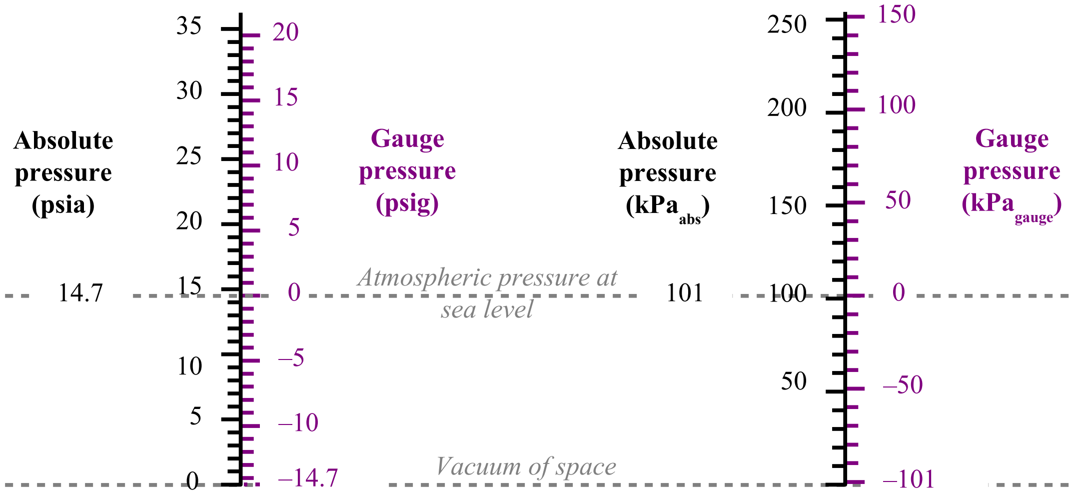
Pneumatics

Properties of Air

In a previous class we discussed the difference between gauge and absolute pressures. This diagram shows pressure scales in U.S. Customary and SI units.



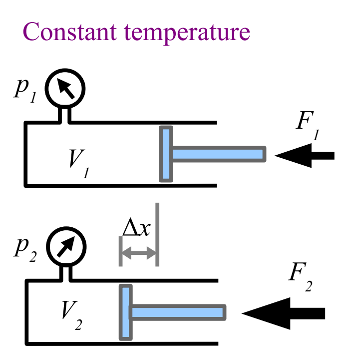
In U.S. Customary units, add 14.7 psi to convert from gauge to absolute pressure; in SI units add 101 kPa to convert from gauge to absolute pressure.

The properties of air change more with temperature and humidity than the properties of hydraulic fluid, so we have to define a baseline condition for all of our calculations. For pneumatic circuit calculations, we define a s*tandard atmosphere* as 68°F, 14.7 psia, 36% R.H. In a pneumatic circuit, we take incoming air and compress it to a higher pressure. The temperature changes from one part of the circuit to another. We also need to remove water from the air, otherwise internal components might corrode. Whatever happens in a pneumatic circuit, we'll calculate pressure and temperature with respect to this baseline condition.

Boyle's Law

Robert Boyle (1627-1691) studied compressed air with laboratory equipment designed and built by his assistant Robert Hooke. The apparatus had a fixed-volume flask, a valve, and a balloon. By moving air between the fixed and variable volume containters, Boyle found a relationship between pressure and volume. Holding temperature constant, $\frac{V_1}{V_2}=\frac{p_2}{p_1}$.

We can use Boyle's Law to calculate the final volume of a cylinder when the load is increased. Consider a cylinder containing a volume of air V_1 under pressure p_1 which is developed by force F_1. If we compress it with force F_2, then we'll develop a pressure p_2, which equals the initial pressure plus the change in force divided by the cross-sectional area of the piston: $p_2=p_1+\frac{\Delta F}{A}=p_1+\frac{F_2-F_1}{\frac{\pi}{4}d^2}$



Using Boyle's law, the volume at the end of the cycle $V_2=\frac{V_1 p_1}{p_2}$.

The distance that the piston travels equals the volume change divided by the cross sectional area of the piston (because volume = area × stroke). $\Delta x=\frac{\Delta V}{A}=\frac{V_2-V_1}{\frac{\pi}{4}d^2}$

For example, let $V_1 = 800\,\text{in.}^3$, $p_1 = 25\,\text{psig}$, $d = 10\,\text{in.}$, and $\Delta F = 100\,\text{lb.}$ Since the initial pressure is given in gauge pressure, we have to convert it to absolute pressure by adding 14.7 psi.

$$p_2 = p_1 + \frac{\Delta F}{\frac{\pi}{4} d^2} = (25 + 14.7)\,\text{psia} + \frac{100\,\text{lb.}}{\frac{\pi}{4}(10\,\text{in.})^2} = 40.97\,\text{psia}$$

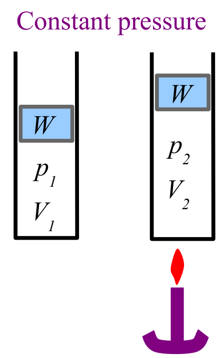
$$V_2 = \frac{V_1 p_1}{p_2} = \frac{800\,\text{in.}^3 (25 + 14.7)\,\text{psia}}{40.97\,\text{psia}} = 775\,\text{in.}^3$$

$$\Delta x = \frac{V_2 - V_1}{\frac{\pi}{4} d^2} = \frac{775\,\text{in.}^3 - 800\,\text{in.}^3}{\frac{\pi}{4}(10\,\text{in.})^2} = -0.32\,\text{in.}$$ The minus sign tells us that the piston is moving in the compression direction, which in this diagram is to the left.

