MENG2520 Pneumatics and Hydraulics

Module 6 – Pneumatic Equipment

-Compressors

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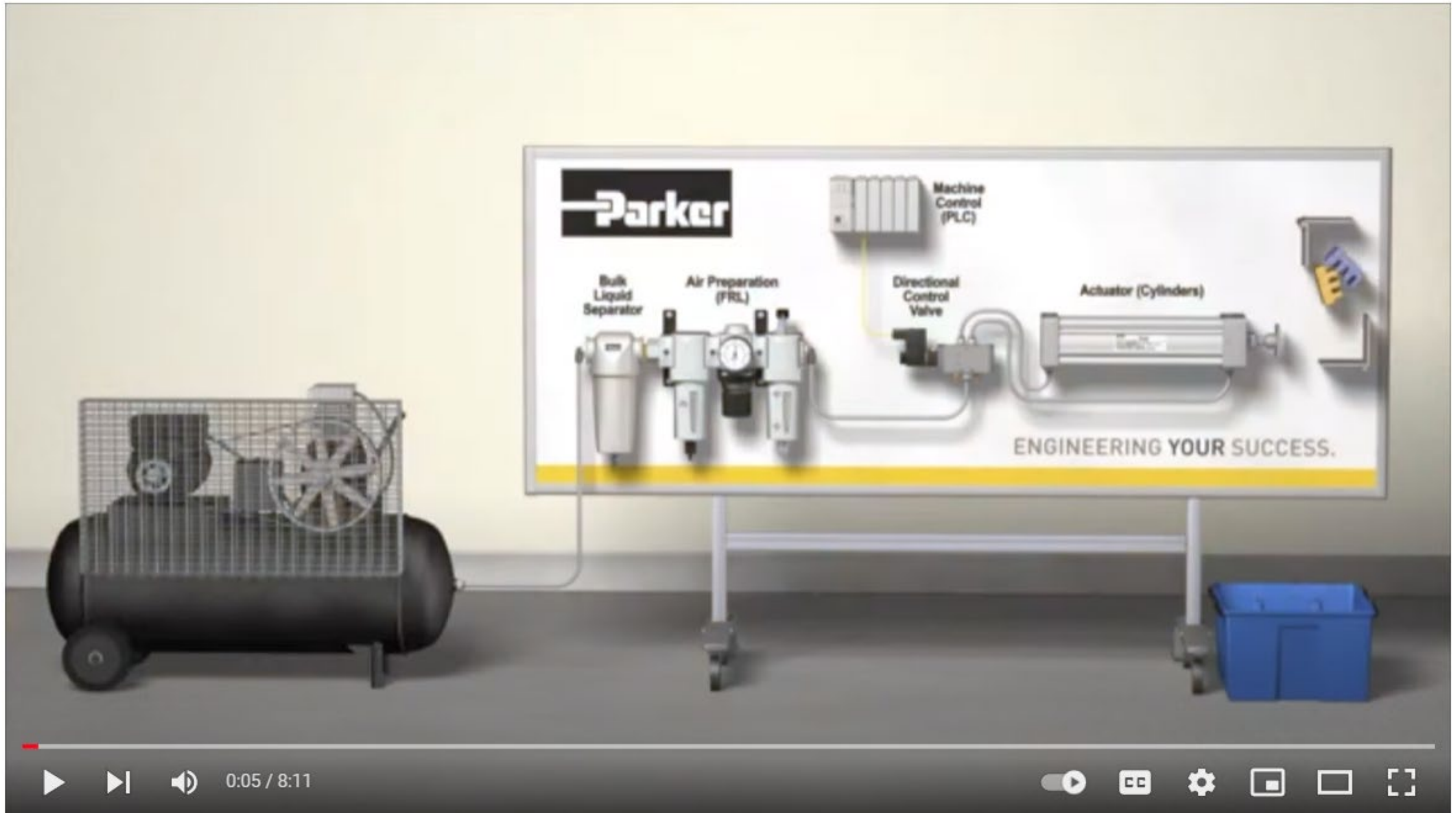
Pneumatic Equipment - Compressors

The compressor is the key to any pneumatic system providing the pneumatic fluid power

In this Module we will study

- **Different types of compressors**
- **Compressor sizing**
- **Receiver tank and sizing**
- **Input power sizing**

A Pneumatic System



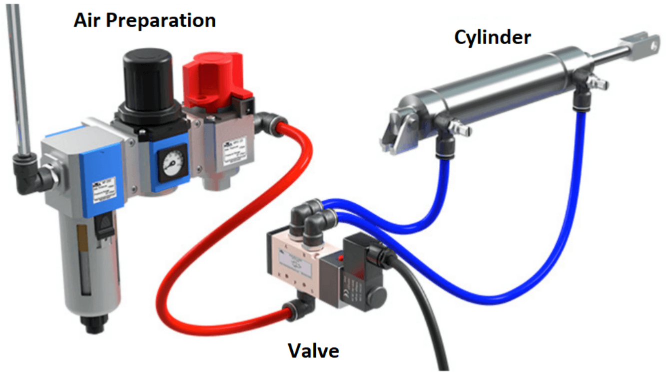
https://www.youtube.com/watch?v=lBARBZNLxQI

Compressor – the Prime Mover

The compressor is a type of converter which converts Mechanical Energy into the energy of a Compressed Gas.

The Compressor in a pneumatic system is equivalent to a pump in a hydraulic system

Transmission of Mechanical Power



A Compressor converts the mechanical energy transmitted by its prime mover (Electric motor, Internal Combustion Engine), into ***pneumatic*** working energy.

https://images.homedepot.ca/productimages/p_1000681001.jpg?product-images=l

https://instrumentationtools.com/wp-content/uploads/2021/06/Basic-pneumatic-system.png

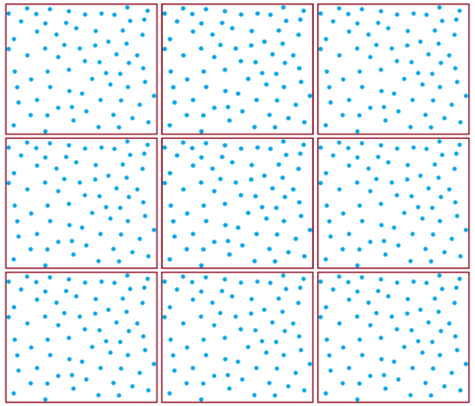
Operating Principles

The Prime Mover (motor, engine…) of the compressor drives a mechanism that is designed to compress gas. This mechanism is in continuous operation creating a steady flow of compressed gas. (Measured in Volume per time) example: CFM

The mechanisms in compressors;

Inhale gas at low pressures and high flow rates and

Exhale gas at higher pressures and lower flow rates.



