Compressors and Compressed Air Systems

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Compressors and Compressed Air Systems

Whether installing a new system or altering an existing plant, compressed air systems provide many opportunities to gain long term dollar savings. The proper design and operation of air compression systems is very critical. It is important to have a complete understanding of the exact requirements for compressed air – how, when, and where it will be used. The purpose of this course is to present fundamentals and general information on compressed air systems.

The course is divided in 30 sections:

1 System overview
2 Compressed air ratings
3 Types of compressors
4 System design considerations
5 Compressor controls
6 Compressor sizing
7 System configuration
8 Air quality
9 Components of compressed air system
10 Compressed air treatment
11 After-coolers
12 Dryers
13 Compressed air filters
14 Six levels of compressed air treatment quality
15 Receivers
16 Compressed air distribution network
17 Piping materials
18 Hose and tubing
19 Condensate control
20 Miscellaneous Elements
21 The cost of compressed air
22 Air compressor installation
23 Maintenance and servicing
24 Trouble shooting
25 Safety considerations
26 Handy rules of thumb
27 Myths and realities of compressed air
28 Planned program for energy efficiency
29 Industry codes and standards
30 Brief academic review

The course includes a glossary at the end.

COMPRESSORS AND COMPRESSED AIR SYSTEMS

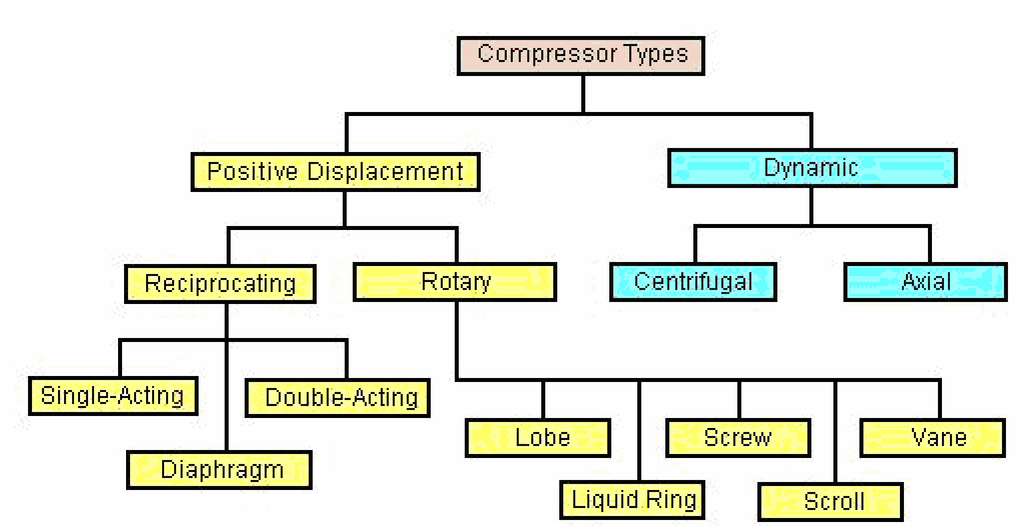
SYSTEMS OVERVIEW

The two broad categories of air compression equipment are dynamic and positive displacement machines.

1. Dynamic machines use axial and centrifugal impellers to impart velocity to the air, which is then converted to pressure. Centrifugal and axial compressors are dynamic machines that often operate at high speeds.

2. Positive displacement machines use reciprocating pistons, rotary screws, or vanes to produce air compression. Screw, reciprocating, lobe, and vane compressors are positive-displacement machines.

There are many different types of compressors on the market, each using a different technology to produce compressed air.



These types are further characterized by:

1. Compression stages:

   Air compressors are available in single or multiple stages of compression.

   Multiple staging is usually adopted when the discharge pressure is greater than 80 psig. Multiple stage compressors offers energy efficiency as air is cooled between compression stages and moisture is removed through cooling. Advantages of multistage compression are:

   - Better mechanical balance and uniform torque of multi-crank machines and a smaller flywheel;

- Increased volumetric efficiency as a result of lower pressure in the IP cylinder clearances;
- Reduction of power to the drive;
- Possibility of operating at high speeds;
- Provisions for better lubrication due to the lower working temperature;
- Smaller leakage loss and lighter cylinders;

3. Type of Cooling:

   Air compressors can be air, water or oil cooled.

   Air-cooled compressors have either integrally mounted or separate oil or air coolers. These require adequate ventilation to perform reliably. Water-cooled compressors require an adequate pressure of quality water. Remember that air compressors typically reject about 2,000 - 2,500 Btu/hr for every hp. Water-cooled units are more energy efficient.

4. Type of Drive:

   The prime mover can be electric motor, engine, steam or turbine driven.

   Electrically motor driven are the most common type found in industrial operations. Engine or turbine driven machines are sometimes used for heavy-duty applications and in mobile units in remote locations where an electrical supply is not available. Such an example would be in a mining operation.

5. Lubrication (oil, oil-free):

   Air compressors are available as dry/oil-free and lubricated. The types of compressors are as follows:

Non Lubricated (Oil Free)	**Lubricated**
Rotary Screw & lobe	Rotary screw & lobe
Reciprocating	Reciprocating
Centrifugal	

In general, oil free compressors are preferable in clean air applications such as the food industry, electronic manufacturing, controls and instrumentation, and hospital services.

Lubricated compressors for utility air services are acceptable if a proper coalescing filtration system is included.

6. <u>Packaged or custom-built</u>

- Usually compressors are packaged items; units are custom built when heavy-duty machines for the mining industry or large energy projects are required.
- Most reciprocating and dry screw air compressors are shipped as self-contained packaged items requiring minimum tie-in connections.
- The centrifugal air compressor package system is typically not shipped as a self-contained packaged system.

7. <u>Operating pressures</u>

Pressure is the main parameter of compressed air which is usually expressed in the units psi or bar (psi = pounds/sq-inch); 1 bar = 10^5 Pa = 10^5 N/m^2 = 14.504 psi).

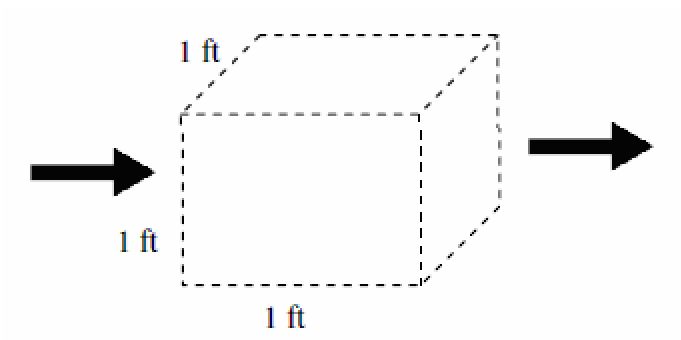
- Low (0 to 150 psi)
- Medium (151 to 1000 psi)
- High (over 1000 psi)

COMPRESSED AIR RATINGS

Compressed air is measured on the basis of the volume used per unit time, cubic feet per minute - CFM at a given pressure, psi (bar). The reference to a volume of compressed air is always based on a measurement of air in its Free State, or atmospheric pressure. This is called standard cubic feet per minute (CFM). When a compressor uses 10 CFM at 100 psi, it is using 10 CFM of free air that has been compressed to 2.46 cu. ft. at 100 psi. The pump is then actually using 2.46 cu. ft. at 100 psi, but the measurement of its consumption is on the basis of “free air” taken into the compressor or 10 CFM. This assures “standard” measurement regardless of pressure.

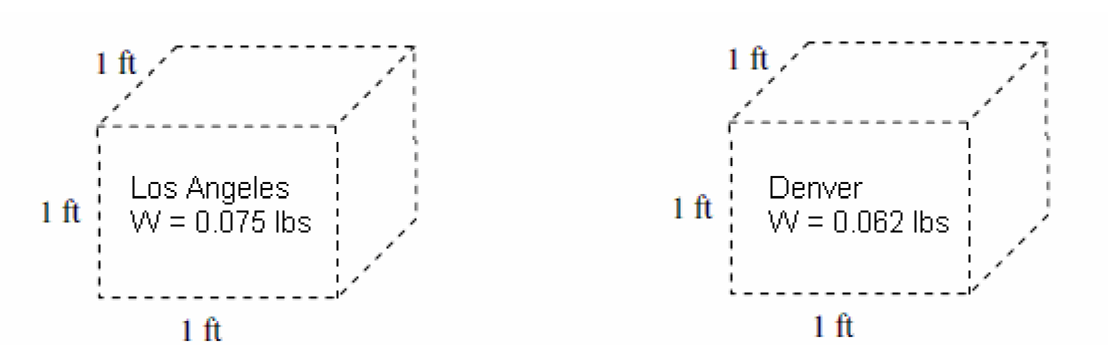
The term CFM is often confusing and difficult to define for one condition, and one definition does not satisfy all conditions we encounter in our customer’s applications throughout the world. The real issue is how much airflow a compressor will deliver at a given pressure. The common terms used to specify a volumetric flow rate in different industries are SCFM, ACFM, ICFM, MCFM, MSCFD, etc. Often times these terms are very vague, and in turn, misunderstood. The primary reason for all the misunderstanding is because air is a compressible fluid, due to the atmospheric variation in air pressure, temperature and density - the fluid properties are constantly changing. The conditions are dependent on location, time of the year, altitude, etc. Thus, it is important to understand that the conditions in Los Angeles vary significantly from the conditions in Denver. The terms SCFM, ACFM and ICFM are often used to define the different instances and conditions of a compressor's capacity and operation. If the CFM terms are used appropriately, they can be useful in the direct and relative comparison to their operating conditions, and to other source systems.

The term cubic feet per minute (CFM) describes the fluid flow rate, (measured in volume - ft^3) not the weight per minute on the inlet side of a compressor. The compressor's performance capability is measured in how many one ft^3 cubes of fluid are able to move per minute through the inlet.



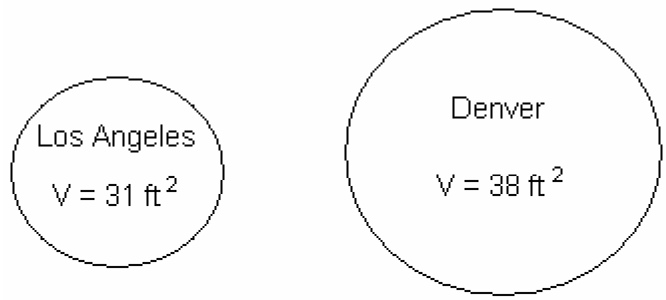
One Cubic Feet of Volume

Now consider the conditions in Los Angeles, where one cubic feet of air weighs 0.075 lbs., and in Denver, where one cubic feet of air weighs 0.062 lbs. Even though the volume is the same, the weight (mass) of the air is different.



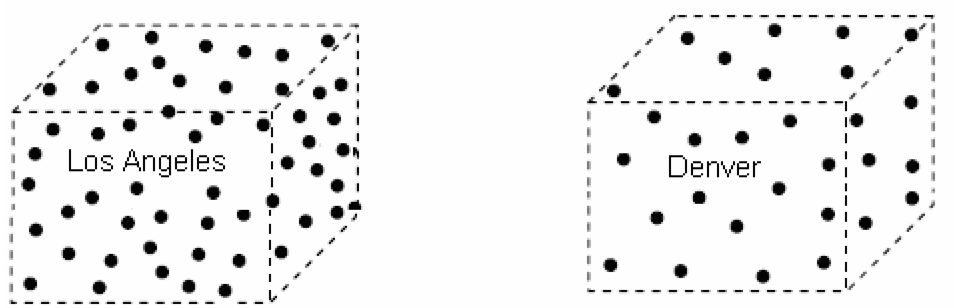
Constant Volume

Now consider a constant weight (mass) condition. A balloon filled with 31 actual cubic feet of air in Los Angeles is then taken up to Denver. The balloon now contains 38 standard cubic feet of air.



Constant Mass

The two examples illustrate the confusion of measuring volume due to the fact air is compressible. In this instance, the number of gas molecules occupying a particular volume, depends on the pressure and temperature conditions of that location. At a microscopic level, the air molecules are closer together (greater air density) in Los Angeles compared to the air molecules in Denver.



Variation in Air Molecule Density

A variation in air pressure results in a variation in air density and is consistent with constant volume concept. Another way to look at this is to analyze the number of air molecules in a 120-gallon receiver tank at 80 psia and 100 psia, where the higher pressure tank occupies a greater number of molecules. The weight and density vary primarily because the atmospheric pressure is significantly different between the two cities, as show in Table below.

Variation in Atmospheric Pressure between the Two Cities

City	Altitude (ft)	Atmospheric Pressure (psia)
Los Angeles	0	14.69
Denver	5280	12.12

Note the terms for “actual” and “standard” for the volumes described above leads us to “SCFM” and “ACFM”.

SCFM and ACFM

SCFM and ACFM are two of the most common methods of rating compressor capacity. It is very important to understand the relationship between SCFM and ACFM.

SCFM - At "standard conditions" - one standard cubic foot of air actually occupy one cubic foot of volume. Another way to express one standard cubic foot of air is .075 of a pound of air. A standard cubic foot varies in volume as it deviates from standard conditions, but it always weighs .075 of a pound. *Therefore, SCFM is a measure of weight, regardless of volume.* Many standards are used to define SCFM - the most common being the Compressed Air & Gas Institute (CAGI) and the American Society of Mechanical Engineers (ASME) standards, which are 14.7 psia, 68°F and 36% relative humidity. This converts to a density of 0.075 lbs/cu-ft for air.

There are other definitions of SCFM.

- The most commonly used definition in the United States is air at 14.696 pounds per square inch absolute (psia), 60°F, 0% Relative Humidity (RH);
- Europeans and the ISO standard normally use 14.7 psia, 68°F, and 0% relative humidity.

The term standard cubic feet per minute (SCFM) is usually used as a standard reference condition for flow rate performance for atmospheric pressure at sea level, as opposed to actual cubic feet per minute (ACFM) is typically used to rate flow rate performance of compressor systems for actual pressure and temperature.

Potential Pitfalls of Failure to Apply Proper Ratings

SCFM is usually established from a weight flow corresponding to some system requirement for oxygen. Therefore, if actual site conditions are different from the standard or reference conditions, corrections must be made to reflect the actual conditions of pressure; temperature and relative humidity (i.e. convert to ACFM). Compressor performance calculations, including head (used for centrifugal compressors) and horsepower, are based on actual (not standard) conditions existing at the inlet and outlet connections of the blower.

The potential pitfalls are:

- Lower than expected output at elevation;
- Potential for seasonal shortfalls in hot and/or humid conditions;
- Mismatch between plant load and compressor capacity;

- Possibility of over-sizing dryer and other equipment.

Relationship between ACFM and SCFM

The relationship between ACFM and SCFM can be expressed as follows:

ACFM = SCFM x $\{[P_S - (RH_S \times PV_S)] / [P_b - (RH_a \times PV_a)]\} \times (T_a / T_S) \times (P_b / P_a)$,

Where

- P_S = Standard pressure (psia)
- P_b = Barometric pressure (psia)
- P_a = Actual inlet pressure (psia)
- RH_s = Standard relative humidity (%)
- RH_a = Actual inlet relative humidity (%)
- PV_S = Saturated vapor pressure of water at Standard temperature (psia)
- PV_a = Saturated vapor pressure of water at Actual inlet temperature (psia)
- T_S = Standard temperature (°R = °F + 460)
- T_a = Actual inlet temperature (°R = °F + 460)

ACFM and ICFM

The term ACFM implies the volume of ambient air that is actually compressed in the first stage of the compressor. ACFM is measured at a set of physical conditions selected by the equipment manufacturer. Some air compressor vendors often improperly use ACFM. For example, an air compressor vendor may state that a 200 HP air compressor is rated for 1,000 ACFM at 100 psig. Taking this phrase literally, the natural assumption is that 1,000 actual cubic feet per minute of compressed air is leaving the discharge of the compressor at 100 psig. This is incorrect. The compressor vendor should have stated that this 200 HP air compressor is rated for 1,000 inlet cubic feet per minute (through the inlet air filter) when operating at a discharge pressure of 100 psig.

The term ICFM (Inlet Cubic Feet per Minute) are the units used by compressor vendors to establish the conditions at the inlet flange of the compressor, whereas ACFM are the units measured at the compressor site location; so what is the difference?

The difference in most cases is the inlet filter. The inlet filter will cause a drop in air pressure as the air is drawn through. Compressor vendors must account for this decrease in air pressure when estimating the compressor performance.