Charles's Law

Jacques Charles (1746-1823) was a professor who dabbled in ballooning. His interest in balloons led him to develop another law of pneumatics: if the pressure is constant, then the volume is proportional to the absolute temperature of the gas, so temperature is in Kelvins, or degrees Rankine, not Celsius or Fahrenheit. Holding pressure constant, $\frac{V_1}{V_2} = \frac{T_1}{T_2}$.

Let's take a cylinder with a piston that weighs a few pounds.



Then we heat the piston, and the volume increases, causing the piston to rise. The pressure in the cylinder = the weight of the piston divided by the cross-sectional area of the piston. Since the weight and cross-sectional area of the piston don't change, the pressure inside the cylinder must remain the same, so $p_1 = p_2$.

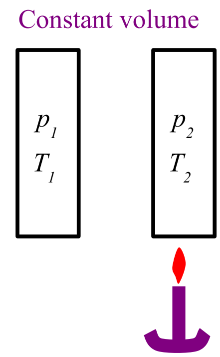
Let's say the temperature of the air inside the cylinder starts at 70°F, and rises to 100°F when we add heat. The initial volume is 10 in.^{3} We can use Charles's Law to calculate the final volume, but first we have to convert from relative temperature units (°F) to absolute temperature units (°R).

$$V_2 = \frac{V_1 T_2}{T_1} = \frac{10\,\text{in.}^3 (100 + 460)\,°R}{(70 + 460)\,°R} = 10.6\,\text{in.}^3$$

Gay-Lussac's Law (General Gas Law)

Jacques Charles did not publish his famous equation because his experimental results did not match the theory well enough. The reason was water vapor; as the temperature dropped, water condensed, reducing the pressure in the system. Louis-Gay Lussac (1778-1850) experimented with gases, but he was careful to dessicate the gases first, so his results were more accurate and matched theory better than other scientists of the day. He published Charles's theory about 15 years after Charles developed it.

Gay-Lussac discovered that if the volume is fixed…like a propane tank…then the pressure is proportional to the temperature. Remember, this is *absolute pressure* and *absolute temperature*…you have to convert first, before solving the equation. Holding volume constant, $\frac{p_1}{p_2} = \frac{T_1}{T_2}$.



Let's take a closed container filled with air at some pressure. As we heat the air in the container, the temperature and pressure both increase. The volume doesn't change, because we've made the walls of the chamber really stiff. Let's say the temperature of the air inside the cylinder starts at 20°C, and rises to 60°C when we add heat. The initial pressure is 50 $\text{kPa}_{\text{gauge}}$.

We can use Gay-Lussac's Law to calculate the final pressure, but first we have to convert the temperature and pressure units from relative to absolute.

$$p_2 = \frac{p_1 T_2}{T_1} = \frac{(50+101)\,\text{kPa}_{\text{abs}}(60+273)\,\text{K}}{(20+273)\,\text{K}} = 172\,\text{kPa}_{\text{abs}} = 71\,\text{kPa}_{\text{gauge}}$$

Look at the unit for absolute temperature. The Kelvin is just a capital K…no degree symbol. It makes things a little difficult, because we use the degree symbol for Celsius, Fahrenheit, and Rankine…but that's the convention.

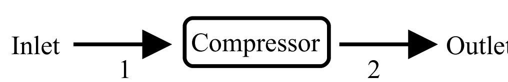
So we've got three equations that are true for three different conditions: constant temperature, constant pressure, and constant volume. Benoit Paul Emile Clapeyron (1799-1864), a French engineer, designed steam engines. In a steam engine, temperature, pressure, and volume are constantly changing. Clapeyron looked at these three equations and combined them together into what we call the general gas law: $\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$. You've probably seen this equation in chemistry, but they write it a little differently to take into account the number of atoms or molecules. In our pneumatic calculations, we assume no change in the number of atoms or molecules…we compress or expand a gas, but it's all the same gas. The important thing to remember with this equation is to use absolute pressure and absolute temperature.

Air Compressor

In a pneumatic system, the first thing we have to do with air is compress it. There's a picture of an air compressor in the textbook. Let's look at some of the features, and why they're used.