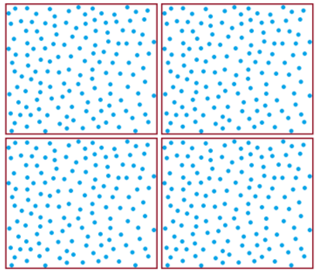
Low Density of Gas at Low Pressure

Flow rate of 9 units per time

Gas Inhaled

Same amount of Gas Inhaled as Exhaled

Gas Exhaled



High Density of Gas at Higher Pressure

Flow rate of 4 units per time

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Compressor Classifications

Compressors

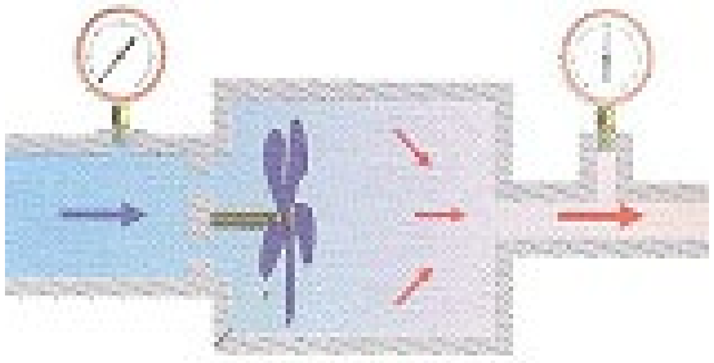
High Volume Low Pressure

DYNAMIC

Draws in gas and compress it by accelerating the gas' mass.

The pressure is increased by adding kinetic energy to the mass of air.

The higher kinetic energy of the gas creates a higher gas pressure.



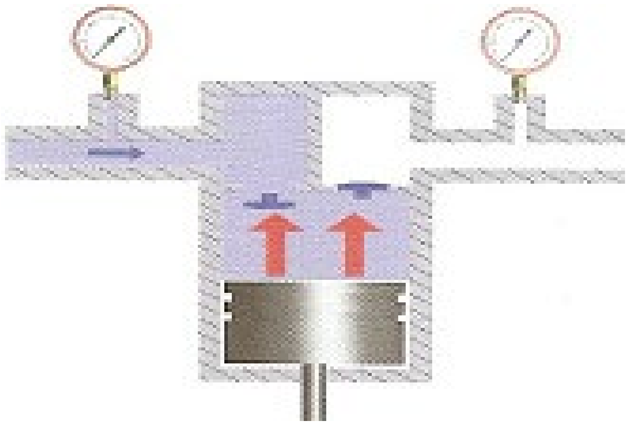
Low Volume High Pressure

DISPLACEMENT

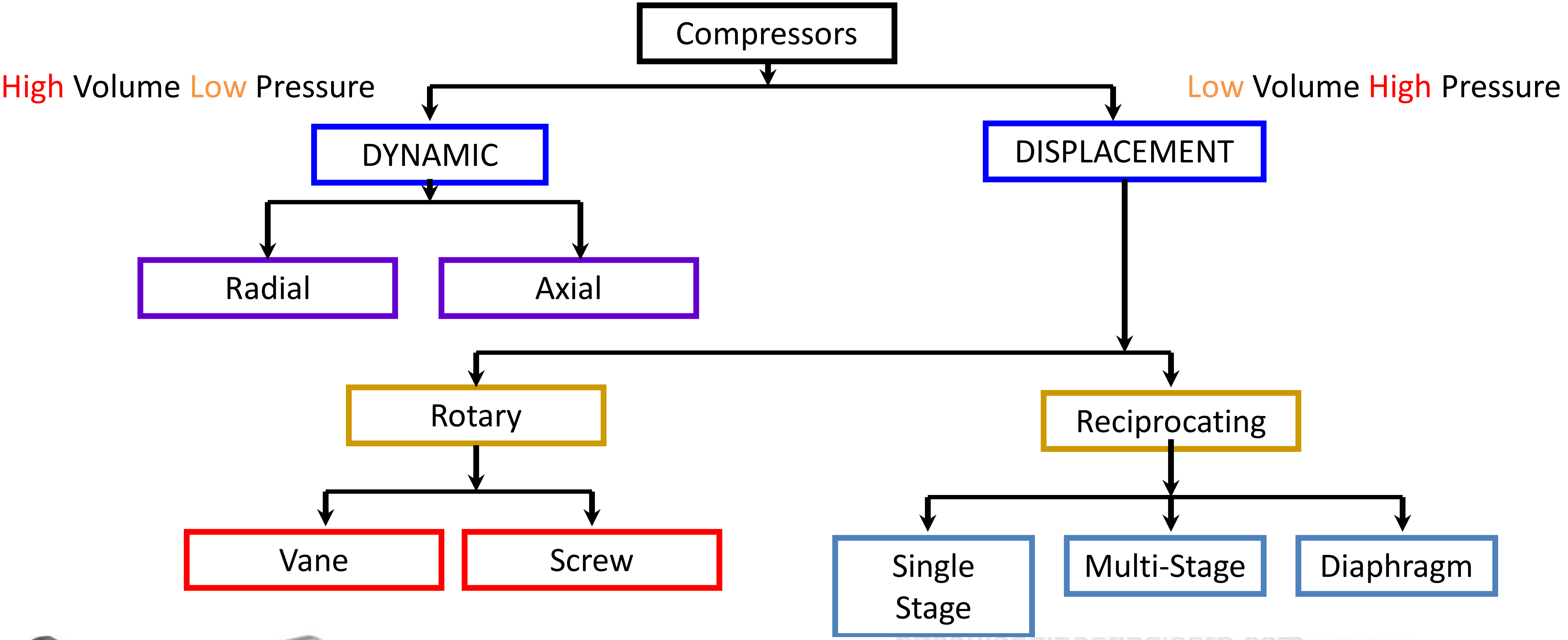
Confines gas in a chamber that can change its volume.

The volume of the chamber is reduced. Reducing the volume Increases the Pressure of the gas.

The gas is then displaced from the chamber at a higher pressure with lower volume.



Compressor Classifications



https://engineeringlearn.com/wp-content/uploads/2021/06/Air-Compressor-1024x539.jpg

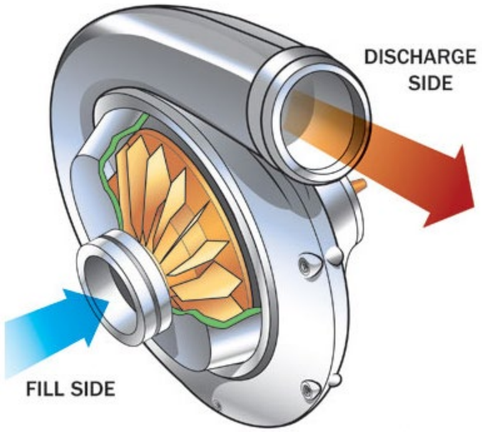
Dynamic Compressors

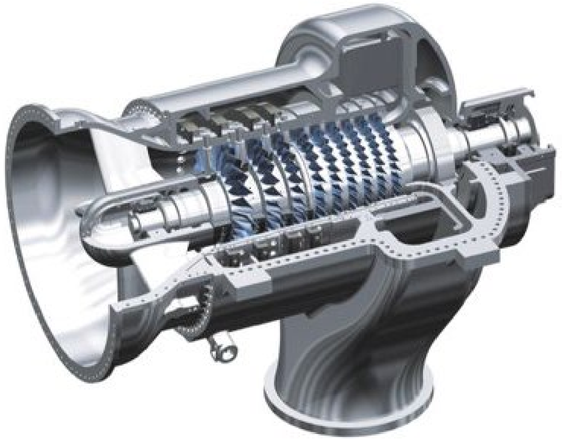
Radial or Centrifugal Type

The Working Fluid flows perpendicular to the axis of rotation.
Delivers compressed air through the use of centrifugal force.
Can create high volume of air output
Low pressures up to 90 psi