Common good engineering practice includes:

1. Use SCFM to compare differences in compressor capacities, and ACFM for actual nonstandard site conditions and proper load applications. ICFM should be used only when a filter, a booster or a blower is added to the system, and should not be used in determining compressor selection.
2. When specifying the compressed air requirement, the worst case conditions should be used (i.e. - generally hot humid days). The reference pressure, temperature, and discharge pressure must be specified, in addition to the required capacity.
3. Use actual cubic feet per minute (ACFM) when sizing air system piping.

It is important to remember SCFM is defined by a fixed set of conditions or common reference point for comparing different compressors systems. When "Demand" is expressed in SCFM it is indicating that this compressor needs to deliver this CFM even at worst-case conditions.

Other important factors to consider in compressor capacity and system sizing are:

- Air requirement or demand in a given day
- Normal operating conditions
- Other operating conditions (hot humid days are the worst)
- Single-stage or two-stage compressor (compression ratio)
- CFM reduction due to flow resistance
- Electrical characteristics and power requirement
- Area classification (Elevation)
- Compressors with a higher CFM rating will pump more air than compressors with lower CFM

TYPES OF COMPRESSORS

Several distinct types of compressors are manufactured for industrial use. The commonly used categories are reciprocating, rotary vane, screw and centrifugal. Within each category there are variations that are highlighted below:

1. **Reciprocating Air Compressors (Sizes at 100 psig --1/2 HP & 1 cfm to 1,250 HP & 6,300 cfm)**

   Reciprocating air compressors use the reciprocating motion of a piston in a cylinder to compress the air. As the piston enters the down stroke, air is drawn into the cylinder from atmosphere through an air inlet valve. During up stroke, the piston compresses the air and forces it through a discharge control valve and out of the compressor. Reciprocating compressors are multiple-cylinder (higher capacity) or multiple-stage (high pressures).

Single-Stage means that air is drawn in, pressurized and discharged in one stroke. Two-Stage Compressors compress air to an intermediate pressure in a first cylinder and then to a higher pressure in a second cylinder.

Single Stage compressors are used for continuous operation pressure ranges up to 100 psi (7 bar) and 150 psi (10.5 bar) for intermittent operation. Two Stage Compressors are used for pressure ranges between 100 psi (7 bar) and 200 psi (14 bar).

Reciprocating compressors most widely used in industry and are suitable for applications that require low flow rates and/or high pressure. Important characteristics are highlighted below:

- Pressure can be developed on one or both sides of the piston. The reciprocating air compressor is said to be single acting when compression is accomplished using only one side of the piston. A compressor using both sides of the piston is considered double acting.
- Single-stage compressors are generally used for pressures in the range of 70 psig to 100 psig. Two-stage compressors are generally used for higher pressures in the range of 100 psig to 250 psig.
- Capacity control is achieved by unloading individual cylinders. Typically, throttling the suction pressure to the cylinder or bypassing air either within or outside the compressor accomplishes this. In engine-driven units capacity control is achieved by varying the speed through fuel flow control.
- Too great a compression ratio (absolute discharge pressure/absolute intake pressure) may cause an excessive discharge temperature, among other problems.
- Reciprocating air compressors are available both as air-cooled or water-cooled, and in lubricated and non-lubricated configurations. They may be packaged, and can be provided in a wide range of pressure and capacity selections.
- Non-lubricated cylinder designs utilize PTFE style rider and wear rings on the pistons. Oil-less designs, utilizing sealed-for-life bearings, are frequently applied in applications that cannot tolerate lubricant contamination in the process or product. If

oil-lubricated reciprocating compressors are used, positive metering, block-type lubricators should be used to reduce excess accumulation of carbon deposits on valves and cylinders.

- For large volumes of compressed air, the reciprocating type is usually the most expensive to purchase and install, and require greater maintenance. However, they may exhibit a lower associated cost at small capacities. Large foundations are required due to their size and the vibration generated. They may not be suitable where noise emissions are an issue. Nevertheless, they are the most energy efficient, both at full and partial load.
- For practical purposes, most plant air reciprocating air compressors greater than 100 horsepower are built as multi-stage units in which two or more steps of compression are grouped in series. Air is normally cooled between stages to reduce the temperature and volume entering the stage following.
- Two major types are single acting (using one cylinder) and double acting (dual cylinder) both of which are available as one or two stage compressors. Single-cylinder, single-stage and double-cylinder, two-stage configurations are the most common styles found in industrial applications.

2. <u>Rotary Screw Compressors</u> (Sizes 30 cfm to 3,000 cfm)

Rotary Screw air compressors are also positive displacement type units. However, instead of a piston, the rotary screw compressor increases pressure through the action of two intermeshing rotors within twin-bore housing. Air is trapped between the rotors and housing. As it moves along the rotor, air volume is decreased and pressure is increased because the allowable space for the trapped air is progressively reduced.

The most common rotary air compressor is the single stage helical or spiral lobe oil flooded screw air compressor. Important characteristics of rotary screw compressors are highlighted below:

- There are no valves. These units are basically oil cooled; the oil seals the internal clearances. The oil coolers, in turn, are either air or water-cooled.
- Screw compressors are available in both oil injected and oil free types. The oil free rotary screw air compressor utilizes specially designed air ends to compress air, without oil, in the compression chamber. This yields true oil free air.

- Since the cooling takes place immediately within the compressor, the moving parts never experience extreme operating temperatures.
- Capacity control for these compressors is accomplished by variable speed or variable displacement. A slide valve is positioned in the casing for the latter control technique. As the compressor capacity is reduced, the slide valve opens, directing a portion of the compressed air back to the suction. Advantages of the rotary screw compressor include smooth, pulse-free air output, in a compact size, with high output volume, over a long life.
- Oil free rotary screw air compressors are available in two configurations: dry and water injected. They have the same benefits of the oil injected screw compressors, but compress in two stages, and have no lubricant in contact with the air during its passage through the compressor.

3. <u>Centrifugal Compressors</u> (Sizes 400 cfm to 15,000 cfm)

The centrifugal air compressor is a <u>dynamic</u> compressor that uses high speed rotating impellers to accelerate air. They are suitable for high gas volume applications in the chemical process industry, steel plants, oil refineries, and gas transmission systems. Important characteristics are listed below:

- Centrifugal compressors produce a high-pressure discharge by converting angular momentum imparted by a rotating impeller (dynamic displacement). In order to do this efficiently, centrifugal compressors rotate at higher speeds than the other types of compressors.
- These types of compressors are designed for higher capacity because air flow through the compressor is continuous.
- Capacity control is achieved variable speed drives or by adjusting the inlet guide vanes. By closing the guide vanes, volumetric flows and capacity are reduced. Centrifugal air compressors have a limited capacity control range, and below 70% percent capacity, the excess air can be blown off to atmosphere.
- Centrifugal compressors run at relatively high speeds and noise control is usually required.
- The centrifugal air compressor is an oil free compressor by design. The oil-lubricated running gear is separated from the air by shaft seals and atmospheric vents.

- To reach operating pressures, several impeller stages are required. They have low installation costs, but are expensive to purchase because they are precision machines. They are fairly efficient down to approximately 60% of their design output.

4. **Vane Compressors**

A Vane compressor is a positive displacement machine having a rotor with metallic sliding vanes inside an eccentric housing. The vanes form pockets of air that are compressed as the rotor turns, until an exhaust port is exposed. This working principle is also widely used in air motors. Important characteristics are highlighted below:

- The sliding vane compressor normally is sold as a package and is available in the range of 10 HP to 200 HP, with capacities of 40 cfm to 800 cfm, and discharge pressures from 80 psig to 125 psig.
- The advantages are: compactness, low first cost, need no for special foundation consideration, and partial load capacity control.
- The disadvantage is: less energy efficient than the rotary screw type, both at full load and partial load.

SYSTEMS DESIGN CONSIDERATIONS

There is a wide choice of different types of compressor designs available today. The type of compressor chosen has direct implications on the lifetime energy costs. When designing a compressed air system, there are a number of issues that require consideration, including:

1. Type of compressor
2. Size of compressor
3. Required pressure
4. Air quality
5. Variable or steady load

Which type of compressor is most suitable?

System selection is a decision controlled by the type of work expected. The variables that need evaluation in order to determine suitability are:

- What are the hours of operation per month or year?
- Is the compressed air demand steady during operations, or does it vary greatly?

- Is the operating environment clean or dirty?
- What are the pressure requirements of the compressed air system?

Comparative Analysis (Reciprocating, Rotary Screw and Centrifugal Compressors)

1. **Reciprocating compressors**

   Single acting, two stage, air-cooled units satisfy most applications. These compressors do well under widely ranging demands because they are relatively efficient at light load, and are less costly to purchase. However, for maximum service life, these compressors must be sized so the maximum demand placed upon them does not exceed 75% to 80% of their full-rated output, for periods of more than one half hour. Exceeding this can lower the service life considerably, and in extreme cases, can lead to valve refurbishing or complete replacement, in less than one year. Dirty conditions shorten the service of all air compressors; however, reciprocating compressors are less affected than rotary screws. Reciprocating compressors are best suited for low volume, high pressure applications.

2. **Rotary screw air compressors** are best suited for steady loads with long hours of operation. Under 24 hour-a-day, 7 day-a-week service, a rotary screw will last longer than a reciprocating compressor. However, it is not as energy efficient under light loads. In addition, at higher pressures (175 psig), they do not produce generally as much volume (cfm) compared to the two-stage piston compressor. For the same rated volume output, they are usually more expensive to purchase. However, under steady load conditions, they can be price competitive since they perform best at full load, in contrast to the reciprocating compressor, which should not be loaded more than 75% over long periods of time. As an example, a 10 HP rotary screw compressor can be expected to produce a steady flow of air that could require a 15 HP reciprocating air compressor to produce at its 75% or 80% load factor.

   Rotary screw compressors are the most widely applied industrial compressors in the 40 HP (30kW) to 500 HP (373 kW) range. The popularity of the rotary is due to the relatively simple design, ease of installation, low frequency maintenance requirement, ease of maintenance, long operating life, and affordable cost.

3. **Centrifugal compressors** are used to supply large quantities of air for a medium to high pressure range. These are better suited for steady state operation, where there is minimum process swings during normal operation. Centrifugal machines are susceptible to surge at low mass flow rates. This instability is very severe in

compressors producing high pressure ratios and it may result in high frequency vibration and damage to bearings, impellers, shaft seals, couplings, etc. At higher mass flow rate, a point is eventually reached where mass cannot be increased any further. This is known as choking.

Positive displacement screw or reciprocating machines are not subject to these dynamic performance characteristics.

In summary, some typical evaluation considerations are discussed below

1. **Short listing based on Application**

- In general, reciprocating compressors are by far the best choice for small volumes in situations where operation is short-term or intermittent, and load is fluctuating. An example would be a tire shop where demand varies.
- Screw compressors are best where the demand for compressed air is relatively constant, as in a production line situation. Reciprocating compressors can be used in conjunction with screw compressor systems to provide smaller amounts of air that may be required on weekends or at nights.
- Centrifugal compressors are better suited for heavy demand applications requiring steady state operation and negligible process fluctuations.

2. **Short listing based on sizes**

- For flow rates below 2,000 SCFM, a choice exists between reciprocating and screw compressors. Typically reciprocating compressors are better in lower ranges below 750 SCFM while screw compressors are preferable between 750 to 2,000 SCFM.
- For flow rates between 2,000 and 4,000 SCFM, both a screw compressor system and a centrifugal compressor system should be evaluated.
- A centrifugal compressor system is most cost effective above 4,000 SCFM.

3. **Partial load efficiency**

Efficiency when operating at partial load is a very important aspect of analysis.

- A screw compressor offers infinite load reduction from 100% to 0% and affords good partial load efficiency.
- A centrifugal machine accomplishes capacity reduction in stages. Partial load efficient of centrifugal machines is poor and significantly impacts annual energy requirements.

- A reciprocating compressors uses stepped capacity control and is more efficient at minimum load than a twin-screw compressor.

4. Air density issues

Changes in air density associated with temperature and humidity will affect the output of an air compressor greatly. During the winter months, compressor capacity is increased as the air is generally denser and dryer. During summer months, air is expanded due to higher temperature and humidity; therefore, capacity is reduced. Similar changes in compressor performance as a result of air density are caused by elevation.

- With positive displacement reciprocating and screw compressors, the air mass flow rate delivered at a given pressure is directly proportional to air density. The average power requirement will vary a total of approximately 2 to 3%.
- Centrifugal machines will experience increased mass flow rates and power requirements during colder ambient conditions. The power can increase as much as 10 to 15% and the machine can surge if the inlet throttle valve located upstream of the compressor fails to compensate the inter-stage pressures.

5. Reliability and maintenance

- The number of moving parts is greatest in the reciprocating compressor while the centrifugal compressor has the least number. The reciprocating compressor can require frequent and considerable maintenance.
- Rotating equipment is subjected to high vibration when operating near a critical speed. The screw compressor is not subjected to high vibration or unbalance problems with rotors operating at half or below the first critical speed.
- Centrifugal machines operate at high speed, between the first and second critical rotational speed. They are susceptible to unbalance and vibration, and require more comprehensive maintenance audits at regular intervals.

6. Field Serviceability

Serviceability of the screw compressor is relatively simple. Because all parts are removable and replaceable, it is serviceable in the field.

- The above is also true for the centrifugal compressor; however, a significant problem is posed with a failed rotor. Each centrifugal rotor is unique. As such, they are not standard equipment or stock items that fit interchangeably with similar units in the field.

- Field serviceability of most reciprocating compressors, while possible, is tedious due to the large number of associated parts.

7. **Stock availability of spares**

   Most screw compressors manufacturers have a number of machines in stock, as well as the rotors, bearings, seals, and so forth.

   - Centrifugal compressor rotors are not stocked and can require 10 to 12 weeks to fabricate.
   - Reciprocating compressors are normally available from local stocks.

8. **Startup Operation**

   - The anti-friction bearing in a dry screw compressor does not require pre-lubrication or post lubrication oil pumping equipment. The screw and reciprocating machines can start-up immediately.
   - Centrifugal machines require between 10 to 20 minutes preheating and circulating the lubricating oil before the machine can be started and fully loaded. Oil is needed to support the impeller shaft and prevent failure of hydrodynamic type bearings during start-up.

COMPRESSOR CONTROLS

Control for Reciprocating & Rotary Compressors

Each compressor type may incorporate any of the different control systems to match the compressor volume and pressure to the demand. The most popular are described here. All of these controls monitor the system pressure and maintain it between a minimum and maximum value.

1. **Start/Stop**

   Start/stop control is frequently used by small reciprocating compressors. In this type of control, the compressor turns itself off and draws no power as long as the discharge pressure remains above a specified level. This is the most energy-efficient type of control since the compressor runs at maximum efficiency when compressing air and turns off when not compressing air.

   But this can not be used in large compressors because of the obvious difficulty involved in frequently starting and stopping a large-rated motor. It is also unsuited for applications where a large pressure control range is not allowable. It is usually used with small compressors supplying infrequent capacity demands.

2. **Load/Unload Control**

With load/unload control, the compressor runs fully loaded, producing compressed air at maximum efficiency until the discharge pressure reaches the upper activation pressure setting, which causes the compressor to unload. When unloaded, the compressor no longer adds compressed air to the system, but the motor continues to run.

Each compressor type performs this cylinder unloading differently. Reciprocating compressors are unloaded by holding the inlet valve open, preventing air induction and compression. Rotary compressors are partially unloaded by controlling the inlet air and bleeding the discharge pressure to the atmosphere. Throttling is employed in rotary compressors by a valve in the air inlet that restricts the airflow in response to the compressor output pressure.

3. **Multistep Partial Load Control (Reciprocating Compressor)**

This type of control uses multiple pressure switches, operating at evenly spaced increments within the pressure control range. An example is a double-acting reciprocating compressor with two control mechanisms. The first control is an inlet valve depressor on each cylinder that is used to unload cylinders, thereby resulting in 0%, 50%, or 100% capacity. The second control is accomplished by using clearance pockets in both cylinders. These pockets are designed to change the volume of the cylinders by 50%. Thus this compressor can work with delivery percentage capacities of 0, 25, 50, 75, and 100 %.

4. **Modulation Control**

With inlet modulation control, the inlet air valve to the compression device is continuously adjusted, restricting the inlet air to vary the compressed air output to meet the demand on the system. Auto-dual control is a combination of modulation and load/unload control in which the compressor operates in modulation control down to a specified pressure and switches to load/unload control below this pressure. With variable displacement control, the effective length of the compressor rotor is varied by valves in the rotor housing. Variable displacement has an effective capacity control range of between 60% and 100% of compressor load. Below 60% load, the compressor must utilize some other form of capacity control. The fallback control is normally modulation.