- **Unloader**. When you start a compressor that's hooked up to a pressurized pneumatic system, the electric motor isn't up to speed, so you don't want to be working against a full load. The unloader relieves the pressure in the cylinders, so the motor can get up to speed with no load.
- **Lubrication system.** The moving parts of the compressor need to be lubricated, so there's a lubrication system just like you'd have in a piston engine. This unit has a sight gauge, so you can tell how much oil is in the sump.
- **Cooling fins**. Friction causes the compressor to heat up, so there are cooling fins cast into the head. Bigger compressors may be liquid cooled, like a car engine.
- **Intercooler**. Intercoolers are used to cool down the air when it's compressed. When the air pressure goes up, its temperature goes up, so we have to get rid of the extra heat somehow.
- **Stages**. A compressor with a single piston can efficiently compress air from atmospheric pressure up to about 150 psi. This compressor has two stages, so the 150 psi exhaust from one cylinder is fed into the intake of a second cylinder. Now we can get up to 500 psi. By adding more stages, we can increase the pressure much more.

Air compressors are rated by cubic feet per minute (cfm) of free air…that is, the actual air before we compress it. If it's a hot, sticky day in Charleston, SC, then free air might be 94°F, 90% R.H., 14.7 psia. If it's a cool, dry day in Boulder, CO, then free air might be 45°F, 15% R.H., 13.5 psia.



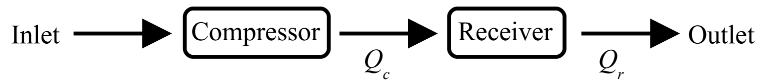
If the air being fed into the compressor is a standard atmosphere (68°F, 36% R.H., 14.7 psia), then the rating is scfm, meaning standard cfm. We can rewrite the general gas law to solve for the incoming volume: $V_1 = V_2 \frac{p_2}{p_1} \frac{T_1}{T_2}$ but that's not really useful.

Instead, we want to know the *rate* of incoming volume, so we divide volume by time to get flow rate: $Q_1 = Q_2 \frac{p_2}{p_1} \frac{T_1}{T_2}$.

Consider a compressor supplying 10 cfm of free air at 80°F, 100 psig. How much air is needed if the local atmosphere is 14.7 psia, 72°F? We have to convert 100 psig to absolute pressure, and the temperatures have to be in absolute units.

$$Q_1 = Q_2 \frac{p_2}{p_1} \frac{T_1}{T_2} = 10\,\text{cfm} \frac{(100+14.7)\,\text{psia}}{14.7\,\text{psia}} \frac{(72+460)\,°\text{R}}{(80+460)\,°\text{R}} = 77\,\text{cfm free air}$$

We don’t use an air compressor directly in pneumatic systems; instead, the air from the compressor goes into a pressure vessel, called a *receiver*.



This is the cylindrical tank that you see on a portable air compressor in a workshop or garage. The receiver does four things:

- It supplies air at a relatively constant pressure to the pneumatic system…± a few psi.
- It dampens the pressure pulses produced by the compressor. A piston produces a pulse on every stroke, and we also get pulses from turning the compressor on and off.
- It dampens the pressure pulses produced by the pneumatic system downstream, as valves open and close.
- It supplies a temporary transient flow that’s greater than the compressor can produce…think of it like a reservoir. Your toilet tank at home does the same thing…it provides water at a higher flow rate than you get from the supply pipe, but it’s transient…the high water flow only lasts a few seconds.

When you’re setting up a pneumatic system, you have to pick a receiver that’s big enough for the job, but not bigger than it needs to be, because cost goes up with size. You can use Equations 13-8 and 13-8M to pick the right size receiver for an application. Equation 13-8 determines the volume of the receiver $V_r = \frac{14.7\ t\ (Q_r - Q_c)}{p_{max} - p_{min}}$ in cubic feet, provided time time *t* is in minutes, flow rate *Q* is in cfm, and pressure *p* is in psia. Equation 13-8M determines the volume of the receiver $V_r = \frac{14.7\ t\ (Q_r - Q_c)}{p_{max} - p_{min}}$ in cubic meters, provided time time *t* is in minutes, flow rate *Q* is in cubic meters per minute, and pressure *p* is in kPa.

For example, let’s say the system consumes 30 scfm for 10 min. between 120 and 90 psi before compressor runs again. The flow rate delivered by the compresser, $Q_c = 0$ when the compressor is turned off. Therefore, $Q_r - Q_c = (30-0)\,\text{cfm}$, and $V_r = \frac{14.7\,\text{psia}\,(10\,\text{min.})(30-0)\,\text{cfm}}{(120-90)\,\text{psia}} = 147\,\text{ft.}^3$.

Now let's run the compressor while the receiver is discharging air. The compressor supplies 5 cfm, therefore $Q_r - Q_c = (30-5)\,\text{cfm}$ and $V_r = \frac{14.7\,\text{psia}\,(10\,\text{min.})(30-5)\,\text{cfm}}{(120-90)\,\text{psia}} = 123\,\text{ft.}^3$; we can use a smaller receiver. The way we run our pneumatic system influences the choice of receiver. It’s an economic decision – the expense of electricity vs. the capital cost of a larger receiver tank.

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