Axial Type

The Working Fluid flows parallel to the axis of rotation.
Delivers compressed air through the use of centrifugal force.
Can create *very* high volume of air output
Capable of pressures up to 90 psi
Moderate pressures





https://totalgyan.com/wp-content/uploads/2017/11/Supercharger.jpg

Applications:
HVAC Blowers
Car turbo chargers

Applications:
Wind Tunnels
Jet Engines

https://www.sunrise-metal.com/wp-content/uploads/2021/09/Figure-2-Different-Types-of-Dynamic-Air-Compressor.jpg

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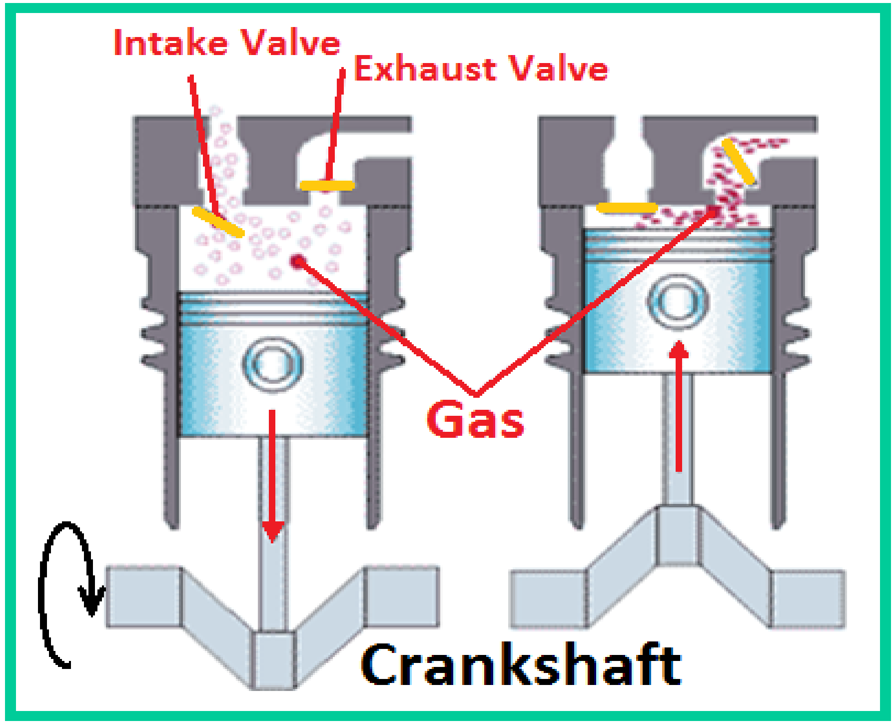
Displacement - Reciprocating

Reciprocating describes the forward (upward) and backwards (downwards), alternating movement of the piston.
Capable of generating pressures from 40 to 4500 psig.



Piston Type

Applications:

- Manufacturing
- Automation
- Automotive
- Construction
- Home use (Recreational)

Piston Type Compressors are the most common type of compressors.

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https://civilmint.com/wp-content/uploads/2022/05/Positive-Displacement-Compressor.jpg

Displacement - Screw

Screw compressors work by pushing air through the continually reducing volume of the screws
Capable of generating pressures up to 120 psig and flow rates up to 1450 cfm

Screw Type

Applications:
- Manufacturing
- Automation
- Automotive
- Construction

Screw compressors are becoming more and more common.

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https://5.imimg.com/data5/TX/AC/MY-27696021/rotary-screw-compressors-500x500.jpg

Compression Types (Adiabatic vs. Isothermal)

Charles' Gas Law dictates the temperature of a gas will increase when it's volume decreases.

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

If we:

1. Do Not Cool: Do NOT let the heat escape. $\longrightarrow$ **Adiabatic Compression**
   Useful in a diesel engine where heat is required to ignite the fuel/air mixture

2. Cool: LET the heat escape. $\longrightarrow$ **Isothermal Compression**
   Useful in reducing energy required to compress gases

   Industrial compressors are Isothermal and are designed to keep (as much as feasible) the delta temperature zero, and hence we can deal (almost) exclusively with Boyle's Law

$$\frac{V_1}{V_2} = \frac{p_2}{p_1}$$

Isothermal Compressor

Compression of air will decrease Volume AND increase Temperature

Many compressors are designed to reduce the temperature rise by using passive cooling such as radiator fins on the piston heads and associated plumbing

Furthermore, when the high temperature air enters the tank, the tank's air and body continue to serve as further heat sinks

Compressors of this type are relatively inefficient and can produce upwards of 120 psi

https://airpress.net/compressor-k-300-600-14-bar-4-hp-360-l-min-300-l-36524-n

Isothermal Multistage Compressor

A multi-stage compressor uses the principles of Gay-Lussac's law to make compression of gas more efficient, and to achieve higher pressures

2 stage upwards of 500 psi
More stage can achieve upwards of 3000 psi

The hotter gas requires a higher amount of energy to be compressed. If it were to be cooled it would decrease in volume and would have less molecular kinetic energy. It would then require less energy to be compressed further.

After the first stage of compression the gas heats up. $T2 = T1 \times P2/ P1$

In addition to the passive cooling of the single stage compressor, a multistage compressor uses an intercooler to remove even more heat from the gas before it is compressed once again. Active cooling, such as a cold-water heat exchanger can be used

After cooling, the gas has a smaller volume. The second stage piston chamber is therefore smaller that the first.

https://i5.walmartimages.com/asr/858cf231-b56d-4cd0-ba9a-91c42cc087e0_1.24d1bfd30f143e422e7f65f0aed3bf22.jpeg?odnHeight=2000&odnWidth=2000&odnBg=ffffff

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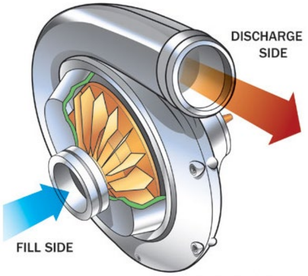
What type of Compressor should you use?

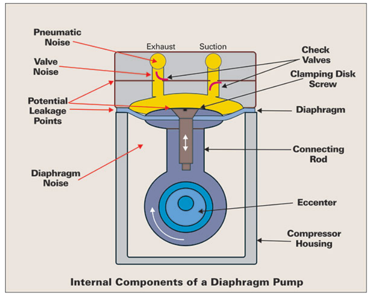
A compressor in a packaging station inflates thousands of paganing bags each hour. The pressure in the bags is very low, under one psi.