5. **Variable Speed Drive Control . . . also known as Variable Frequency Drive**

   Since compressor output is a function of rotor length and rotor speed, the variable frequency drive equipped compressor matches supply to demand by varying the speed of the rotors. As system pressure rises toward a set point, the variable frequency drive reduces compressor speed by reducing the frequency of the power it supplies to the motor. As system pressure reduces, signaling a need for more air, the drive increases compressor speed by increasing the frequency of the power to the motor. This capacity control system achieves highly efficient partial loading between 20% to 100% of compressor capacity. Below 20% loading, the inlet valve closes and the compressor simply shuts off.

Control for Rotary Compressors

Most rotary compressors are unable to run in start/stop mode, thus, the compressor continues to run even as the demand for compressed air declines or ends. Most rotary compressors use either load/unload, inlet modulation, auto-dual, or variable displacement control.

Recently, rotary compressors with variable speed motor drives have become available. Variable-speed compressors vary the speed of the compressor motor to meet the compressed air demand. In general, for variable torque loads such as air compression, the load on the motor varies with the cube of the motor speed. Thus, decreasing the speed of the motor during periods of low compressed air demand significantly decreases the load on the motor, and variable-speed compressors operate very efficiently at low loads.

Control for Centrifugal Compressors

From energy efficiency point of view, variable speed motor is the best control option.

Adjustable inlet guide vanes are the most frequently used control for the centrifugal compressor. While not energy efficient, they produce excellent partial load performance over a wide control range.

The adjustable diffuser vane mechanism is another type of control possible in such compressors.

Multiple Compressor System Controls

Many compressed air systems require simultaneous operation of more than one compressor. When operating a facility with multiple compressors, an efficient overall control design must focus upon the following four areas:

1. Shut off of unwarranted compressors;

2. Delay bringing additional compressors on-line as long as possible;
3. Fully load as many compressors as possible and partially load only that compressor that has the most efficient partial load performance;
4. Reduce plant pressure to its absolute minimum.

Older control methods use sequencing while more modern methods use programmable logic controllers (PLCs) that can significantly reduce the overall energy requirements of the system by optimizing the performance.

The simplest sequencing systems are pressure controlled only, sequentially loading and unloading different compressors. Pressure and time control systems incorporate one or more time delays in the start/stop cycling of the various compressors. Recycle timers are used to reduce the frequency of starting. Some set a minimum-on or minimum-off time. More complex systems use a combination of two pressure switches and timers to reduce the system pressure band.

More modern approaches make use of a master controller that will coordinate the operation of each compressor individual controller within their functional range. Ideally this master controller should be able to interpret the air demand within the system and select the best combination of compressors to fill the supply requirements.

In the case of multi-compressor installations, compressors fitted with variable frequency drives (VFDs) controlled by a PLC system will be the ideal system for maximum energy savings.

COMPRESSOR SIZING

Two factors affect the determination of the total compressor capacity.

1. The required compressor capacity (flow) in SCFM (or Nm^3/hr);
2. The maximum air pressure (psig or bar gauge) required.

Estimating Capacity

When selecting an air compressor for a new or retrofit application, the following assessments should be made:

Determine the functional and operational requirements by assessing the user points (tools, instruments, machinery, blow-guns, etc.) and load profiles including location, hours of operation, number/type of equipments/tools being used etc.

In new installations, the compressor is generally sized by adding all the likely individual plant loads allowing for: simultaneous use; constant demand requirements; and intermittent air users by employing diversity factors. Ideally, the total capacity would be based on exact knowledge of the equipment or process requirements.

In existing installations, it may be possible to monitor current demand and use this to size a replacement compressor.

When estimating the total air capacity required, one must account for all losses. These must be added to the required SCFM in order to deliver the required capacity for the facility. Adding excessive or arbitrary "future changes" or "standby" margins to the output of selected compressors should be avoided to ensure energy efficiency. Standard practice calls for a 10 to 15% allowance to be included as a contingency for unpredictable demand, air losses, leakages, equipment wear, and so forth. In addition, a 15% purge requirement should be included if heat-less type desiccant dryers are used. (Refer to the section on air treatment for additional information on this topic).

Potential Pitfalls of Failure to Conduct Correct Sizing

- If the total air consumption is underestimated, the compressor will be sized too small and will be unable to maintain the required pressure in the system.
- If the total air consumption is greatly overestimated, there may be excessive capital investment and reduced efficiency. Oversized air compressors are extremely inefficient.

Evaluating Pressures

When designing (and operating) a system it is important to correctly evaluate the amount of pressure required. Air must be delivered to the point of use at the desired pressure and in the right condition.

<u>Step # 1</u>

Walk through the facility and make a list of the items (tools, instruments, machinery, blow-guns, etc.) that use compressed air. Consult the data sheets/catalogues of this pneumatic equipment for the effective pressure ranges. Generally most instrumentation applications are satisfied with a pressure of 100 psig. Some special plant or service air applications may require a pressure of 150 psig or higher.

<u>Step # 2</u>

Next, take into consideration the pressure drop through the piping system as well as heat exchangers, dryer(s) and filter(s). Generally 10 to 20 psig over the maximum pressure required at a given point of use is satisfactory. Thus, to assure a 100 psig header pressure, the compressor should be rated at a minimum of 125 psig.

Potential Pitfalls of Incorrect Pressure Determination

- Too low a pressure will impair tool efficiencies and affect process time.
- Too high a pressure may damage equipment, will promote leaks, and will increase operating costs. For example, an extra 200 kPa of pressure could be responsible for approximately 8 to 16% of a plant's total energy costs.

Verifying Capacity (Illustration)

A compressor, that has a 25 gallon receiver tank, bears a tag stating that the unit delivers 6.5 HP and 10 cfm at 90 psi. The task is to verify if this is really true.

Trigger a refill cycle by bleeding out air slowly with the relief valve.

Observe on the tank gauge, not the downstream gauge that the compressor "cuts in" at 85 psig and again, "cuts out" at 102 psig.

With a stopwatch, measure the time duration between cut-in and cut-out. Assume that it operates for 35 seconds to build up that pressure.

Divide the tank volume in gallons by 7.48 (1 cubic foot = 7.48 gallons) to determine the tank volume in cubic feet. Thus the tank volume is 25 gallons ÷ 7.48 gal/cu-ft = 3.3 cubic feet.

Since 1 atmosphere (atm) of pressure = 14.7 psi, the observed cut-in and cut-out pressures can be converted to 5.8 atm and 6.9 atm, respectively. Consequently, the compressor adds 1.1 atm of pressure (6.9 – 5.8) during the operational cycle.

When a compressor pumps one "CFM" (cubic foot per minute), it means it drew in one cubic foot of "free air", or air at atmospheric pressure. Thus in one cycle, the rate at which air is being pumped into the subject tank, is the pressure rise multiplied by the volume of the tank, or 3.3 cubic feet times 1.1 atm = 3.6 cubic feet in 35 seconds. To arrive at the pumped volume per minute, the 35 second cycle time must be converted to minutes by multiplying by 60/35, resulting in 3.6 * 60/35 = 6.2 cfm (at 85 psi).

The error range in this estimate is perhaps about 30 percent, meaning the true value might be perhaps as much as 8 cfm or as little as 4 cfm. Certainly this is not performing at the 10 cfm data plate rating.

This is one simple technique, using just a stopwatch, to verify capacity. It could also be applied to leakage estimation. The example above considers on-off type control of the compressor;

however, the same technique could be applied to the load-unload type of control by listening carefully to the compressor's operational noise pattern.

SYSTEM CONFIGURATIONS (Matching Loads)

The required system configuration should be determined based on the quantity and individual unit capacity; the total capacity, and operational requirements; and reliability, and maintenance considerations.

It is very important to correctly size the system, as oversized air compressors are extremely inefficient. Constant speed air compressors are most efficient when operated at full load. Consequently, select the size of the compressor that operates as closely as possible to full load.

The next step is to provide the correct number of compressors, each of suitable capacity, to meet the maximum plant demand. The selection process should also include a standby compressor that will support the maximum plant demand, thus allowing for maintenance on any given compressor, without interrupting system service.

Because modern compressors have high reliability, standby plant requirements should be carefully considered and not estimated. It is good practice to include a standby compressor equal in size to the largest capacity machine. However, it is possible to reduce capital costs by opting for a smaller capacity standby compressor. This will be determined based on the down-time that can be accommodated and/or the availability of mobile units.

Typically, peak demand periods are of shorter duration than say, second, third or weekend shifts. Having one compressor sized for peak demand will mean it is operating inefficiently an average of 85% of the time. Installing multiple compressors to match the peak while incrementally matching other lower compressed air demand periods, will pay for the additional procurement costs in energy savings. It is usually more efficient to run a smaller compressor at full load rather than a large one at low load.

Demand Patterns and Compressor Combinations

Demand patterns for compressed air can be relatively constant, stepped, or widely fluctuating, and will vary considerably from factory to factory.

When designing a system it is important to understand not only how much air is required, but when it is needed. The first task is to determine if any processes can be altered to flatten the load. If a simple change in the timing of an activity can occur, it may result in reduced peak demand, thereby lowering costs.

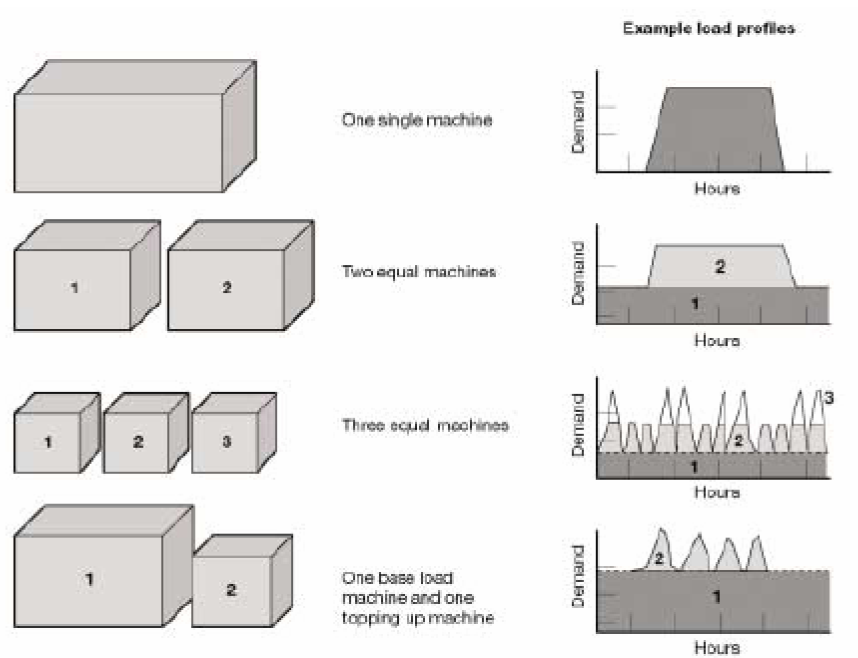
Load will also affect compressor selection. If the load is constant for all periods, then clearly a single, correctly sized compressor will efficiently do the job.

However, with stepped or fluctuating loads, it is often more efficient to use a combination of compressors and controls (including variable output and variable speed technology) rather than one large compressor running at partial load. Remember, air compressors are most efficient when operating at, or near, full load.

The figure below presents some examples of demand patterns and how they can be satisfied efficiently with combinations of multiple compressors.

In addition, demand peaks can be smoothed and peak loads reduced by using storage receivers. A storage receiver can typically store 5% to 10% of the compressor capacity, thus avoiding excessive cycling and partial load operation. This improves energy efficiency and reduces wear on the compressor. During periods of sudden high demand, an extra receiver near the point-of-use may preclude the need to provide extra capacity.

Meeting Demand Patterns Efficiently with Combinations of Compressors



It is usually more efficient to run a small compressor at full load as opposed to a large one at low load.

Do not install an oversized compressor to meet anticipated future demand. It is usually more economical and more efficient to install an additional, appropriately sized compressor, when a future need develops.

Choose suitably sized receivers to act as buffers between output and demand.

AIR QUALITY

The required "Quality" of air has three main considerations:

1. Maximum acceptable moisture content or pressure dew point;
2. Maximum acceptable oil content;
3. Maximum acceptable particulate concentration.

Different end-uses require different levels of air quality. The quality of the compressed air produced by a system can range from normal plant air to high quality breathing air.

Air Quality (in descending quality)	Applications
Breathing Air	Hospital air systems, refill diving tanks, respirators for cleaning and/or grit blasting and spray painting
Process Air	Food and pharmaceutical process air, electronics
Instrument Air	Laboratories, paint spraying, powder coating, climate control
Plant Air	Air tools, general plant air

Dryness and contaminant level are the two key factors for distinguishing low quality air from high quality air. The higher the quality, the more the air costs to produce. Higher quality air usually requires additional equipment, which not only increases initial capital investment, but also makes the overall system more expensive to operate with regards to energy consumption and maintenance costs. It is therefore important, when designing the system, to accurately assess the level of air quality required.

Internationally, guidelines are available for the specification of air quality. An example is ISO Standard 8573, which defines different classes, as shown in table below:

<u>ISO 8573 Air Quality Classifications</u>

Class	**Oil Carryover (mg/m^3)**	**Dust Carryover (mg/m^3)**	**Moisture carryover (mg/m^3)**
1	0.01	0.1	0.003
2	0.1	1	0.12
3	1	5	0.88
4	5	8	6
5	25	10	7.8
6	-	-	9.4
7	-	-	-

When selecting a compressor, consideration should be given to the level of air quality required. If lubricant-free air is required, it can be achieved with either lubricant-free compressors, or with lubricant-injected compressors that support additional separation and filtration equipment. Lubricant-free compressors usually cost more to install and have higher maintenance costs.

Lubricant-injected compressors, while more economical to purchase, have the additional associated capital, energy, and maintenance costs, of separation and filtration equipment. Before selecting a lubricant-free or lubricant-injected compressor, careful consideration should be given to the specific end-use for the lubricant-free air, including the risk and cost associated with product contamination. The table below lists some of the characteristics of these two types of compressors.

Characteristics of Lubricated and Non-lubricated Compressors

Non Lubricated Compressor	**Lubricated Compressor**
May require fewer filters and oil changes	Considerably lower capital costs
Longer operational life	Oil provides a cooling effect
Often preferred when manufacturing sensitive products such as food or pharmaceutical applications	Lower speeds and temperatures

Non Lubricated Compressor	**Lubricated Compressor**
High capital costs. Routine service costs usually high	Filter maintenance and oil changes require quite often
To reach high pressure need multistage compression.	Due to pressure drop air treatment capital and running costs are higher

Instrument air service preferably would use the non-lubricated compressor. ANSI/ISA 7.0.01, Quality Standards for Instrument Air, specifically states, "Although not recommended, if lubricated compressors are used, lubricant removal is required to avoid damaging effects on air system components and end-use devices."

In addition to understanding air quality requirements and compressor types, efficient methods to reduce contaminants should be investigated. Prior to the compression cycle, an air compressor draws in water vapor, dirt, and atmospheric pollution.

During the compression process the volume of air is reduced, resulting in an increase in the concentration of contamination. Additionally, further contaminants such as oil vapor or wear particles can be introduced by certain types of compressors during the compression process.

A high concentration of contaminants almost always means that the compressed air cannot be used without some form of treatment. A wide range of filtration and drying equipment is available to improve air quality. However, it should be remembered that careful selection, installation, and maintenance of treatment equipment is required to reduce the energy costs of air treatment. These costs can be quite high and can include the direct energy cost for running the equipment, the extra power generation cost needed to overcome additional pressure drops, and the possible cost of purging air.

COMPONENTS OF COMPRESSED AIR SYSTEMS

Most compressed air systems consist of following three major sub systems:

1. Compressors with drives and controls, inter-cooling, compressor cooling, waste heat recovery, and air inlet filtration;
2. Conditioning equipment consisting of after coolers, receivers, separators, traps, filters and air dryers;

3. Air distribution subsystems, including main trunk lines, drops to specific usage, valving, additional filters and traps, air hoses, possible supplementary air conditioning equipment, connectors, and often pressure regulators and lubricators.