Solution: A dynamic compressor – high volume low pressure



A packaging machine in a food processing plant blows a quick burst of air at the opening of a bag allowing food to be inserted into the bag.

Solution: Diaphragm compressors seal contaminants from the pump shaft and mechanism. They are used where the compressed air must have no contaminates in it.



blog.knfusa.com

What type of Compressor should you use?

A paintball gun equipment suppler has a compressor for filling high pressure (4500 psi) CO2 tanks.

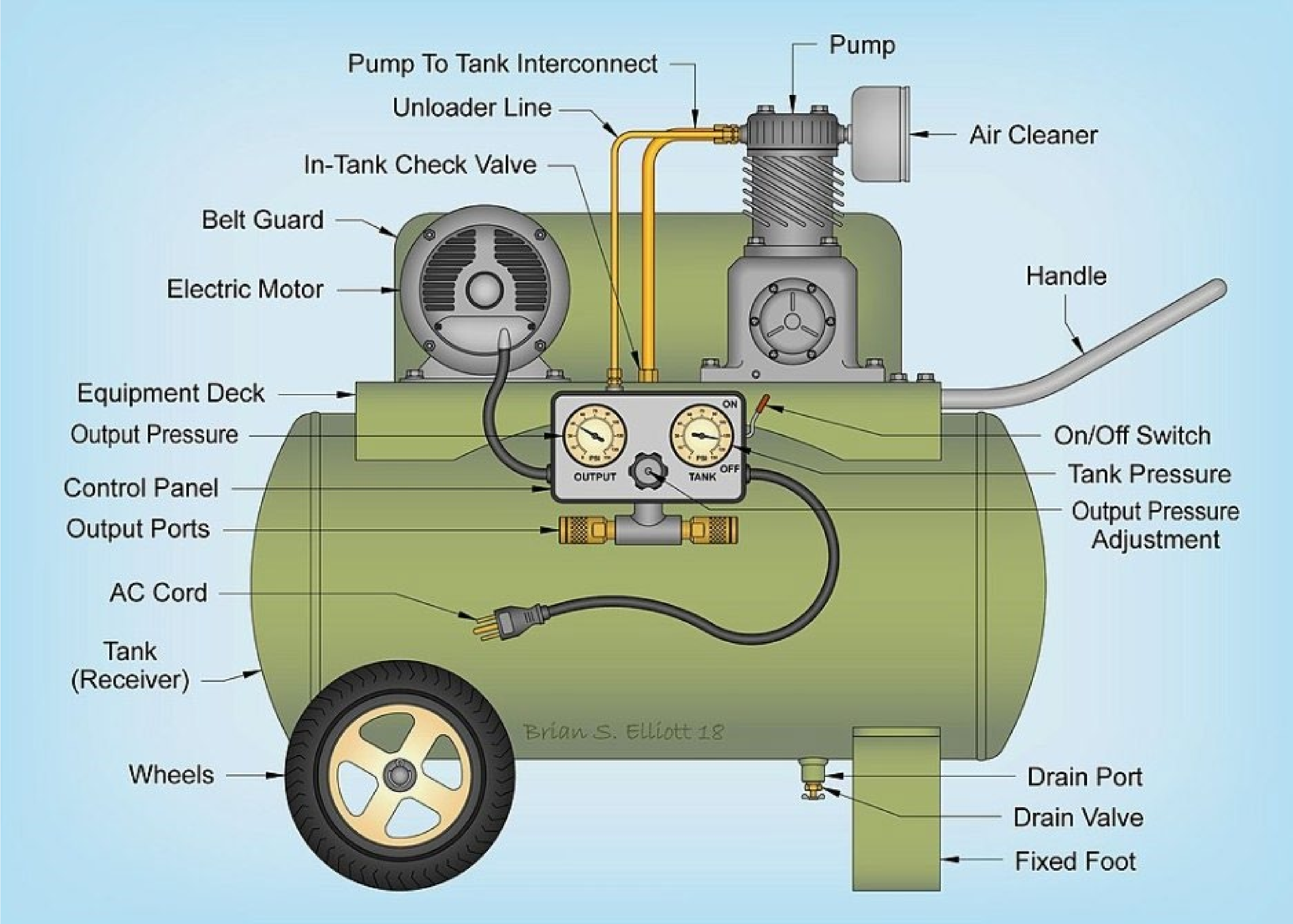
Solution: A multistage compressor is required to generate very high pressure.

A house fabricator has a factory that assembles pre-fab homes. The workers in the factory uses air tools that run on pressure sunder 80 psi.

Tools such as impact wrenches and rivet guns and well as air blowers.

Solution: Air tools require a VERY HIGH CFM, a large single stage compressor is a good choice.

Compressor Components



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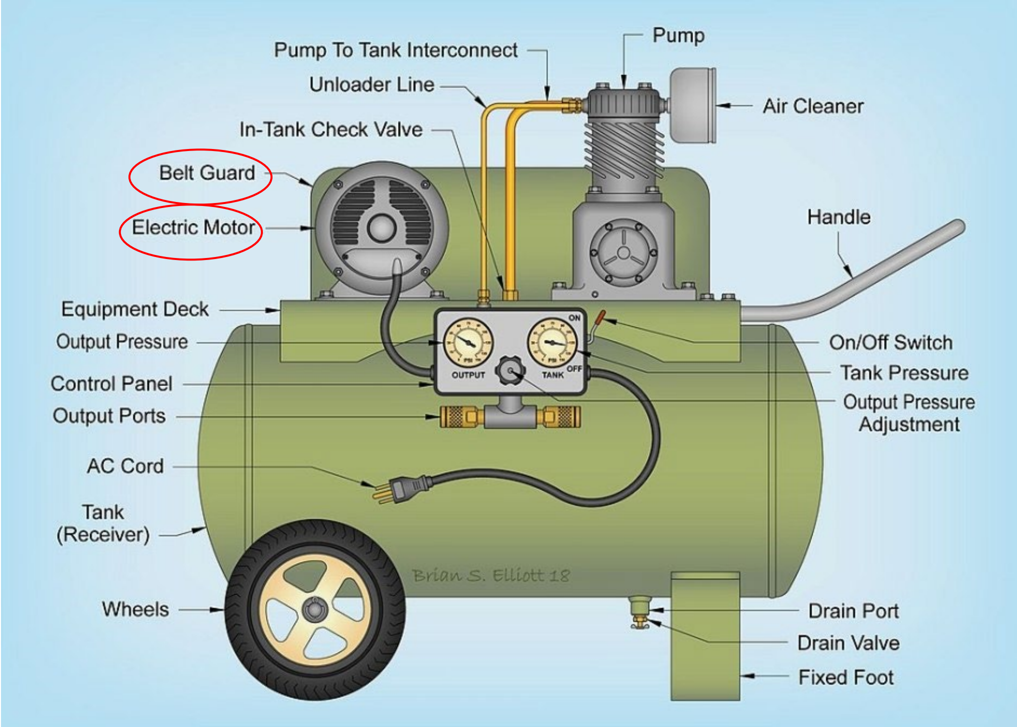
Compressor Components

Motor (Prime Mover)- this drives the pump, may run on 110 volts or 220 volts depending on size of unit.

Drive belt - depending on size of the pump there may be two or more belts. Some models have a direct drive coupling between the motor and pump. Chains are never used! If the compressor seizes the prime mover will be damaged. Belts will allow slippage and will burn out like a fuse.



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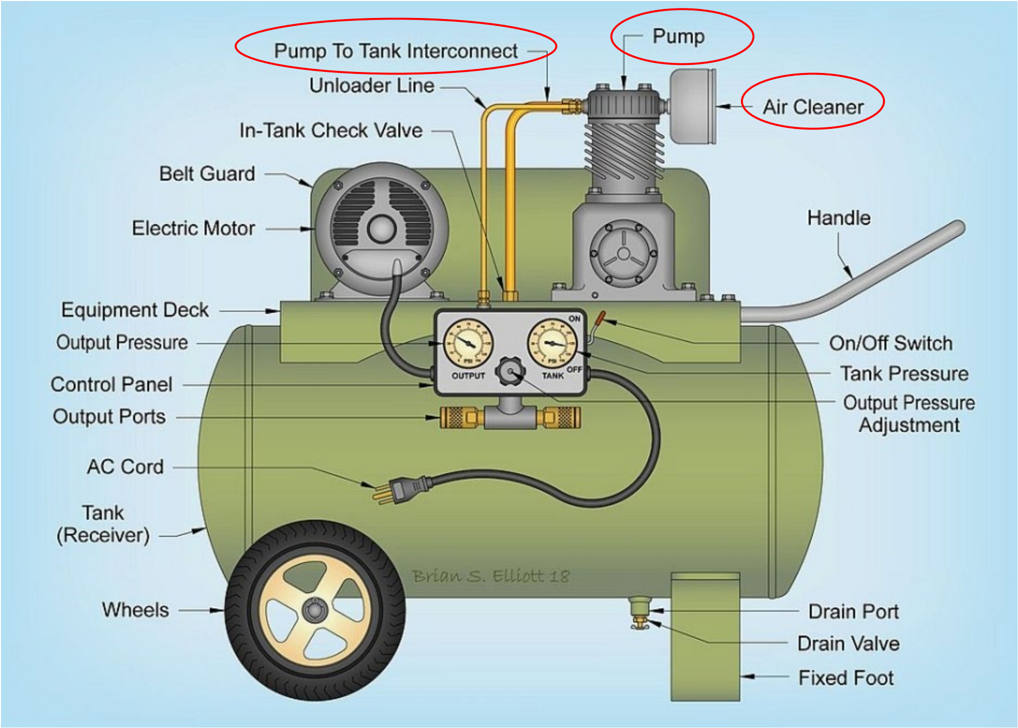
Compressor Components

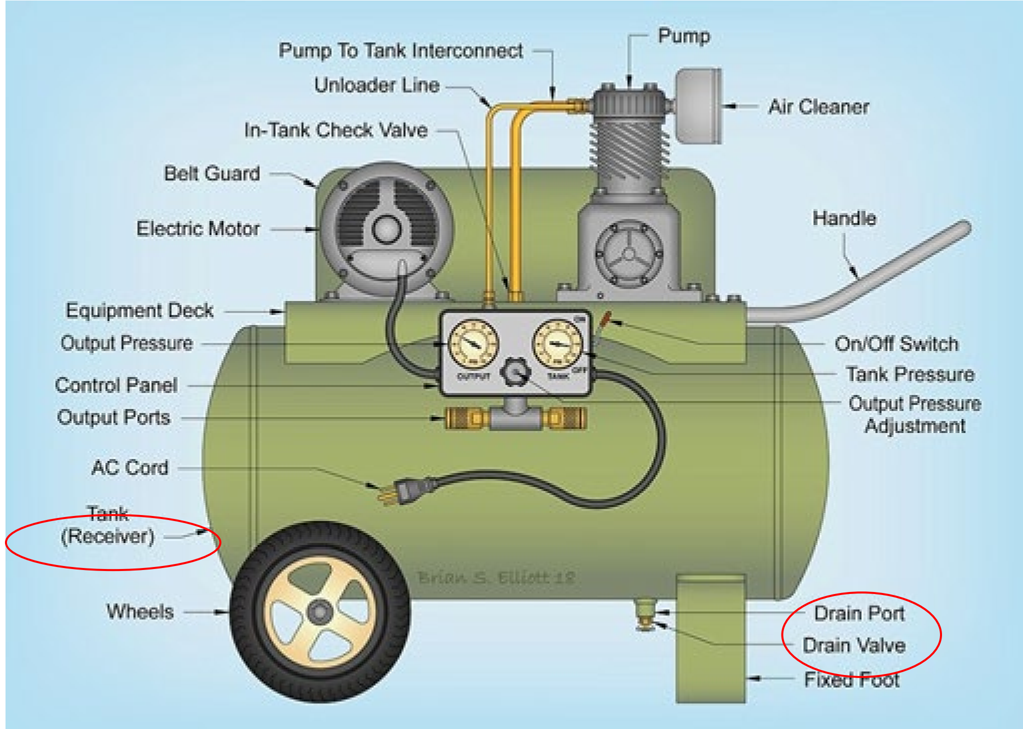
Compressor pump - may have one or more cylinders with a piston and crankshaft, or a rotary vane. Through a system of valves in the head air is drawn IN and then forced OUT under pressure into the holding tank.
Inlet (Air Cleaner) – air inlet into cylinder through this filter.
Outlet (Interconnect) - compressed air enters the tank through this pipe, it may be coiled or finned to help cool the air.



Compressor Components

Air tank (Receiver Tank) - special tank built to withstand high volume of air pressure. It must be certified as an air tank.

Water drain – the valve to drain water that collects in the tank. Automatic drains are available, otherwise these should be manually opened to drain water frequently.



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Compressor Components

Control switch - automatically switches ON and OFF the Prime Mover at predetermined settings.