The important components of the system are:

1. **Inlet Filter:** Removes particles from the air entering the compressor.
2. **Compressor:** Compresses air to a smaller volume, increasing the pressure.
3. **Motor:** Drives the compressor.
4. **Compressor Controller:** Directs the compressor's output. It may be microprocessor, electromechanical or pneumatically based. Advanced controllers include machine protection and information management.
5. **Aftercooler:** Compression leaves the air hot and wet. The aftercooler lowers the temperature of the air, thus condensing and removing the water.
6. **Separator:** Removes liquids from the compressed air. These are generally installed in compressor after the aftercooler.
7. **Receiver:** Stores a large reserve of compressed air to maintain a smooth flow to the plant.
8. **Air line Filter:** Removes solids and liquids from the compressed air stream. Filters can be placed throughout the system.
9. **Dryer:** Helps to eliminate any remaining moisture in the compressed air by using either a refrigerated condenser or a desiccant. Refrigerated condensers cool the air to condense water vapor into a liquid that is then drained from the system. Desiccants are powders or gels that remove water by absorbing it.
10. **Condensate Trap:** Collects and discharges liquid that condenses out of the air stream. Integral part of after coolers, dryers and separators
11. **Distribution Piping:** Links the components. It distributes the air from a main header to branch lines and sub headers to drop points connected to individual tools.
12. **Pressure regulator:** Controls air pressure and flow at individual points of use.

COMPRESSED AIR TREATMENT

Compressed air leaving the air compressor is usually of too low a quality for the intended use. This is due to several factors.

- The air discharged from the compressor is saturated with moisture;
- If the compressor is the lubricated type, the air discharged has oil traces;
- Other contaminants in the intake air are compressed and carried along, the concentration of which depends on the outdoor air quality and the efficiency of intake filter.

Moisture in compressed air systems can cause many problems, among the most serious of which are:

1. Rust and scale forms in the air piping and is blown into sensitive equipment.
2. Lubrication is washed away in air tools and process equipment increasing maintenance and reducing equipment life.
3. Product damage, such as "fish eyes" in spray paint applications.

Why is there so much water within a compressed air system?

All atmospheric air contains a certain amount of water vapor which is mixed with other gases making up the air. This water vapor is drawn into the compressor with the incoming air. The act of compression generates large amounts of heat which allows this water to remain in a vapor state. As the air/water mixture cools, either in a receiver, dryer, or in the system piping, the vapor condenses to liquid, and falls out of the air stream.

The table below provides information on the quantity of water, in gallons, passing through a 1,000 cfm compressor, during 24 hours of operation, at an operating pressure of 100 psig.

Entering Air Temp	**Relative Humidity %**				
	20	**40**	**60**	**80**	**100**
110°F	128.98	257.99	386.97	515.98	644.97
100°F	97.62	195.28	292.94	390.58	488.22
90°F	73.06	146.13	219.19	292.25	360.37
80°F	54.02	108.04	162.03	216.05	270.07
70°F	39.42	78.84	118.26	155.21	194.64

Entering Air Temp	Relative Humidity %				
	20	**40**	**60**	**80**	**100**
60°F	28.38	56.76	85.14	113.52	141.90
50°F	20.13	40.26	60.41	80.55	100.68
40°F	14.08	28.16	42.21	56.29	70.37
30°F	9.56	19.12	28.68	38.24	47.79
20°F	6.10	12.2	18.30	24.40	30.50
10°F	3.83	7.66	11.56	15.34	19.02
0°F	2.37	4.74	7.14	9.56	11.88
-10°F	1.41	2.79	4.20	5.61	7.01
-20°F	.82	1.63	2.47	3.29	4.10

It's worth noting that air at higher pressure cannot hold as much moisture as free air at the same temperature. Moisture would normally condense during compression but because the temperature of the air increases, which increases its ability to hold moisture in vapor form, there is no condensation.

In lubricated compressors oil vapor can condense with the water and form an emulsion. Unless removed, these contaminants can travel throughout the system and create downstream equipment operational problems, lead to corrosion, produce high pressure drop, and result in serious and damaging effects on instrumentation, processes, pneumatic tools, and products.

Compressed air drying and filtering, or in some cases just filtering, is an important decision. Experience indicates that a dryer performs best on the control of condensate. An aftercooler is normally a standard attachment with the compressor that greatly assists in dryer load reduction.

The following sections investigate the various technologies available to treat compressed air. Their efficient operation to save energy and money is explained.

AFTERCOOLERS

Air's ability to hold moisture approximately doubles for every 20°F (11°C) incremental increase in atmospheric temperature!

Or stated conversely, the moisture holding capacity of air reduces by 50% for every 20°F (11°C) drop in compressed air temperature.

Aftercoolers are heat exchangers that use either water or ambient air to cool the compressed air. As the water and lubricant vapors within the compressed air cool, a significant amount condenses into liquid. The amount of condensation depends upon the temperature of the air when it leaves the aftercooler. When the compressed air is cooled in the aftercooler, the air is unable to hold all the moisture and it condenses out in the form of liquid water. Good aftercooling can extract 70 to 80% of the moisture in the air and dramatically reduce the moisture loading on air dryers.

Most modern air compressors have an aftercooler located immediately after the compressor as a standard fitting to perform the function of removing water and some oil vapor.

Air temperatures are typically as high as 260°F at the outlet of the air compressor. Aftercoolers can be either air-cooled or water-cooled. The water-cooled type typically results in an outlet air temperature of approximately 80 to 110°F, e.g. an approach of 10 to 15°F. The air-cooled aftercooler is generally less efficient, resulting in higher outlet air temperatures. However, in smaller applications they are often more economical to operate than water-cooled units.

Water-cooled aftercoolers are more efficient because the cooling medium of water is usually considerably cooler than the surrounding air. The cost of the water-cooled aftercooler equipment is low; however, the cost of the cooling water can be very high. Consider that in many areas not only is there a cost for water, there can be a sewage charge to dispose of the resulting warm water. For energy conservation reasons, it is wise to consider waste heat recovery possibilities, e.g. process water or boiler water preheating, as a part of an overall energy efficiency program.

In most cases the aftercooler is part of the compressor package. The aftercooler operation consumes approximately 2% of the total package power.

In undried systems, an air-cooled aftercooler with a coalescing filter normally will be placed near, or as an integral part of the compressor, to eliminate the large amount of water condensed.

COMPRESSED AIR DRYERS

Atmospheric air entering a compressor has certain humidity or contains some water vapor. The moisture in compressed air can be liquid water, aerosol (mist), and vapor (gas). The most noticeable and easily removable forms of moisture are water and aerosol. They can be removed by high efficiency filtration in conjunction with refrigeration dryers. Water vapor is more difficult to remove and requires the use of a dryer (desiccant type) in conjunction with high efficiency filtration.

There are various drying options; the specific method used depends upon the desired compressed air quality requirements and entering ambient air conditions. Five different compressed air dryers are available, each having different characteristics and each having a different degree of dew point suppression.

The general measurement of air dryness is Dewpoint. Dewpoint is the temperature at which air becomes saturated with moisture and the moisture begins to condense. Lowering the dew point effectively means the system can endure much lower temperatures before water droplets begin to condense.

It should be noted that to prevent corrosion, air's relative humidity (RH) should be 2% or lower. Air at 2% RH is equivalent to a dryness of –30°C pressure dewpoint.

The table below provides a comparison guideline for air dryness.

Dewpoint	Relative Humidity
+10	54%
+3	34%
-20	5%
-30	2% (limit of corrosion)
-40	0.7%
-70	0.016%

Selecting a Dryer

Because compressed air dryers vary in relation to their dewpoint, initial cost, and ongoing maintenance requirements, a determination of the most cost-effective system suitable for a given application must be made. The factors to be considered include:

- The required dewpoint temperature: it should be below the lowest ambient temperature the compressed air system will encounter. Consideration must be given to the location of the air lines. For instance, are they located in front of open doors or windows, within air conditioned or unheated areas, running underground or between buildings.
- The types of dryers that will produce the required dew point
- The initial and on-going operating costs. The lower the dewpoint requirement, the more expensive the dryer's purchase price, as well as the operational cost.

After identifying the type of drying system, the actual conditions under which the dryer will be operating must be determined. This allows for the correct dryer size selection. Actual conditions include:

- Maximum flow capacity (cfm, l/sec)
- Maximum acceptable pressure dew point (°F, °C)
- Minimum inlet air pressure (inches water gauge, kPa)
- Maximum and minimum inlet air temperature (°F, °C)
- Maximum ambient or cooling water temperature (°F, °C)
- Maximum allowable pressure drop (inches water gauge, kPa)

There are 5 main types of dryers suitable for compressed air systems and each will perform differently and will be suited to different applications. More detailed descriptions of each dryer type follow.

Refrigerant Dryers (35 to 50°F Dew Point)

The refrigerant dryer depresses the dewpoint by cooling the incoming air, so condensing moisture out of the air. The dried air is passed through an additional air-to-air exchanger where it is re-heated while the incoming air is pre-cooled. As the temperature of the incoming air to the dryer is reduced, the heat load on the refrigeration system also is reduced. Typically, pressure dewpoints of 35°F are reached which will remove an additional 28% of the initial water content following the aftercooler.

The refrigerant circuit is hermetically sealed and the heat rejection through the refrigerant dryer can be accomplished by air or water. Some 5% is added to the cost of generating the compressed air by this method when the power needed for the refrigeration circuit and the filter pressure drop are taken into account. Refrigeration dryers use well-proven technologies that experience few problems when properly installed and maintained. The problems that can affect the performance, and hence energy consumption, include:

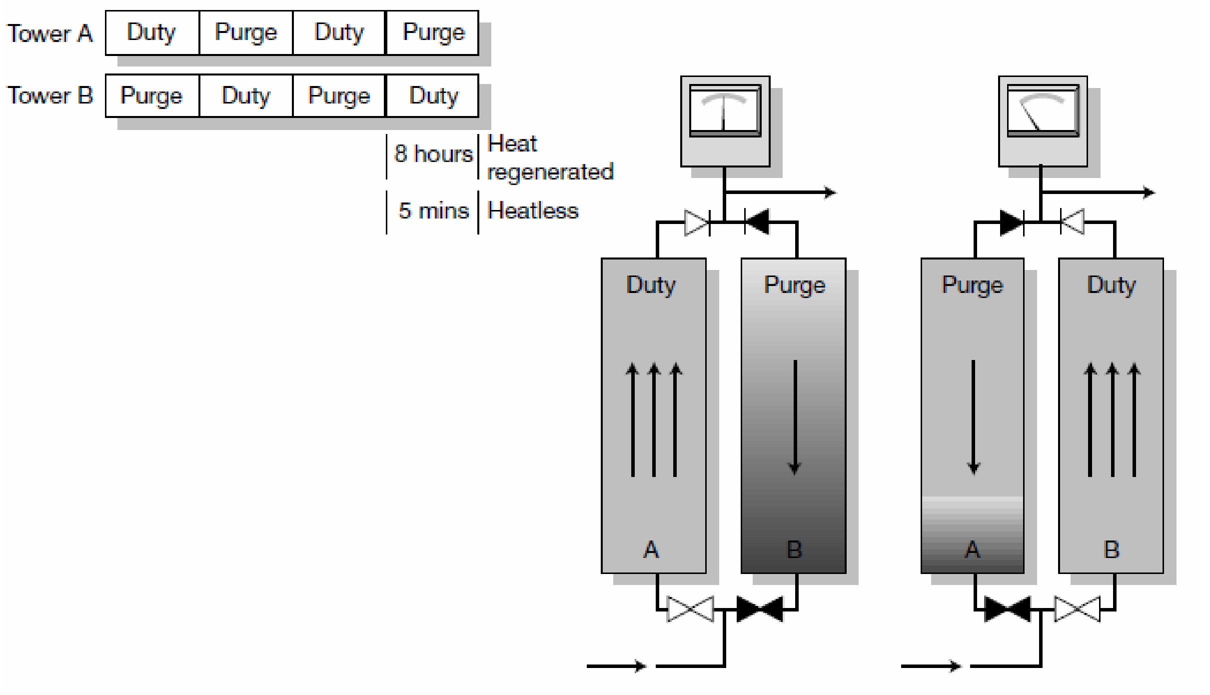
- Internal contamination which effects dewpoint;
- High compressor delivery temperatures;
- High ambient temperatures;
- Poor installation preventing proper ventilation;
- Faulty drain traps that allow liquids to reside downstream of the dryer;
- Loss of refrigerant.

The selection of a compressed air dryer should be based upon the required pressure dew point and the estimated cost of operation. The required pressure dew point for the application at each point-of-use will eliminate certain types of dryers. This method of drying is very popular because it produces dewpoints that are adequate for most duties, in an energy efficient and reliable manner. The estimated electrical load, excluding pressure drop through the dryer, is 0.54 kilowatts per 100 cfm. Some of features that attribute to its popularity are:

- Simplicity and low operating costs;
- Easily serviced by qualified refrigeration technician or firm;
- Facilities with dual tower desiccant dryers that need only to keep dewpoint just below ambient, can use refrigerated dryer most of the year. A PLC control can be used to monitor outside ambient temperature;
- Desiccant dryer would start when air drops below 45°F and refrigerant dryer would start if air rises above 45°F;
- Significant savings can be achieved by non-operation of the desiccant dryer 6 to 8 months per year.

Desiccant Dryers (-40°F to -100°F Dewpoint)

When better dewpoints are needed than those which can be achieved from refrigerated dryers, desiccant dryers are used. In this class of machine the desiccant bed is regenerable. Therefore, all designs have an alternating duty section through which the compressed air being dried is fed, and a non-duty section which is being regenerated (refer figure below). These units can remove vapor phase moisture only and liquid water will pass through or destroy the desiccant.



Regeneration of the desiccant material is required once it reaches near saturation and is unable to retrain additional moisture. Regeneration is accomplished by either heated or heatless dryers.

1. **In heatless or cold regenerative dryers,** 10 to 15% of the dried air is diverted from the outlet of the duty tower to regenerate the desiccant in the non-duty tower. Heatless dryers can be costly to operate because of the high consumption of dry compressed air for wet tower purging. It can be up to 15-17% of the dry air volume.

2. **In the heated type,** purge air is heated to 300 to 400°F and directed through the non-duty tower. Relatively little purge air (1 to 7%) is diverted from the dried air stream in these designs, offering significant operating cost savings in applications over 500 cfm. Maintenance items associate with heated regenerative dryers include heating element failures, switching valve repair or replacement, blower failures, pre-filter and after-filter elements. Moreover, tower desiccant bead replacement is required every 2 to 3 years if the required winter dew point of –40° F must be attained.

3. **No Purge** low energy-use desiccant dryers have recently been introduced in the dryer market. These dryers work on a principle similar to that of the standard desiccant

dryers, however, regeneration is carried out by the use of heated ambient air being drawn through the non-duty section while under vacuum.

Efficient operation of a desiccant dryer can be hampered by,

- Poor cooling of inlet air;
- Poor pre-filtration causing liquid phase water and oil carry-over;
- High peak loads causing desiccant bed fluidization (twin tower type only);
- Faulty changeover valves, resulting in continuous purge;
- Faulty controls causing poor or no regeneration of individual towers;
- Desiccant contamination by oil.

Other Facts

1. The diameter and length of desiccant beds determine drying efficiency. The bed diameter defines the air velocity through the bed. If the velocity is too high, the desiccant will float or fluidize, resulting in significant desiccant degradation. The bed length determines dewpoint consistency; the bed must be of sufficient length to insure proper contact time between the wet air and the dry desiccant to reach the required outlet dew point.
2. Desiccant dryers are reliable, well-proven machines; however, it is important that they be correctly sized, controlled, and maintained. Otherwise they have the potential to be costly, high-energy users. Because the dryer has a fixed purge, it is important that it not be oversized, particularly the heatless models.
3. Considerable energy is wasted if the actual demand is considerably less than the dryer design flow. Dryers supplied with energy management control systems and equipped with dewpoint dependant switching make desiccant dryers more efficient. Dewpoint switching changes the degree of regeneration directly based on the load.
4. Dryers of this type normally have a built-in regeneration cycle that is controlled by a timer, dewpoint control, or a combination of both.
5. Since most use part of the dried air to regenerate the dryer beds, it also has an effect on compressor capacity required. These dryers are more expensive to purchase and are less energy efficient that the refrigerated or deliquescent dryer.
6. These dryers are used in plants that cannot tolerate any amount of water in the compressed air. Chemical, oil, and metal processing industries use these dryers.

7. Most standard regenerative desiccant type dryers provide a pressure dew point of -40°F. Excluding the pressure drop through the dryer, the estimated load is 1.8 kW per 100 cfm to 2.7 kW per 100 cfm.
8. Contrary to the best-intended opinions of those who feel the only way to dry and condition compressed air is by applying desiccant dryers on a 24 hour, 12 month per year basis, the application of a refrigerating air dryer during the summer months can be a viable and more economical option.
9. An optimum mode of operation could be to changeover to the refrigerating dryer during the summer when a pressure dew point of 36 to 39° F is acceptable and, apply the existing desiccant dryer during the winter season when pneumatic valve freezing can be a problem.