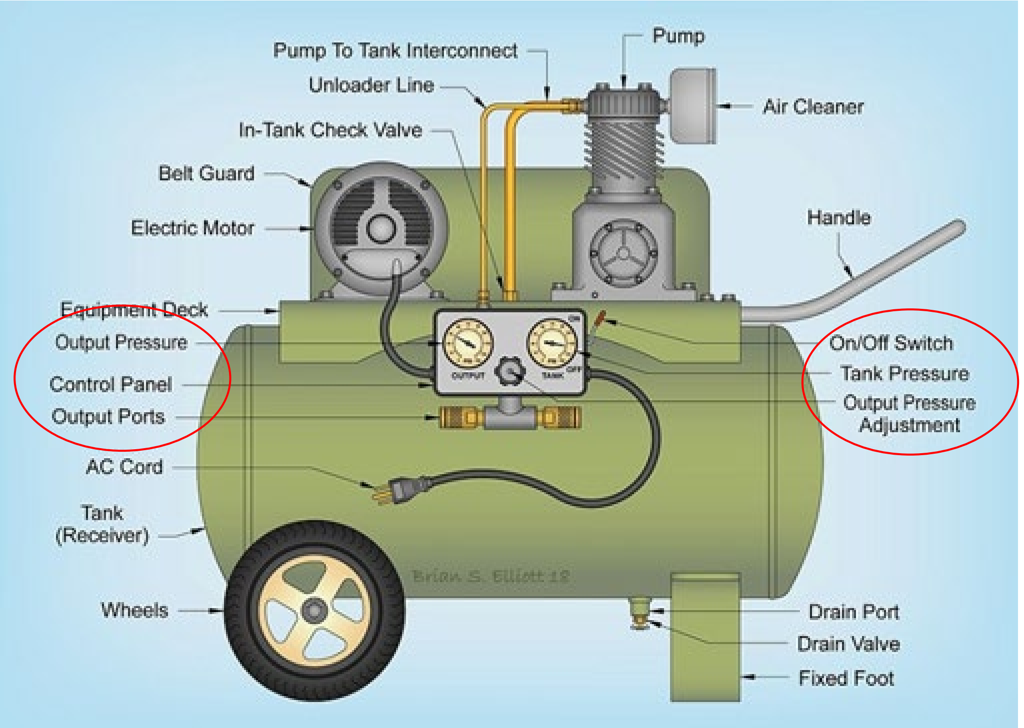
Relief valve - opens to release air in tank if the pressure exceeds a safe limit.

Pressure gauge - measures pressure of air in the tank in (psig).

Manifold - a fitting with several outlets to connect control valves, pressure relief valves, gauges, etc..

Regulator - controls the amount of pressure leaving the tank.

Output Ports – This is the Output of the Compressor or the Output Air Line. This line is the conduit for the pneumatic energy to be distributed to various actuators.



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Gas Flow Rates

There are various ways of looking at gaseous flow rates:

CFM - Cubic Feet Per Minute (Ft^3/min).

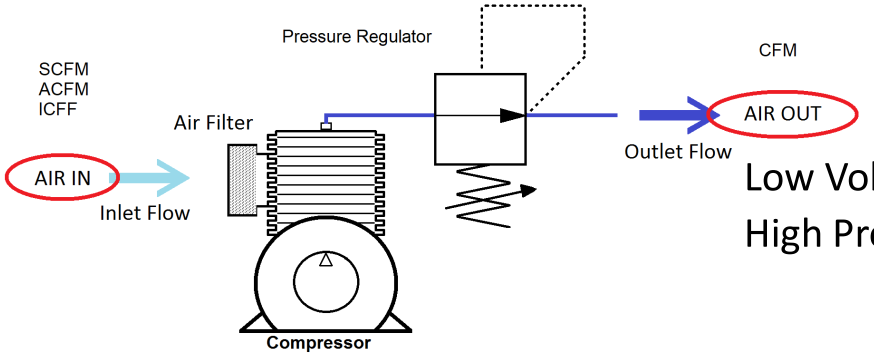
SCFM - Standard Cubic Feet Per Minute (Ft^3/min).

14.7 psia. (101,325 Pascals) and 68°F (20°C) at 36% Humidity

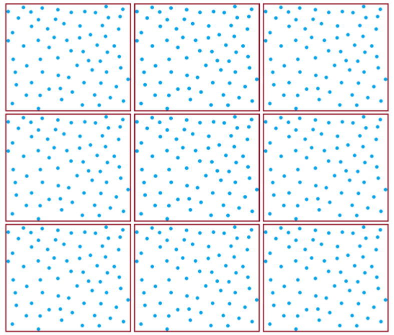
ICFM - Inlet Cubic Feet Per Minute (Ft^3/min).

ACFM - Actual Cubic Feet Per Minute (Ft^3/min). (Ambient Air)

High Volume
Low Pressure

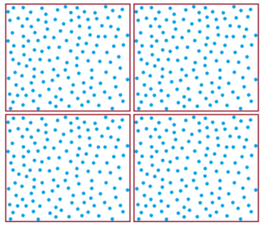


Low Volume
High Pressure



Gas Inhaled

Gas Exhaled

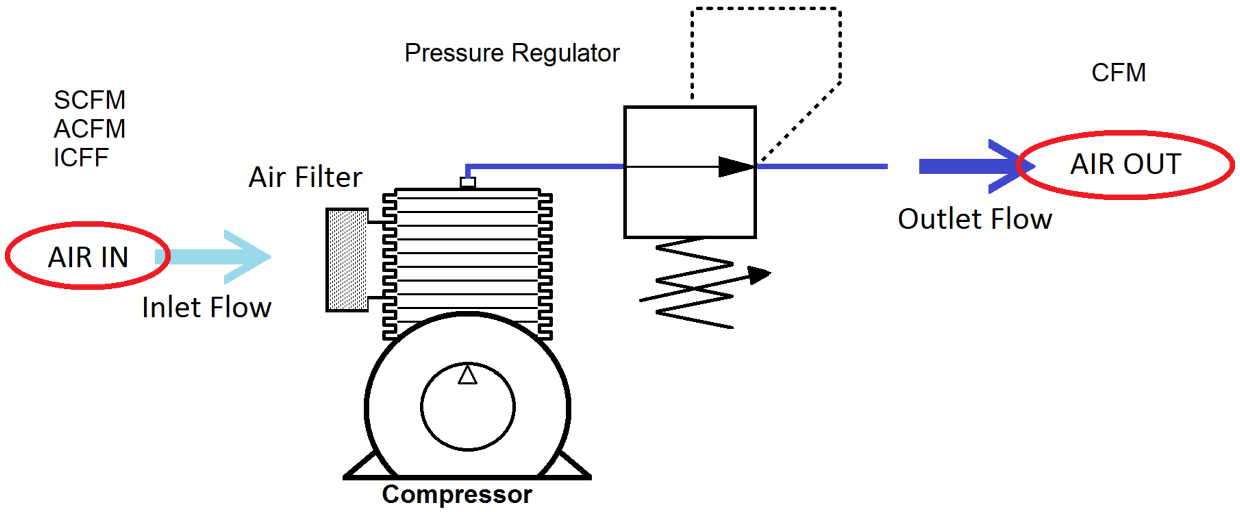


Same amount of Gas Inhaled as Exhaled

High Density of Gas at Higher Pressure
Flow rate of 4 units per time

Low Density of Gas at Low Pressure
Flow rate of 9 units per time

Compressor Inlet Air Flow vs. Outlet Air Flow



Most manufactures rate their compressors for their Outlet Flow Rate

- CFM

It’s not as commonly found, but some manufactures rate their compressors for their Inlet Flow Rate

- SCFM
- ACFM
- ICFM

And some manufactures rate CFM at the outlet but call it SFCM – confusing and incorrect!

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Compressor Rated in CFM

When a compressor is rated in **CFM** it means that it will produce a cubic flowrate at a specific pressure.

18.5 CFM at 100 psi

When the pressure changes, the CFM changes
By the Gas Laws

https://www.kbctools.ca/ecomm_images/items/large/6-125-112.jpg

Converting Flow Rates

General gas Law: $$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

dividing both sides by time yields $$\frac{p_1 V_1}{T_1 t} = \frac{p_2 V_2}{T_2 t}$$

And flow rate $Q = \dfrac{V}{t}$

If we assume isothermal compression, that is T_1=T_2, yields

$$Q_1 p_1 = Q_2 p_2$$

Or

$$Q_1 = \frac{Q_2 p_2}{p_1}$$

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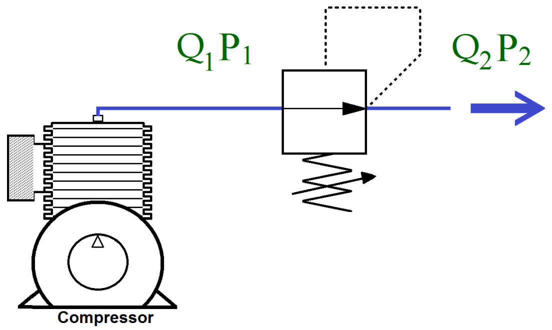
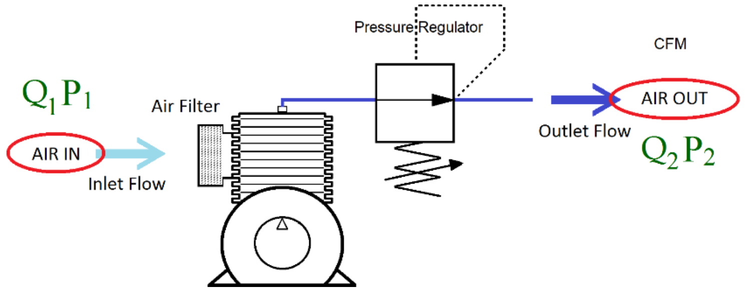
SCFM and CFM Flow Rate Conversions

The flow rate formula can be applied in two ways. $$Q_1 = \frac{Q_2 p_2}{p_1}$$



Q_1 = air into the pressure regulator
Q_2 = air out of the regulator

OR



Q_1 = air into the breather of the compressor
Q_2 = air out of the regulator

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Compressor Selection Example - 1

Air is used at a rate of 30 cfm from a receiver at 90°F and 125 psi. If the atmospheric pressure is 14.7 psia and the atmospheric temperature is 70°F, how many cfm of free air must the compressor provide? (remember to work in absolute temperature and pressure)

Solution Substituting known values into Eq. (13-7) yields

$$Q_1 = Q_2\left(\frac{p_2}{p_1}\right)\left(\frac{T_1}{T_2}\right) = 30 \times \frac{125 + 14.7}{14.7} \times \frac{70 + 460}{90 + 460}$$

$$= 275 \text{ cfm of free air}$$

In other words, the compressor must receive atmospheric air (14.7 psia and 70°F) at a rate of 275 cfm in order to deliver air (125 psi and 90°F) at 30 cfm.

Compressor Selection Example 2

Example:

A pneumatic system in a manufacturing plant runs on 110 psi. It has

- 20 linear actuators consuming 0.05 cubit feet per minute each to run
- 10 rotary actuators consuming 0.2 cubic feet per minute to run each.

Assume this DeWalt compressor is being considered for the job. It is rated to be able to produce flowrate of 4.0 CFM at 90 psi.

Assume isothermal compression, that is $T_1=T_2$

Will this compressor be sufficient to power the actuators?

DEWALT D55153 15 Amp
1-Horsepower 4 Gallon Oiled Twin Hot Dog Compressor

by DEWALT

49 customer reviews | 15 answered questions

Available from these sellers.

- 4.0 CFM delivered at 90 PSI to provide rapid recovery
- Oil-lubricated pump improves durability
- Cast-iron cylinder enhances pump life
- High-flow regulator for increased performance
- Four-gallon twin-stack tank design with proven acceptance in the market

› See more product details

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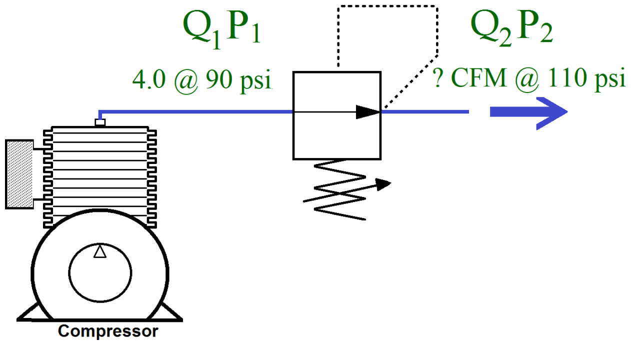
Compressor Selection Example 2 - Solution

The compressor is rated for a flow rate of 4.0 CFM at 90 psi, so what would the flow rate be it the pressure was turned up to 110 psi? (remember to work in absolute pressure)



Let Q_1 be the compressor rated flow rate (4.0 CFM @ 90 psi) and Q_2 be the system requirements of 3 CFM @ 110 psi:

$P_{A1} = P_{G1} + P_{ATM}$
$P_{A1} = (90 + 14.7)\ lb/in^2$
$P_{A1} = 104.7$ psia

$P_{A2} = P_{G2} + P_{ATM}$
$P_{A2} = (110 + 14.7)\ lb/in^2$
$P_{A2} = 124.7$ psia

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

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

$$Q_2 = \left(\frac{104.7\ lb/in^2}{124.7\ lb/in^2}\right) 4.0\ ft^3/min$$

$$Q_2 = 3.36\ CFM$$

Required flow rate is 20x0.05ft^3/min+10x0.2ft^3/min=3 ft^3/min
Q_2=3.36>required, so yes the compressor will do the job, but near 100% capacity

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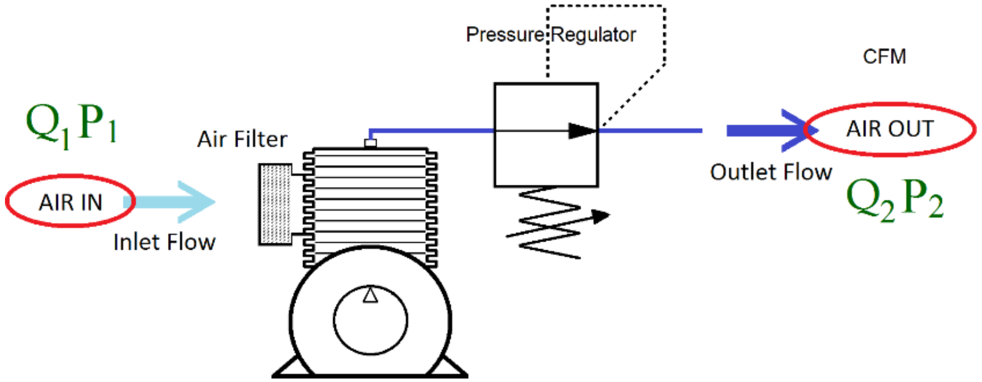
Compressor Selection Example 3

Example:
A pneumatic system in a manufacturing plant has 30 linear actuators and 5 rotary actuators. Altogether, the linear actuators require 2-cubic feet per minute to run and the rotary actuators require 5 cubic feet per minute to run, for a total of 7-cubic feet per minute . All actuators run on 100 psi.
What is the flowrate into the breather of the compressor?