General notes applicable to Desiccant dryers:

Typical purge volumes will be from 15-17% of flow diverted from the "dry" side into the "wet" side to dry out the desiccant.

The operating cycle is usually defined as the amount of time it takes for a regeneration cycle to dry the desiccant in each tower. For example, if it takes 4 hours to dry the desiccant in a tower, the operating cycle is 8 hours.

Some manufacturers of desiccant dryers with a heat reactivated (regenerating) system will direct up to 4% of the system's compressed air from the dry tower for some period of time, to cool the hot desiccant.

Deliquescent Dryers (50°F to 52°F Dewpoint)

Deliquescent air dryers rely on chemical action using a salt bed that absorbs the moisture. As moisture is absorbed, some of the salt is dissolved in the water and is lost during periodic draining of the water. This salt consumption is an operating expense.

These dryers are not regenerative.

Deliquescent dryers do not lose air volume (unless fitted with an automatic draining system - generally a timed drain) and have virtually no energy loss.

These dryers are very energy efficient because the only extra energy consumption required is to overcome the pressure drop that occurs within the dryer. However, due to the poor dewpoint, high maintenance, corrosion problems and Health and Safety considerations, this method is now uncommon.

Deliquescent dryer efficiency is hampered by the following factors:

- The deliquescent material needs to be regularly replaced, incurring higher labor and material costs;
- If the dissolved deliquescent material is not correctly drained it can cause pressure drop and blockage of the after-filter;
- In addition, the mixture of salt and water forms brine that is very corrosive. Even with stainless steel drain valves and piping, maintenance is high on the brine drain system.
- The condensate is corrosive and maintenance requirements are relatively high. They are recommended in special situations.
- Corrosion, health, and safety issues also need to be considered when using this method of drying;
- The deliquescent dryer has been supplanted in most applications by the refrigerated dryer. This type of dryer still has its uses however. One is in conjunction with a refrigerated dryer for producing low dew points for compressed air systems in temperatures below freezing.

Membrane Dryers (40 to -40°F Dewpoint)

These dryers diffuse the moisture from atmospheric compressed air to produces dry air with pressure dewpoints typically at +40°F to -40 °F.

The process is quite simple: compressed air passes through a bundle of hollow membrane fibers and the water permeates the membrane walls. The dried air continues down the tubes and into the downstream air system.

Membrane dryers are mostly used in localized areas of a system where low dewpoints are required.

The membranes are highly susceptible to oil and dirt fouling, which causes the membranes to break down quickly. Because the membrane structure is microscopic, it cannot be cleaned and must be replaced.

In oil free environments the membrane dryer should last for many years. Membrane dryers cost as much to operate as heatless desiccant dryers without the advantage of a lower pressure dewpoint. Certain types of membrane can reduce the oxygen content of the compressed air and therefore should not be used in breathing air applications.

The main drawback of the membrane dryer is the relatively large amount of costly and unrecoverable compressed air, called sweep air that is lost through the membrane walls along with the water vapor.

These dryers can prove to be very costly, particularly when operated at light load levels.

Sorption Dryers

Sorption dryers can only be used with an oil-free compressor. Compressed air travels through a sealed segment of a drum that contains the drying medium. A very small motor slowly rotates the drum, drying the air. A portion of the drum is regenerated by hot air taken from a previous process, i.e. by the compressor's waste heat. The cost to provide air by this method is typically around 3% more than delivering aftercooled air.

It is possible to produce dryer air with pressure dewpoints typically at -15 °C to -40°C

Limitations of sorption dryers are:

- Units must be accurately matched to an individual compressor and cannot be shared by multiple compressors;
- The dewpoint output is directly related to the temperature of the cooling medium used;

Sorption drum replacement is expensive.

Treatment Costs

The results, from many practical tests, of the energy consumption versus the achieved air quality in dewpoint terms, of all the types of treatment systems known are shown below. The additional spend on energy is expressed as a percentage of the basic cost of compressed air.

Typical additional costs for drying compressed air

Pressure dewpoint	Dryer type	Typical levels of filtration installed	Added energy cost
+10°C	Deliquescent	Nil	1%
+3°C	Refrigeration	General purpose	5%
-20°C	Membrane	High efficiency	28%
-20°C	Waste heat regenerative	Depends on compressor configuration	3 - 5%
-40°C	Desiccant heatless	High efficiency before, and dust removal after	10 - 15%
-40°C	Desiccant heated or external blower	High efficiency before, and dust removal after	8 - 12%
-70°C	Desiccant heatless	High efficiency before, and dust removal after	21%

COMPRESSED AIR FILTERS

Filtration is a key factor in the proper operation and performance of a compressed air system. Removal of liquid and particulate contaminants is the basic requirement of a filtration package; however, the requirement for vapor removal, ultra-fine filtration, and catalyst filtration are encountered in specialized applications.

Air filters can be located throughout the system and the number and type of filters will vary according to the quality of air required.

The air inlet filter for air compressors is intended to protect the compressor, but often is inadequate to protect downstream equipment. The compressor itself may add contaminants, including wear particles, carbon deposits, and lubricant. These require filtration.

Filters should be selected based on flow rates and pressure drop rather than pipe size. Excess pressure drop causes increased operating costs, short filter element life, and overall reductions in system performance.

Air filters can be divided into two categories:

- Pre-filters, which operate prior to compression and/or drying and,
- After-filters, which are put in place after the air is dried.

Pre-Filters

1. **Inlet Filters** are provided to protect the compressor from incoming dirt. These filters use power to overcome pressure drop, however, this is taken into account in the compressor package performance figures. These filters will affect efficiency when they become dirty and can typically cause an increase in power consumption of 3%. Therefore, it is important to change the filters as recommended by the compressor service manual.

2. **General Purpose Filters** are usually installed between the aftercooler and drying process. Filters remove the contaminants from compressed air (water, particulate and oil) and are, therefore, required by non-lubricated and lubricated compressors.

   A refrigerant type dryer may not essentially require a pre-filter, but a desiccant or deliquescent dryer requires a pre-filter to protect the drying medium, or desiccant, from being rendered ineffective from contamination. An after-filter also is required to catch desiccant from being carried downstream to sensitive equipment. It is a good idea to consider pre-filtration for all types of dryers. Pre-filters help in reducing the amount of liquid water, thereby reducing the load on the dryer or increasing the efficiency of dryer.

3. **High Efficiency Oil Removal Filters** provide air quality, technically oil-free, similar to that supplied by an oil-free machine. It is capable of removing almost all water and air aerosols.

After-Filters

1. **Particulate Removal Filters** remove physical debris such as rust, scale and dust from the system and are available to 0.1 micron and smaller. The higher the degree of contaminant removal, the higher the resulting pressure drop and the energy cost of compression.

   These are most commonly used with a desiccant dryer to remove the desiccant fines that are collected and carried downstream as the air encounters the drying process.

2. **Adsorption activated carbon filters** are generally used to remove vapors, harmful chemicals, taste, and odor from the compressed air systems. Most filter elements contain activated carbon granules having an extremely high surface area and dwell time. This medium is for the adsorption of vapors only.

   These are used if the air is required for breathing, mixing with food, pharmaceutical products, or other such duties. While other filters will remove water, liquid oil, oil aerosols, and dirt, only carbon filters will eliminate oil vapors and oil (and other hydrocarbon) odors. Catalysts are required to convert harmful carbon monoxide to carbon dioxide.

3. **Coalescing filters** capture small droplets of moisture or oil from the air stream and coalesce them into larger liquid droplets. Coalescing of small droplets at the 0.01 micron level is not uncommon. The coalesced liquid gravity flows to the bottom of the filter bowl and is drained, usually automatically. To prevent accumulation of removed liquids, coalescing filters should be drained periodically by means of an automatic drain device.

   A coalescing filter is recommended before any dryer whose drying medium may be damaged by lubricant. Filter material should be compatible with the type of lubricant being used.

4. **Hopkalite Filters** are required if the air is required for breathing and there is a risk of carbon monoxide being present in the system.

   These filters are used in conjunction with desiccant dryers, which with the use of the correct desiccant, can reduce carbon dioxide levels and are required to keep the Hopkalite active.

5. **Sterile Filters** eliminate microorganisms from compressed air and are used in processes which require the highest air quality. Sterilized filters are designed to be re-sterilized in place using steam.

6. **Point of Use Filters** are used to remove particles that have accumulated during distribution of compressed air. This contamination often occurs in piping, particularly in aging, large systems where rust and pipe scale can collect.

   Filters cause pressure drop and are often responsible for compressors operating at pressures well above that required for the process. This occurs if filters are clogged, undersized, or poorly maintained. Other problems relate to incorrect filter selection and incorrect quantity.

When designing new or reviewing older systems it is recommended that the following points be considered:

- Peak air demand;
- Pipe size and material type;
- Pipe contamination levels including effects from treatment changes;

- Required air quality at each usage points and the demand for each quality;
- Compressor configuration;
- Compressed air temperature and ambient temperature at filtration points;
- Air dryer configuration;
- Isolation valves in the system

Pressure differential gauges show when filters need to be replaced and should be fitted to all filters. Maintenance of filters is very important and will lower compressed air costs. Studies have shown that the economic offset between cost of element replacement and cost of energy to overcome pressure drop is 35 kPa. It is therefore paramount that a high efficiency filter be used to remove all contamination while simultaneous exhibiting the lowest possible pressure drop.

SIX LEVELS OF COMPRESSED AIR TREATMENT/QUALITY

There are six generic filter quality levels for compressed air:

1. Filtered centrifugal separators;
2. Refrigerated compressed air dryer (RCAD) and air line filter;
3. Refrigerated compressed air dryer (RCAD) and oil removal filter;
4. Refrigerated compressed air dryer (RCAD), oil removal filter and oil vapor absorber;
5. Air line filter, oil removal filter, low dew point desiccant dryer;
6. Breathing air system (continuous or portable).

S.N	Elements	Function	Application
1	Filtered Centrifugal Separator	Removes all solids to 3 microns and larger. Removes liquids: 99% of water droplets, 40% of oil aerosols.	Shop Air

2	Refrigerated Compressed Air Dryer, Air Line Filter	Removes moisture and produces a 35¼ F to 50¼ F-pressure dew point. Removes 70% of oil aerosols and all solid particles to 1 micron and larger.	Air Tools, Sand Blasting, Pneumatic Control Systems
3	Refrigerated Compressed Air Dryer, Oil Removal Filter	Removes moisture and produces a 35¼ F to 50¼ F-pressure dew point. Removes 99.999% of oil aerosols and all solid particles to .025 microns and larger.	Instrument Air, Paint Spraying, Powder Coating, Packing Machines.
4	Refrigerated Compressed Air Dryer, Oil Removal Filter & Oil Vapor Adsorber	Removes moisture and produces a 35¼ F to 50¼ F-pressure dew point. Removes 99.999+% of oil aerosols and all solid particles to .025 microns and larger. In addition, removes oil vapor, oily smell and taste.	Food Industry, Chemical and Pharmaceutical Industry, Laboratories Breweries, Dairy Industry.
5	Air Line Filter, Oil Removal Filter, Low Dew Point Desiccant Dryer	Removes moisture and produces a -40¼ F to -150¼ F pressure dew point. Removes 99.99+% of oil aerosols and all solid particles to .025 microns.	Outdoor Pipelines, Pneumatic Transport of Hygroscopic Machines.
6	Breathing Air System (Continuous or Portable)	Removes common harmful compressed air contaminants and will produce Grade D breathing air.	Breathing Air

Is Dry, Dry Enough?

All compressed air needs some form of treatment to achieve the desired air quality. Air purification techniques normally use simple air filtration, moisture separators, and/or dryer/filtration combinations, depending on the end users air quality requirements.

Moisture Removal	Treatment
50%	Air Cooled Aftercooler - able to reduce air temp to ~80°F
75%	Water Cooled Aftercooler - able to reduce temp to ~60°F
90%	Refrigerating Dryer - able to reduce air temp to ~38°F
99%	Desiccant Dryer - able to reduce air temp to ~ -40°F

An additional coalescing filter should be placed immediately adjacent to the compressed air user for systems, processes, and compressed air using equipment that is sensitive to water. To effectively stop water, in most applications it will be less expensive to install a central dryer rather than a large number of small filters at each point of use.

Compressed Air Equipment for ISO's Class Requirements

Follow the chart below to assemble a complete energy-efficient Air System Solution

ISO Standar	Air Compressor and After Cooler	Dryer	Filtration
Class 1	1. Non-Lubricated or, Lubricated compressors with proper oil aerosol (coalesces) and oil vapor removal (carbon adsorbers) equipment. 2. For more critical applications like process instrumentation, food and pharmaceutical Industry, non-lubricated	Regenerative Blower Purge Dryers, -100° F (-72° C) pressure dewpoint.	Coalescer Pre-filter for dryer, Particulate after filter for dryer, Carbon adsorber for oil vapor removal with lubricated compressors and 0.001 micron final filter.

ISO Standar	Air Compressor and After Cooler	Dryer	Filtration
	compressors are the equipment of choice. 3. The compressors may be air or water cooled, depending on the satisfactory availability of the cooling sources - air or water, location, and cost factors. 4. The 'Aftercooler' may be air or water cooled depending on the satisfactory availability of the cooling sources - Air or Water, location and cost factors.		
Class 2	----- do-------	Regenerative Blower Purge Dryers, -60° F (-51° C) pressure dewpoint.	Coalescer Pre-filter for dryer, Particulate after filter for dryer, Carbon adsorber for oil vapor removal with lubricated compressors and 0.1 micron final filter.
Class 3	----- do-------	Regenerative Blower Purge Dryers, -40° F (-40° C) pressure	Coalescer Pre-filter for dryer, Particulate afterfilter for dryer

ISO Standar	Air Compressor and After Cooler	Dryer	Filtration
		dewpoint.	
Class 4,5,6	----- do-------	Refrigerant Dryers - For Compressors with After Coolers.	Pre-filter, removes oil and dirt, and keeps dryer heat exchangers clean to provide reliable performance.

AIR RECEIVERS

An air receiver is a storage vessel for compressed air that acts as a buffer reservoir so that short-term demand spikes can be met. It allows the compressor capacity to be temporarily exceeded. Often systems will operate a secondary compressor to cater to intermittent demand, compressor failure, or short-term energy outages. The installation of air receivers may enable the secondary compressor to be shut-down.

Receivers create more stable pressure conditions, work to dampen compressor pulsation, separate out particles and liquids, make the compressed air system easier to control, and additionally, act as a secondary cooling device and as a condensate collector.

Installing a larger receiver tank to meet occasional peak demands can even allow a smaller compressor to be utilized.

In most systems, the receiver will be located before the dryer, as the accumulation in the receiver is dried enough through cooling condensate rejection. This reduces the load on the dryer thus increasing its efficiency. Alternatively, use can be made of multiple receivers, one prior to the dryer, and others closer to the points of intermittent/high demand.

On most installations, the receiver is fed from the aftercooler. On installations where an aftercooler is not installed, the receiver is located where the most condensed liquid is formed.

An adequately sized drain trap, preferably automatic, is essential to remove the collected condensate and any carry-over solids such as dust, scale, carbon, and so forth.

A 1/16" to 1/8" corrosion allowance is typically used for the bottom head of carbon steel receivers. A 1/16" corrosion allowance is usually used for the remainder of the receiver components.

Receiver sizing & Location

To size a receiver tank one can use a common rule of thumb - one-gallon of receiver volume per SCFM of air. Another rule of thumb for the compressor output is a common discharge rate of approximately 4 SCFM per horsepower. Therefore, the combined rule of thumb approximations imply a minimum receiver volume of 4 gallons per compressor horsepower. Though popular and easy to remember, it does not take system events into account.

Receivers are sized to prevent frequent compressor start or a standby compressor start events, to accommodate large intermittent system air demand, and to meet sudden high rate- of-flow requirements of critical pressure users. It may be more cost effective to increase the receiver size rather than to add air compression capacity, to meet peak loads.

The sizing of an air receiver is a function of usage and the allowable system pressure drop. Receiver size varies with the type of compressor, the application, and the operating characteristics.

In a central compressor configuration, avoid placing any receiver capacity upstream of dryers or filters. Receiver capacity should always be installed downstream of air treatment to avoid surges across this equipment that could result in carry-over to the system.

Locate receivers in the plant at high use locations. This will help resolve local pressure/velocity issues and help reduce the overall pumping set point.

Whenever possible the receiver should be placed in a cool location, further reducing the temperature of the compressed air and increasing the amount of water and oil condensation.