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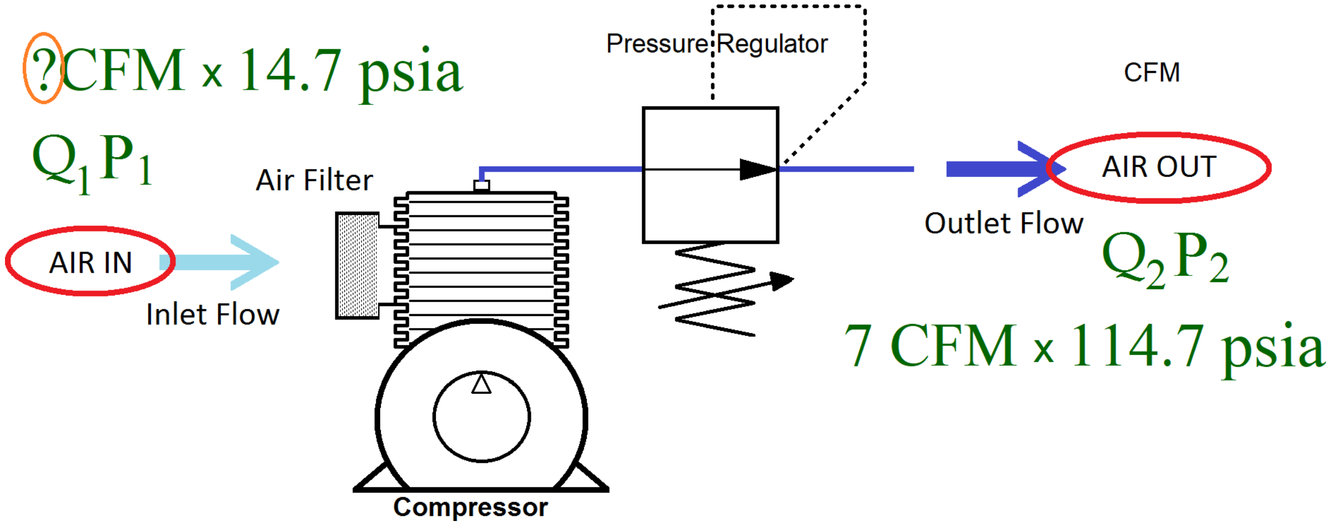
Compressor Selection Example 3 - Solution

The total flow rate required to run all actuators Q_2=7 CFM @ 100 psi (114.7psig). This is the outlet air Q_2. We need to find Q_1 at 14.7 psia.



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

$$Q_1 = \left(\frac{114.7 \text{ lb/in}^2}{14.7 \text{ lb/in}^2}\right) 7 \text{ ft}^3/\text{min}$$

$$Q_1 = 54.6 \text{ SCFM}$$

Therefore, the Inlet Air Flow required to create an Outlet Air Flow of 7 CFM at 100 psia. is 55 SCFM.

Select a compressor with 55 SCFM.

Compressor Selection Example - Solution

Let’s make it better:

If our pneumatic system requires an inlet flow rate of 55 SCFM to operate, and our compressor is rated at 55 SCFM then the compressor is running at 100% duty cycle

Good design principles state that we at least **double the flow rate** SCFM to reduce the duty cycle to 50%.

Therefore, the compressor required should be rated around 110 SCFM.

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Receiver Tank

A receiver is an air reservoir to supply air at essentially constant pressure.

It also serves to dampen pressure pulses either coming from the compressor or the pneumatic system during valve shifting and component operation.

The receiver must be capable of handling the transient demand in excess of the compressor capability.

https://www.kbctools.ca/ecomm_images/items/large/6-125-112.jpg

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Sizing the Receiver Tank

The sizing of air receivers requires taking into account parameters such as system pressure and flow-rate requirements, compressor output capability, and the type of duty of operation.

$$V_r = \frac{14.7t(Q_r - Q_c)}{p_{\max} - p_{\min}}$$

where t = time that receiver can supply required amount of air (min),
Q_r = consumption rate of pneumatic system (scfm, standard m^3/min),
Q_c = output flow rate of compressor (scfm, standard m^3/min),
$p_{\max}$ = maximum pressure level in receiver (psi, kPa),
$p_{\min}$ = minimum pressure level in receiver (psi, kPa),
V_r = receiver size (ft^3, m^3).

This is the starting point and the tank is typically upsized (x2) to accommodate transient overloads and future expansion

Sizing the Receiver Tank - Example

Calculate the required size of a receiver that must supply air to a pneumatic system consuming 20 scfm for 6 min between 100 and 80 psi before the compressor resumes operation.

$$V_r = \frac{14.7t(Q_r - Q_c)}{p_{max} - p_{min}}$$

$$V_r = \frac{14.7 \times 6 \times (20 - 0)}{100 - 80} = 88.2 \text{ ft}^3 = 660 \text{ gal}$$

What size is required if the compressor is running and delivering air at 5 scfm?

$$V_r = \frac{14.7 \times 6 \times (20 - 5)}{100 - 80} = 66.2 \text{ ft}^3 = 495 \text{ gal}$$

Compressor Input Power

The prime mover to the compressor provides mechanical input power and the compressor converts that into pneumatic power.

$$HP_{theoretical} = \frac{p_{in}Q}{65.4}\left[\left(\frac{p_{out}}{p_{in}}\right)^{0.286} - 1\right]$$

p_{in} = inlet atmospheric pressure (psia)
p_{out} = outlet pressure (psia)
Q = flow rate (scfm)

The consider the overall compressor efficiency

$$HP_{act} = \frac{HP_{theoretical}}{\eta_0}$$

Compressor Input Power Example

Determine the actual power required to drive a compressor that delivers 100 scfm of air at 100 psig. The overall efficiency of the compressor is 75%.

Since absolute pressures must be used we have
p_{in} = 14.7 psia
p_{out} = 114.7 psia.

$$HP_{theoretical} = \frac{p_{in}Q}{65.4}\left[\left(\frac{p_{out}}{p_{in}}\right)^{0.286} - 1\right]$$

$$\mathrm{HP_{theor}} = \frac{14.7 \times 100}{65.4}\left[\left(\frac{114.7}{14.7}\right)^{0.286} - 1\right] = 18.0 \text{ hp}$$

The actual horsepower required is

$$\mathrm{HP_{act}} = \frac{\mathrm{HP_{theor}}}{\eta_o} = \frac{18.0}{0.75} = 24.0 \text{ hp}$$

Chapter Reading

Chapter 13

13.4