The receiver inlet should be located in the lower portion of the vessel and the discharge in the upper portion to assist in the settling of moisture. In addition, the inlet and outlet should be oriented at a 90-degree angle to help prevent moisture carryover.

Common Receiver Sizes:

Size in inches	Volume in cu. ft.	Volume in Gallons

Size in inches	Volume in cu. ft.	Volume in Gallons
16 x 38	4	30
20 x 48	8	60
20 x 60	11	82
24 x 72	19	141
30 x 48	35	257
36 x 96	57	423
42 x 120	96	720
48 x 144	152	1,128
60 x 168	275	2,062
60 x 192	314	2,356

COMPRESSED AIR DISTRIBUTION NETWORK

The role of the distribution network is to deliver the compressed air from the compressor discharge to the points of use with minimal leakage, minimal loss of pressure and minimal effect on the quality of the air.

Friction and leaks cause a pressure drop between the compressor output and eventual point of use. This lost energy in the distribution network is largely due to its design and layout.

Compressed Air Piping

The cost of the air mains frequently represents a high proportion of the initial cost of a compressed air system. Therefore, smaller diameter pipe is often specified to save on capital cost. However, this is false economy since the restriction due to the smaller piping causes greater pressure drop across the system, resulting in higher energy consumption.

The air system piping is sized using velocities based on flow volumes at actual conditions (ACFM) rather than at standard conditions.

A poorly designed compressed air system can,

- Increase energy costs;
- Promote equipment failure;
- Reduce production efficiencies and;
- Increase maintenance requirements.

It is generally considered a fact that any additional monetary expenditure toward improving the compressed air piping system will pay for itself many times over during the life of the system.

1. **Compressor Discharge Piping**

   Discharge piping from a compressor not containing an integral aftercooler can have very high temperatures. The discharge pipe must be able to handle these temperatures. The high temperatures can also cause thermal expansion of the pipe, which can add stress to the pipe. Check the compressor manufacturer's recommendations on discharge piping. Install a liquid filled pressure gauge, a thermometer inserted in a thermo-well in the discharge airline before the aftercooler to monitor conditions.

   Pipe must be sized carefully and arranged to minimize pressure drop. A good rule of thumb that is commonly used is to limit pressure drop to less than 1 psig per 100 linear feet of pipe. This applies to the rate of flow through any particular section of piping, and has little to do with total compressor capacity. Certain point of use applications may take compressed air at a rate of flow greater than the capacity of available compressors for a short duration. If the piping is sized per the capacity of the available compressor(s) rather than the rate of flow, it might represent a restriction that causes pressure to drop system-wide.

2. **Piping and Fitting Pressure Drop**

   Pressure drop in a compressed air system is a critical factor. Pressure drop is caused by friction of the compressed air flowing against the inside of the pipe and through valves, tees, elbows and other components that make up a complete compressed air piping system. Pressure drop can be affected by pipe size, type of pipe used, the number and type of valves, couplings, and bends in the system.

The cost of piping pressure loss can be calculated in real dollars. For every 2 pounds per square inch gauge (psig) loss in pressure, 1 percent more total kilowatts (kW) are required to overcome the loss. For example, a 10 psig pressure drop in a 200-kW system operating 4,000 hours per year at 8 cents per kilowatt-hours (kWh), will cost an additional $3,200 in energy annually.

When condensate traps are faulty, air quality suffers tremendously, potentially affecting product quality. Look for operational problems and leaks, and be aware of where the condensate is going. Consider upgrading electrically timed solenoid drains because they waste a considerable amount of energy. Demand-type drains are available to bleed condensate without wasting air.

To avoid carryover of condensed moisture to tools, outlets should be taken from the top of the pipeline. Larger pipe sizes, shorter pipe and hose lengths, smooth wall pipe, long radius swept tees, and long radius elbows all help reduce pressure drop within a compressed air piping system.

The connection points on air-consuming machinery and air tools are always a potential air leak point. Make sure connections are tight and hoses are in good working condition. Pressure loss can be costly if the piping is not designed properly. It is always better to oversize the compressed air piping system; it pays for itself and allows for expansion of the system.

Air receivers also are collection points for contaminants and are used to mechanically separate condensed liquids. If the condensate traps are not working properly, air receivers can fill with condensate and contaminants, not compressed air. Make sure the drains work correctly and replace them if necessary.

Point of use components

Air must be delivered to the point of use at the desired pressure and in the right condition.

- Too low a pressure will impair tool efficiencies and affect process time.
- Too high a pressure may damage equipment, and will promote leaks and increase operating costs.

It's a balancing act, but getting it 'just right' delivers good savings for you.

Rate of flow considerations at the point of use is much more important than in sizing distribution piping. When end users complain of low pressure, the first thing blamed is the piping because "the user is at the other end of the system" or "the piping system has been expanded haphazardly over the years" (or whatever the excuse). The real problem is not necessarily the piping. The real source of problems described as “low pressure” usually resides in the choice of installed point of use components. While some loss in pressure is to be expected, a properly designed system should have a pressure drop below 10% of the compressor’s discharge pressure.

Pipe drops, filters, regulators, lubricators, quick disconnects, and hose must all be sized for the rate of flow at the point of use. A common mistake is to buy a tool that uses 100 scfm, apply a 10% utilization factor to it and size all of the in-line components for 10 scfm. The components need to be sized for the 100 scfm rate of flow, not some averaged demand level used to size compressors!

The incorrect sizing of pipes can result in excessive pressure drop. Air should travel at a velocity of approximately 6 to10m/s. The higher the velocity, the higher the pressure drops.

Additional ways to minimize pressure drop are:

- Properly design the distribution system. For example, minimize bends in the piping and reduce the distance the air travels;
- Operate and maintain air filtering and drying equipment to reduce the effects of moisture, such as pipe corrosion;
- Select aftercoolers, separators, dryers, and filters that have the lowest possible pressure drop for the rated conditions;
- Specify pressure regulators, lubricators, hoses, and connections that have the best performance at the lowest pressure;
- When purchasing components, work with suppliers to ensure that products most efficiently meet the desired specifications for the air pressure required, taking into account all of the system characteristics.

Carefully consider the possibility of separate dedicated air systems where the service varies significantly. For example, shop air; tank agitation air, and instrument air should generally not be combined on the same distribution circuit.

It is always beneficial and efficient to seek ways to reduce pressure drop rather than increase discharge pressure or add additional compressor capacity.

Piping Layout

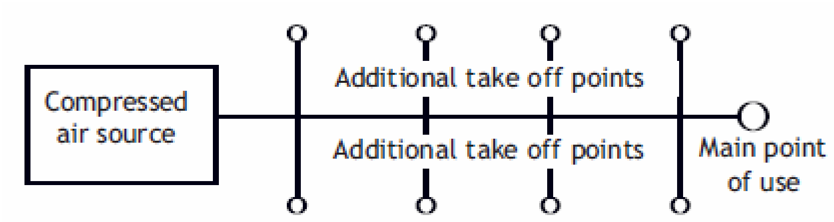
All compressed air distribution pipelines should be designed with the following points in mind:

- Pipe diameters should be selected that minimize pressure drop and allow for possible expansion.
- Fittings and valves should be selected that create the minimum restriction to airflow. Large radius bends are preferred to elbows.
- All piping must be well supported to minimize movement and sagging. This will help to minimize leaks, avoid build up of corrosion and fluids and lengthen the life of the pipeline.

The two basic distribution systems for compressed air are:

Single Main

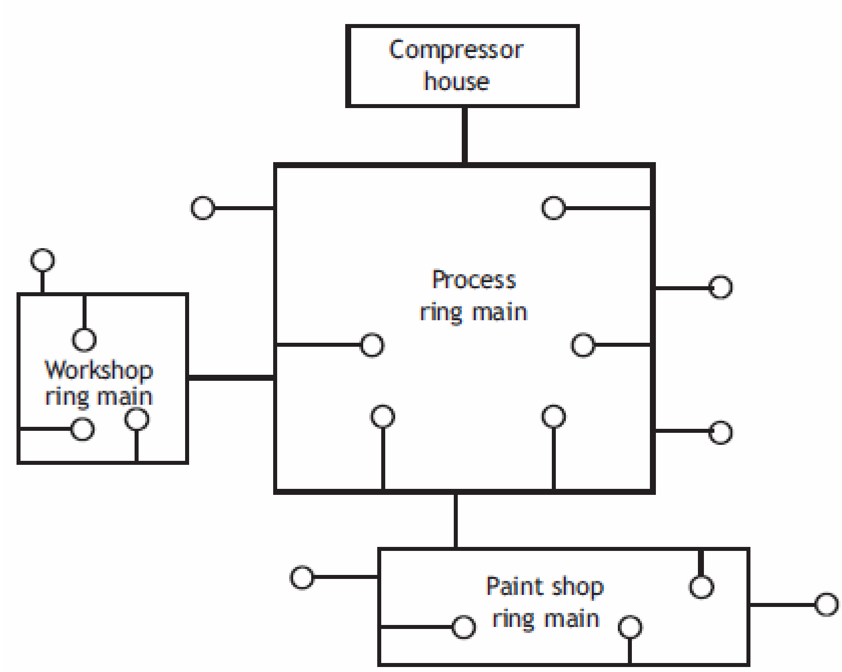
This is most suitable for simple installations where the points of use and the supply are relatively close together. In a well designed system, the maximum pressure should be nor greater than 0.2 bar. In practice, try to make the main pipe as large as possible, especially if there may be future expansion of the system.



Single Main Pipe with Branch Lines

Ring Main

For larger systems with numerous take-off points, a ring main allows airflow in two directions to a point of use. Because air is supplied to any piece of equipment from two directions the velocity is halved and the pressure drop reduced. Another advantage is that isolation valves can be incorporated to enable specific sections of the system to be shut down for servicing without interrupting the air flow to other users. Such systems are more energy efficient.



Ring Main with Take-off Points

In cases where there is a large volume user, an auxiliary receiver can be installed. This reduces the velocity, which reduces the friction against the pipe walls and reduces pressure drop. Receivers should be positioned close to the far ends or at points of infrequent heavy use of long distribution lines. Many peak demands for air are short-lived, and storage capacity near these points helps avoid excessive pressure drop and may allow a smaller compressor to be used.

Valves

Although valves are used primarily for isolating a branch or section of the distribution network, they are also used for flow or pressure control.

Ball valves are recommended because they cause almost zero pressure drop when fully open. This is because the throat diameter of the valve is equal to the pipe bore. The quick action handle clearly indicates if the valve is open or closed.

Gate valves are often used due to their low purchase price. But, because their throat diameter is smaller than the pipe bore, they present a constriction and cause pressure drop. In addition, when set fully open, the sealing surfaces can erode over time, making it impossible to obtain an airtight seal. Gate valves are often left partially open due to the number of turns required to go from fully closed to fully open. The glands are often a source of leaks.

Some other valves such as diaphragm and globe valves cause the larges pressure drop and are not recommended for compressed air systems.

PIPING MATERIALS

Corrosion-resistant piping should be used with all compressed air piping systems using oil-free compressors. A non-lubricated system will experience corrosion from the moisture in the warm air, contaminating products, and control systems.

The compressed air piping materials can be divided into two basic types: metal and non metal.

Metal pipe can be black iron, stainless steel, aluminum with proper thermal pressure characteristics.

Black Iron or steel pipe in compressed air systems will corrode when exposed to condensate (H_2O) and thus become a major source of contamination to the whole system. This pipe is usually threaded connected 3' diameter and smaller, welded with larger diameters. Compared to other alternatives, it is much heavier and harder to work with, but less expensive. The internal corrosion issue is much more significant with oil-free air than with lubricated compressors. The question of galvanized piping comes up often in compressed air piping instead of schedule 40 black iron for the nominal 100 psig air systems. GI piping has the advantage of resisting corrosion better than standard iron pipe. However, overtime when the corrosion does set in, the GI material peels off. The inlet pipe is now a producer of potentially very damaging, sold contaminants between the filter and compressor. This would be particularly dangerous to the mechanical integrity of a centrifugal compressor. It is therefore not recommended.

Stainless steel is often a good selection particularly when exposed to oil free wet air and its extremely high acid level condensate (before the dryers). Threaded stainless steel often tends to leak. Ring seals such as those used in Victaulic connections can work well.

Aluminum compressed air pipe has become very popular particularly in the automotive support industry with changing assembly and sub-assembly areas.

Plastic piping may be also used on compressed air systems; however, caution must used since many plastic materials are not compatible with all compressor lubricants.

PVC and ABS are the two plastic pipe materials commonly used in airline distribution systems of which ABS is a preferred choice.

PVC pipe, upon failure, will shatter into small pieces, sending sharp pieces throughout the area. Propelled by rapidly expanding gas, the shards can cause, in addition to property damage, serious personal injury or death to people in the immediate area of the failure. When ABS fails, it ruptures but does not shatter. This is an advantage that ABS pipe has over PVC pipe. For this reason, ABS pipe is a much safer choice for use if at all compressed air distribution is considered. However, plastic pipe materials have three significant limitations:

- For both ABS and PVC, the pressure rating reduces as the operating temperature increases - the maximum non-shock operating pressure is a function of temperature. The heat of compression should be fully dissipated so that the maximum temperature ratings (140°F for ½" and 120°F for ¾") are not exceeded in the pipe system. The pressure ratings for typical thermoplastic piping and fittings are about a constant 185 psig for all sizes in the temperature range -20°F to 100°F and are gradually reduced above 100°F. PVC for instance is limited to about 160°F at 125 psig, but it actually starts to weaken at 70F.
- Most of these materials are not compatible with compressor oils in general and particularly many synthetics.
- Ultraviolet light (sun light) may also reduce the useful service life of some plastic materials.

An advantage of plastic and stainless steel pipe over carbon steel pipe is that neither material will rust internally from moisture entrained in the compressed air. In particular, compressed air systems without a dryer can be aggressive to carbon steel piping and valves. Non-dried compressed air is saturated with moisture and is therefore aggressive to carbon steel piping and valves. GI and PVC plastic pipe is NOT appropriate for compressed air distribution piping.

HOSE AND TUBINGS

Hose used in pneumatic systems:

In order to isolate the vibration of the compressor from the distribution piping, hose is often used to connect the compressor to the airline distribution system. Obviously, a rigid fluid conductor will not allow any movement between two components. Hose is also used between drop points in the distribution system and air tools as well as between valves and actuators where some sort of pivot mount is used to mount the actuator.

Hoses used to power pneumatic tools should be fitted with a velocity fuse. A velocity fuse is a valve that closes when excessive flow begins to pass through it. This prevents whipping of the hose should it become severed. Hoses used for service air stations should be fitted with flow limiting check valves to avoid loss of service air pressure due to hose ruptures or other failures.

Tubing used in pneumatic systems

Tubing is used for low flow rates and the size of the tubing ranges from 1/8” through 1/2” OD. A viable alternative to carbon steel pipe in airline distribution systems is copper tubing. Hard drawn copper tubing has many positive features:

- Copper tubing does not cost much more per foot than steel pipe. The increased cost of copper tubing is more than offset by the reduced time it takes to install compared to threaded steel pipe.
- Copper tubing is much lighter than steel pipe, making assembly easier. Most airline distribution systems are located overhead. It’s much easier, and safer, to lift relatively light weight copper tubing into place for assembly. Hefty supports and brackets are not needed.
- Sweat (soldered) fittings used to join lengths of copper tubing are inexpensive as well as quick and easy to install. Time is not wasted performing a threading operation. Threading pipe is a messy, noisy, dirty job. It takes much less time to solder a copper union than it takes to thread and screw together a threaded union, or to weld a steel butt or socket weld union.
- Copper tubing is seamless; it is drawn over mandrel. It does not have a slag puddle like the inside of welded pipe, so there is less initial internal contamination.
- Unlike carbon steel pipe, copper tubing will not rust internally.
- Cutting into a length of copper tubing is quick and easy. If a tubing cutter is used, chips will not be generated, reducing the introduction of contamination to the system. Consequently, additions to the system are easily made.
- Unlike PVC pipe, copper tubing will not shatter.
- Copper tubing is less expensive than ABS pipe and it is readily available.

Plastic tubing is widely used downstream of the airline distribution system to connect components. Nylon, polypropylene, and polyethylene are the three most common materials for this tubing.

Plumbing a system with plastic tubing is quick and easy in comparison to installing copper or stainless steel tubing. In comparison to some rubber hose, there is less OD expansion when plastic tubing is pressurized. This is because plastic tubing is more rigid, but yet still flexible, providing better system response.

Adaptors Used in Fluid Power Systems:

Adaptors are used to connect conductors, i.e. pipe, tubing, and hose, to fluid power components. At a minimum, an adaptor has two ends: the port end and the conductor end.

Pneumatic systems generally use pipe threads for port connections. Where the flow rate is high, large piping and ANSI flanges are commonly used.

Sooner or later, threaded pipe operated at high pressure will leak. It is strongly advised that all pipe connections be either welded or flanged. All fittings such as junction elbows, tees, and crosses must be installed with SAE Code 61 and 62, 4-bolt flange interfaces, simplifying the construction of header systems.

CONDENSATE CONTROL

Condensation control must be considered when installing a compressed air piping system. Reliable operation requires drain traps to be included for expelling condensate from the system. Drip legs should be installed at all low points in the system. A drip leg is an extension of pipe below the airline that is used to collect condensation in the pipe. The air mains should slope to drain legs located at strategic intervals. The recommended distance between drain points is approximately 100 feet.

The main header pipe in the system should be sloped downward in the direction of the compressed air flow. A general rule of thumb is 1inch per 10 feet of pipe. The slope directs the condensation to a low point in the compressed air piping system where it can be collected and removed.

In order to remove the water, drain traps (preferably an automatic drain) should be fitted to the drip legs. Drain traps eliminate the expense of bleeding expensive compressed air through petcocks or manually draining compressed air lines and equipment. A ball valve should precede all drain traps to facilitate routine maintenance without interruption.

Make sure that the piping following the aftercooler slopes downward into the bottom connection of the air receiver. This helps with condensate drainage as well as possible internal water leakage from the water-cooled aftercooler. Such leakage would drain toward the receiver and not the compressor.

To eliminate oil, condensate, or cooling water (if the water-cooled aftercooler leaks), a low point drain should be installed in the discharge pipe before the aftercooler. Be sure to connect the aftercooler outlet to the separator inlet when connecting the aftercooler and the moisture separator together. If they are not connected properly, it will result in either poor aftercooling or poor separation.

Another important aspect is to take all branch connections from the top of the main airline. This prevents water entering the branch connection from the main pipe and allows it to continue to the low points in the system. Branch lines should be equipped with manual isolation valves and looped back to the main header where practical. Branch line pipes should also be drained.

MISCELLANEOUS ELEMENTS

Drain Traps

There are a variety of drain traps available with large differences in efficiency.

Manual traps are often left open and are known to be responsible for significant compressed air leakage. Reliable automatic condensate traps are available that insure water is regularly drained away; they provide good energy efficiency.

The most common type of drain trap is the ball float, which opens only if water is present and closes immediately when the water has cleared. If large quantities of water are likely to enter the trap, a balance pipe must be fitted that allows displaced air to be forced back into the main system.

Alternatively, electronic condensate drain traps are also available in a range of sizes from very small units attached to the bottom of filters to larger units for air receivers. The advantages of this type of trap are no air loss during discharge, low maintenance, and high reliability.

In order to insure drain traps perform efficiently, it is strongly recommended that simple wire type strainers be fitted prior to the drain trap to prevent particulate contamination of the trap. Occasional maintenance is also required. Oil or emulsion build-up should be removed regularly and if the build-up is heavy, drain trays, which have a blast action discharge, should be considered. Making wise drainage decisions can save up to 10% of the costs of compressed air.

Condensate from lubricated compressed air systems must be disposed in a responsible manner and in accordance with local regulations and bylaws. Most local regulations require oil separation from this condensate before disposal in the municipal system. The costs associated with this disposal can be minimized by the use of adequate condensate management systems, commonly know as “oil-water separators”.

Regulator

Regulators control pressure and allow a compressed air system to supply air at different pressure while minimizing waste. If an application requires air at a pressure lower than the main supply, and it is not practical to install a separate pressure system, a regulator should be installed. Such an example might be the use of compressed air for control and instrumentation. By not over supplying air pressure and decreasing pressure at the point of use, efficiency improves and monetary savings can be achieved. Regulators can also help maintain pressure at the minimum acceptable level. The air consumption of most air-using devices, such as air tools, spray guns, and air knives, increases in proportion to the operating pressure ratio.

THE COST OF COMPRESSING AIR

A common means of comparing different air compressor types is expressed in brake horsepower (bhp) per 100 CFM with a compressor discharge pressure of 100 psig. The compressor capacity in CFM is the amount of air delivered from the compressor, but measured at prevailing ambient inlet conditions.

The bhp per 100 CFM can range from about 18 kW for an efficient two-stage, water-cooled reciprocating compressor, to 30 for a small single-stage, air-cooled reciprocating compressor.

A single-stage oil-injected rotary screw compressor has a power consumption of about 22.2 bhp per 100 CFM. Using a drive motor with a full load efficiency of 92 percent, and knowing that 1 bhp equates to 0.746 kW, results in an electrical power consumption of 18 kW per 100 CFM.

Note that this calculation procedure is based upon 100 psig at the discharge of the air compressor and not at the point of use. Pressure drops will occur through piping and components downstream of the air compressor, resulting in a lower pressure at the point of use. If it is necessary to raise the discharge pressure of the compressor to achieve a required pressure at the point of use, it will be necessary to insure that the air compressor is capable of the higher discharge pressure.

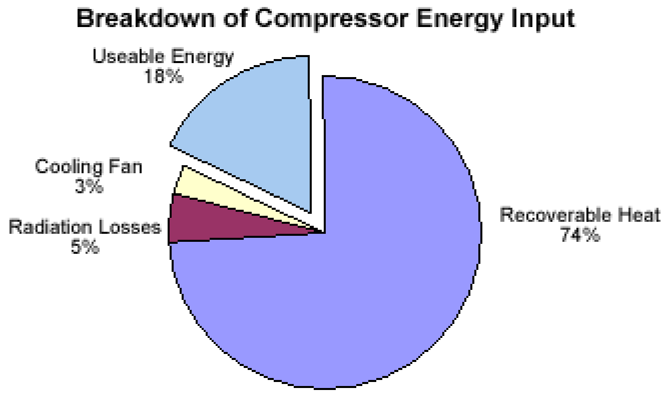
Note also that the power consumption will increase by **1 percent for each 2 psig** increase in compressor discharge pressure. Compressing air to a higher pressure than required wastes energy and adds to plant energy cost

In addition, compressors normally do not operate continuously at full capacity. While the average amount of air used may be less than the capacity of the air compressor, the reduction in the power requirement is not directly proportional to the actual capacity. Rotary air compressors using inlet valve throttling do not provide a significant reduction in bhp as the capacity is reduced.

The cost of treatment of the compressed air also must be taken into account. Regular monitoring and maintenance are essential to minimizing the cost of a compressed air system by avoiding pressures that are higher than needed for desired applications, minimizing pressure drops, and eliminating leaks. Condensate drain traps must be checked for proper operation so that condensate is not allowed to build up and be carried downstream.

Compressed Air System Energy Efficiency

It has been estimated that the energy available to do useful work is less than 20% of the compressor input energy. Motor energy is converted to heat in the compression process.



If the air is compressed to 100 or 110 psig, by time it is cooled, dried and delivered to the point of use, the pressure may only be 85 to 95psi. Depending on the application, the air may be regulated down, or exhausted at greater than atmospheric pressure (10 to14 psig exhaust for air tools).

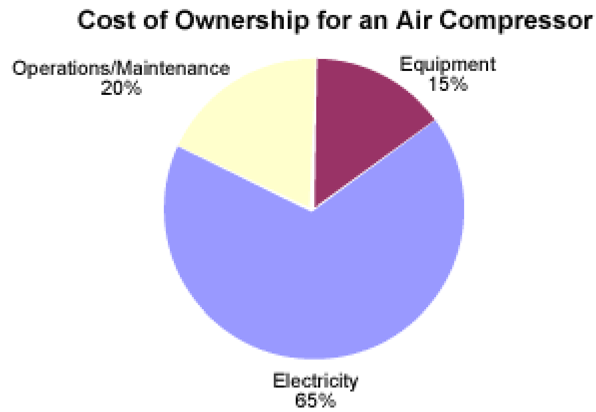
A typical air tool application may have an overall efficiency of only 12 to15% and an application where the air is regulated down to 50 psig prior to use, would have an overall efficiency of only 7 to 9%.

At $0.06/kwh, a single stage rotary screw compressor costs about $10,000 per year per 100 cfm to operate!
(This is based on electricity only, at 8,000 hours per year runtime)

Life Cycle Cost Analysis of a Compressor

Operating costs are the largest component of the cost of ownership of a compressed air system. Nearly 2/3 of the cost of ownership is electrical power and the remaining 1/3 is composed of the purchase and maintenance costs. Before purchasing any equipment, consider compressor control systems with load/no-load features; be aware of compressor efficiencies, and size filters for the lowest pressure drop possible. A two psi pressure drop will increase electrical operating cost by 1%. Use zero purge types of dryers when possible.

In deciding what compressor to purchase, there may be more important factors than cost. The graph below shows a 10-year life cycle cost for a screw compressor.



It has been estimated that for a typical compressed air system over a 10 year period, 75% of the total cost is for energy consumed, 15% for capital, and 10% for maintenance.

There are six steps that can be taken to reduce energy waste and increase energy savings:

1) Evaluate your costs for compressed air. To do this, add up all the compressor horsepower, calculate the average air demand, and determine the percentage of full load power.

2) Identify the volume of wasted air. This is accomplished by checking the leakage rate during off periods, determining required point of use pressure, and calculating wasted air through "over" pressurization.

<u>Leakage Test</u>

To conduct this test, close all the valves at the equipments where compressed air is in use. Drain the air receiver completely and start the compressor. Note down the time taken by the compressor to maintain the system pressure i.e. up to compressor unloads. This is compressor on load time in seconds. Due to the leakages in the systems (if present), the pressure in the receiver drops to the cut off pressure and again compressor starts. Note down the time taken by system pressure to drop up to cut off pressure. This is compressor off load time in seconds. The readings should be taken minimum three times and the average values are to be used to determine leakages in the lines. Feed these two values in seconds in the formula to determine leakages and its potential.

Leakages (CFM) = FAD x T1 / (T1 + T2)

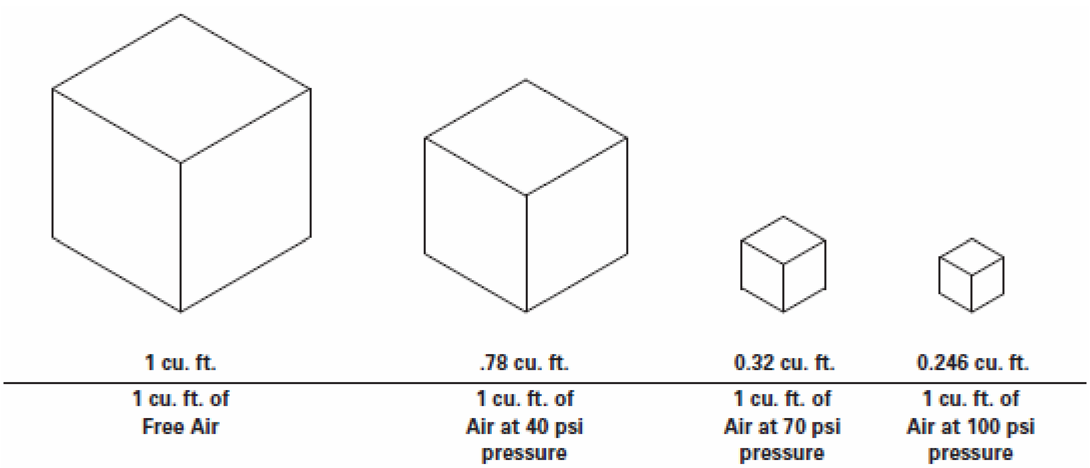
Where

- FAD - Actual free air delivery of compressor (SCFM)
- T1 = Average on load time of compressor (min)
- T2 = Average off load time of compressor (min)

3) Calculate specific performance at rated pressure, compare it with different brands, and select the most efficient compressor control. Turn the control selector switch to dual control, or check with the manufacturer for retrofit.

<u>Low Pressure Benefits</u>

Figure below shows the economical benefit of operating a compressor at the lowest possible air pressure that will still meet the minimum requirements of the compressor output. When 40 psi, 70 psi and 100 psi pressures are applied to one cubic foot of free air, the degree of air compression increases with the increase in pressure. As rapid expansion of the compressed air to a lower pressure occurs, system operating pressure determines to what point expansion stops. The further the compressed air is allowed to expand, the more air volume the compressor will be able to supply to the air motor. More air volume for motor consumption means the compressor will work less at 40 psi to produce the same amount of air volume as in a 100 psi system.



4) Reduce the pressure drop in your compressed air system. You can do this by measuring the pressure drop at the maximum flow across all of the system components. After that, increase the pipe size of the loop piping system, properly maintain the filters, drain valves, dryers, and compressors.

5) Stabilize and/or reduce the system pressure downstream of the air drying equipment. Installing a flow controller in conjunction with additional air receivers will accomplish

this. Use the 2-4 gallon receiver capacity/CFM, and install a sequencer in multiple compressor installations.

6) Evaluate the potential for heat recovery. Explore applications that involve heating, analyze existing costs for these applications, and implement a compressor duct system or liquid/oil heat exchangers.

AIR COMPRESSOR INSTALLATION

Proper installation of the air compressor is essential for safe and trouble-free operation. Air compressors are easy to install provided the equipment is installed in accordance with the manufacturer's recommendations and with all applicable federal, state and local requirements.

Some common installation recommendations:

1. Rotary and tank mounted reciprocating compressors require a floor capable of supporting the static weight of the compressor package.
2. Larger reciprocating compressors may require a concrete foundation or structural steel support designed to offset unbalanced forces that are present during normal operation.
3. Locate the compressor in an area where the added noise will not interfere or violate OSHA regulations.
4. All compressors produce heat during the compression process. This heat must be removed from the compressor room for proper operation of the compressor. Be sure to provide sufficient ventilation for all equipment that may be installed in the compressor room. All compressor manufacturers publish allowable operating temperatures.
5. Properly vent the exhaust from engine driven compressors. Be sure that the exhaust cannot be redrawn into the plant through HVAC systems or drawn into the air inlet of compressors.
6. Leave sufficient space around the compressor to permit routine maintenance. It is also suggested to provide space for the removal of major components during compressor overhauls.
7. Select piping systems that have low pressure drop and provide corrosion free operation. When selecting the main air headers, size for a maximum pressure drop of 1 to 2 psi. It is good to oversize the header as one size higher will not add much to the cost. This will provide additional air storage capacity and allow for future expansion. The acceptable pressure drop at the farthest point in mains header of an industrial compressed air network is typically 5 psig.

8. In the installation of compressed air piping, maximize energy efficiency by minimizing pipe runs and associated pressure drops. A ring main distribution header has the advantage of allowing more than one path for air flow and reduces pressure drop.
9. Ample compressed air storage in air receivers is desirable close to the compressor to prevent frequent loading and unloading. Secondary storage, close to points of intermittent but substantial demand, prevents sudden pressure drops in the system and allows recovery time before the next demand cycle.
10. Provide means to drain moisture that may accumulate in piping. Headers should be pitched to enhance drainage and drip legs should be installed in all low points.
11. Connect all drain valve outlets to an approved drain. Be sure the drain is vented. Do not pipe drain valves into a common closed pipe or header.
12. Condensed moisture may contain compressor lubricants and other chemicals that must be disposed of in accordance with all federal, state and local regulations.
13. If equipment, piping, or drains are exposed to freezing temperatures, be sure to insulate and heat trace them to prevent freezing.

MAINTENANCE & SERVICING

Air compressors, like all mechanical equipment, require periodic maintenance to provide a long and reliable life. Proper maintenance can also increase operating efficiency, reduce long term operating costs and minimize downtime. Some of the key maintenance areas are:

1. **Compressor package:** The compressor and intercooling surfaces should be kept clean. Fans and water pumps should be inspected to insure that they are operating at peak performance. Check the system for compressor and motor lubricant leaks and cleanliness.
2. **Inlet filter cartridges:** Inspect and clean or replace inlet filters and inlet piping should be maintained at least per manufacture's specifications, taking into account the level of contaminants in the facility's air. Small reciprocating compressors, typically 1.5 to 30 hp (1.1 to 22 kW), require the periodic replacement of inlet air filters, oil filters, and oil.
3. Drain traps: Clean out debris and check operation periodically.
4. **Compressor lubricant level:** Inspect daily and top-off or replace as per manufacturer specifications. Change the lubricant filter as per manufacturer's specifications.

5. **Air lubrication separator:** change as per manufacturer specifications, or when the pressure drop exceeds an acceptable level.
6. **Lubrication selection:** The compressor lubricant and lubricant filter must be charged per the manufacturer's specification. Lubricants can become corrosive and degrade both the equipment and system efficiency. For lubricated-injected rotary compressors, the lubricant serves to lubricate bearings, gears, and intermeshing rotor surfaces, acts as a seal, and removes most of the heat of compression. The oil level must be checked daily at a minimum. Lubricant change-out depends on the type lubricant and can vary from 1,000 to 8,000 hours.
7. **Check all belt drives:** If the compressor is belt driven, check that the belts are correctly tensioned. If they are slack, energy loss will occur due to belt slippage. If they are too tight, the belts will be subject to excessive stress and the compressor and motor bearings will be placed under extra load.
8. **Belt condition:** Check belts for wear and adjust tension as per manufacturer's recommendation.
9. **Operating temperature:** Verify the operating temperature.
10. **Air line filters:** Replace particulate and lubricant removal elements when excessive pressure drop occurs or otherwise, also periodically.
11. **Water cooling system:** For water cooled systems check the quality of water, especially the pH and TDS, and the flow and temperature differential. Regularly clean and replace filters.
12. **System leaks:** Check line joints, fittings, drains, relief valves, clamps, drain valves, hoses, disconnects, regulators, filters, lubricators, gauge connectors, and end-use equipment for leaks.
13. **Compressor drive:** Lubricate and clean electric motors. Poor maintenance will waste energy and may cause failures before expected lifetimes.

Important Checklist:

1. **Leak control:** Determine source of leaks and take corrective action immediately. A common method of leak detection involves spraying pipes with soapy water and looking for bubbles. Another method involves the use of ultrasonic detectors. Establish a strategy for reporting/detecting leaks. If a leak is found, quick repairs or replacement of

the part are necessary. A good time to check for leaks is after normal operating hours when factory equipment is quiet.

2. **Air Inlet Temperature:** Locate the intake suction source at a cool place. If possible duct outside air to the inlet to reduce temperature.
3. **Pressure Drop:** Thoroughly clean dryers and filters. Check all other elements where pressure drop is exceeding the desired limit.
4. **Service:** Service equipment to manufacturer's specifications using a authorized representative. Develop a maintenance plan specific to plant conditions. Use only genuine parts.
5. **Energy Audit:** Conduct periodic audits in-house or by and external Energy Efficiency Company.

Routine preventive maintenance is a useful tool. Conduct necessary inspections and maintenance on a schedule that will minimize disruption to plant operations. Maintenance contracts have become a popular method for compressor owners to plan and budget for equipment maintenance.

TROUBLE SHOOTING

It is best to enter into a service contract with the supplier/authorized representative. Follow the generic guidelines tabulated below.

Troubleshooting Compressed Air Systems		
Problem	**Probable Cause**	**Remedial Action**
Low pressure at point of use	Leaks in distribution piping	Check lines, connections and valves for leaks
	Clogged filter elements	Clean or replace filter elements
	Fouled dryer heat exchanger	Clean heat exchanger
	Low pressure at compressor discharge	See below

Troubleshooting Compressed Air Systems		
Problem	**Probable Cause**	**Remedial Action**
Low pressure at compressor discharge	For systems with modulating load controls, improper adjustment of air capacity system	Follow manufacturer's recommendation for adjustment of air capacity system
	Worn or broken valves	Check valves and repair or replace as required
	Improper air pressure switch setting	Follow manufacturer's recommendations for setting air pressure switch
Water in lines	Failed condensate traps	Clean, repair, or replace the trap
	Failed or undersized compressed air dryer	Repair or replace dryer
Liquid oil in air lines	Faulty air/oil separation	Check air/oil separation system; change separator element
	Compressor oil level too high	Follow manufacturer's recommendation for proper oil level
Dirt, rust or scale in air lines	In the absence of liquid water, normal aging of the air lines	Install filters at point of use
Excessive service to	System idling too much	For multiple compressor system:

Troubleshooting Compressed Air Systems		
Problem	**Probable Cause**	**Remedial Action**
load/hour ratio		consider sequencing controls to minimize compressor idle time
		Adjust idle time according to manufacturer's recommendations
	Improper pressure switch setting	Readjust according to manufacturer's recommendations
Elevated compressor temperature	Restricted air flow	Clean cooler exterior and check inlet filter mats
	Restricted water flow	Check water flow, pressure, and quality; clean heat exchanger as needed
	Low oil level	Check compressor oil level, add oil as required
	Restricted oil flow	Remove restriction, replace parts as required
	Excessive ambient temperature	Improper ventilation to compressor; check with manufacturer to determine maximum operating temperature

SAFETY CONSIDERATIONS

The compressed air system should be periodically inspected by trained technicians. Operators need to be aware of the following:

Air receivers:

1. The maximum allowable working pressures of air receivers should never be exceeded except when being tested. Only hydrostatically tested and approved tanks shall be used as air receivers.
2. Air tanks and receivers should be equipped with inspection openings, and tanks over 36 inches in diameter should have a manhole.
3. The intake and exhaust pipes of small tanks, similar to those used in garages, should be made removable for interior inspections.
4. No tank or receiver should be altered or modified by unauthorized persons.
5. Air receivers should be fitted with a drain cock that is located at the bottom of the receiver.
6. Receivers should be drained frequently to prevent accumulation of liquid inside the unit. Receivers having automatic drain systems should also be checked.
7. Air tanks should be located so that the entire outside surfaces can be easily inspected. Air tanks should not be buried or placed where they cannot be seen for frequent inspection.
8. Each air receiver must be equipped with at least one pressure gauge and an ASME safety valve of the proper design.
9. A safety (spring loaded) release valve shall be installed to prevent the receiver from exceeding the maximum allowable working pressure.
10. Only qualified personnel should be permitted to repair air tanks, and all work must be done according to established safety standards.

Air Distribution Lines:

1. Airlines should be made of high quality materials and must be suitable for maximum working pressures.
2. Only standard fittings should be used on airlines.
3. Operators should avoid bending or kinking air hoses.
4. Air hoses should not be placed where they will create tripping hazards.

5. Hoses should be checked to make sure they are properly connected to pipe outlets before use.
6. Air lines should be inspected frequently for defects, and any defective equipment repaired or replaced immediately.
7. Compressed air lines should be marked with the maximum allowable working pressure.

Pressure regulation Devices:

1. Only qualified personnel should be allowed to repair or adjust pressure regulating equipment.
2. Valves, gauges, and other regulating devices should be installed on compressor equipment in such a manner so as not to become inoperative.
3. Air tank safety valves should be set no less than 15 psi or 10 percent, whichever is greater, above the operating pressure of the compressor, but never higher than the maximum allowable working pressure of the air receiver.
4. Air lines between the compressor and receiver usually should not be equipped with stop valves. Where stop valves are necessary and authorized, ASME safety valves should be installed between the stop valves and the compressor.
5. Safety valves should be set to blow at pressures slightly above those necessary to pop the receiver safety valves.
6. Blow-off valves should be located on the equipment and shielded so sudden blow-offs will not cause personnel injuries or equipment damage.
7. Cast iron seat or disk safety valves should be ASME approved and stamped for the intended service application.
8. If the design of a safety or a relief valve will allow liquid to collect on the discharge side of the disk, the valve should be equipped with a drain at the lowest point where liquid can collect.
9. Safety valves exposed to freezing temperatures should be located so water cannot collect in the valves. Frozen valves must be thawed and drained before operating the compressor.

Air Compressor Operation:

1. Only authorized and trained personnel should operate air compressor equipment.

2. The air intake should be from a clean, outside, fresh air source. Screens or filters should be used to clean the air.
3. Air compressors should never be operated at speeds faster than the manufacturer's recommendation.
4. Equipment should not become overheated.
5. Moving parts, such as compressor flywheels, pulleys, and belts that could be hazardous should be effectively guarded.

Compressed Air Equipment Maintenance

1. Only authorized and trained personnel should service and maintain air compressor equipment.
2. Exposed, non current-carrying, metal parts of compressor should be effectively grounded.
3. High flash point lubricants should not be used on compressors because of high operating temperatures that could result in a fire or explosion.
4. Equipment should not be over lubricated.
5. Gasoline or diesel fuel powered compressors shall not be used indoors without proper ventilation.
6. Equipment placed outside but near buildings should have the exhausts directed away from doors, windows and fresh air intakes.
7. Soapy water of lye solutions can be used to clean compressor parts of carbon deposits, but kerosene or other flammable substances should not be used. Frequent cleaning is necessary to keep compressors in good working condition.
8. Air systems should be completely purged after each cleaning.
9. During maintenance work, the switches of electrically operated compressors should be locked open and tagged to prevent accidental starting.
10. Portable electric compressors should be disconnected from the power supply before performing maintenance.

Safety checklist for machine shops (in addition to the above)

The following precautions pertain to the use of compressed air in machine shops:

1. All pipes, hoses, and fittings must have a rating of the maximum pressure of the compressor.
2. Air supply shutoff valves should be located as near as possible to the point-of-operation.
3. Air hoses should be kept free of grease and oil to reduce the possibility of deterioration.
4. Hoses should not be strung across floors or aisles where they are can cause personnel to trip or fall. When possible, air supply hoses should be suspended overhead, or otherwise located to afford efficient access and protection against damage.
5. Hose ends must be secured to prevent whipping if an accidental cut or break occurs.
6. Pneumatic impact tools, such as riveting guns, should never be pointed at a person.
7. Before a pneumatic tool is disconnected (unless it has quick disconnect plugs), the air supply must be turned off at the control valve and the tool bled of stored energy.
8. Compressed air must not be used under any circumstances to clean dirt and dust from clothing or off a person's skin. Shop air used for cleaning should be regulated to 15 psig unless equipped with diffuser nozzles to provide a lesser pressure.
9. Personnel using compressed air for cleaning equipment must wear goggles or other eye shield protection.
10. Static electricity can be generated through the use of pneumatic tools. This type of equipment must be grounded or bonded if it is used where fuel, flammable vapors, or explosive atmospheres are present.

Items requiring extra precaution

The only real dangers in any air system come from:

1. A poorly maintained compressor with a faulty relief valve;
2. Devices operated at excessive pressures which may cause them to self-destruct, sending parts flying, and;
3. Bad connections at fittings, which might allow a hose to become loose
4. A loose and flying air hose, especially one with a metal fitting attached, can present a real hazard even at moderate pressures; the only way to prevent this is to close the valve at the source. Do not try to grab it! Just in case, a master shutoff valve should be provided at the compressor's tank.

HANDY RULES OF THUMB FOR ESTIMATING

1. Air compressors normally deliver 4 to 5 SCFM per horsepower at 100 psig discharge pressure.
2. Power cost for 1 horsepower operating constantly for one year at 10 cents per kWh is about $750 per year.
3. Every 7°F rise in temperature of intake air will result in 1% rise in energy consumption.
4. It takes 7 to 8 hp of electricity to produce 1 hp worth of air power.
5. Air compressors typically reject about 2,000 - 2,500 Btu/hr for every hp.
6. In a compressed air system approximately 10 percentage of energy reaches the point of final use.
7. Size air receivers for about 1 gallon of capacity for each cfm of compressor capacity.
8. Compressor discharge temperatures are a key indicator of compression efficiency. Un-cooled compressed air is hot, as much as 250 to 350° F.
9. Typical discharge temperature values before aftercooling are: Screw (175°F), single stage reciprocating (350°F), two stage reciprocating (250°F).
10. Most water-cooled aftercoolers will require about 3 gpm per 100 cfm of compressed air at a discharge air pressure of 100 psig, and will produce about 20 gallons of condensate per day.
11. Locate filters and a dryer in the airline before any pressure-reducing valve, i.e. at the highest pressure, and after air is cooled to 100°F or less, the lowest temperature.
12. Depending on the size of the system, compressed air costs about 25 to 42 cents per thousand cubic feet of free air induced by the compressor. This includes operating and maintenance costs.
13. A 50 horsepower compressor rejects approximately 126,000 btu per hour that is available for heat recovery.
14. The water vapor content at ~100° F of saturated compressed air is about two gallons per hour for each 100 cfm of compressor capacity.
15. Every ~20°F temperature drop in saturated compressed air at constant pressure, results in 50% of the water vapor condensing to liquid. Stated conversely, at 100 psig, every ~20°F increase in saturated air temperature doubles the amount of moisture in the air.

16. Every 2 psig change in operating pressure equals a 1% change in horsepower.
17. Most air motors require 30 cfm at 90 psig per horsepower of output.
18. For every 10 inches of water gauge pressure lost at the inlet, compressor performance is reduced by 2%. Intake filters should be regularly cleaned well before dirt causes significant pressure restrictions.
19. A device that will satisfactorily perform its function with 50 psig of air pressure uses approximately 75% more compressed air when it is operated with air at 100 psig.
20. The acceptable pressure drop at the farthest point in mains header of an industrial compressed air network is 5 psig.
21. The number of leaks required to create 80 cfm at 100 psig is:
    - Three 1/8" air leaks at 78 cfm or,
    - One 1/4" air leak at 100 cfm.

MYTHS & REALITIES OF COMPRESSED AIR

Many plant personnel believe compressed air is free; it most definitely is not. It is often the most expensive utility in a facility.

Compressed air is free – as a power source, it is nine times more expensive to use than electricity.

All of the air need to be at the same pressure – If the pressure for a particular area of application is less than 2 barg, a blower is usually more cost effective than compressing air at 7 barg and then regulating it down to a much lower level.

More pressure is better – raising pressure system-wide will require more power on-line. Pressure problems are best solved at the point of use where they exist, not with more power in the compressor room.

"Our system operates at 100 psig" – not likely since most compressed air systems have pressure variations of 10% before the air leaves the compressor room.

Production needs 100 psig – maybe one or two applications are thought to require 100 psig, but for the most part, the true minimum requirement for the majority of the plant is much less.

Reducing compressor operating pressure will save energy– how far pressure is reduced will determine the savings. The further it is reduced the less stable and reliable the system will become. The first time production is interrupted, operating pressure will be returned to previous levels and savings will disappear.

Increasing compressor operating pressure increases operating costs – while it is true that compressing a cubic foot of air to a higher pressure requires more energy, overall operating costs will increase only if the entire system is allowed to operate at the elevated pressure.

Receiver sizing rule of thumb: 1 gallon per cubic foot of compressor rating – receivers are sized to manage events in the system, this rule of thumb gives no attention to the needs of the system.

Fixing air leaks is an easy energy saving measure – reductions in on-line power are seldom seen until a majority of the system air leaks are repaired.

Dryer is better – some facilities install -40° F pressure dewpoint dryers in hopes of fixing their moisture carry over problems. Often the problems have little to do with dryer type. Installing this type of dryer can pose a whole new set of system problems that must be dealt with – like adding 15% more compressor power to accommodate the dryer's purge requirements!

A filter removes 99.9999% of 0.01-micron particles – filter performance is tested per the DOP (dioctylphthalate) test that measures the amount of carry over downstream of the filter being tested. DOP is used because it consistently generates particles that range in size between 0.3 and 0.6 microns, with little variance. A claim that a filter can remove smaller particles is based on the results of this test and variances in filtering media, not actual results with 0.01 micron particles.

Many of the assumptions listed above are real barriers to operating compressed air systems efficiently. Education is the best first-step measure that can be taken for improving compressed air system operating efficiency.

PLANNED PROGRAM FOR ENERGY EFFICIENCY

Whether you are building new facilities or modifying existing facilities, it is usually possible to design a large system so that it is modular, with isolation points. This allows parts of the system to be operated independently.

Energy saving areas and opportunities in compressed air systems generally can may be classified in the categories of:

1. Compressed air generation;
2. Distribution and utilization of compressed air.

These categories can be further divided into smaller areas that can be examined as part of a planned program aimed at cutting the cost of the compressed air. These areas are:

Compressor selection: Compressor selection should be based on the pressure required and the average and maximum loads. Multistage compressors are more efficient especially when the air is cooled between stages. While it may be possible to operate very efficient full load compressors, their performance capability may be negated if the system's demand is only sufficient to operate them at partial load capacity. Thus it is very important to match the type and size of compressor to the load cycle of the system.

Location of compressor: Locate the compressor intake in cool, clean, and dry place. Providing cooler air to the compressor at the intake can provide rewarding savings. If air is drawn from a cool, dry source, rather than from a hot compressor house, the system will operate more efficiently.

Pressure reduction: Power consumed by a compressor depends on its operating pressure and rated capacity. If a process or equipment does not need high pressures, then operating compressors at elevated pressures is a waste of energy. It is important to insure that the air pressure at the compressor is the minimum required for sufficient service.

Controls: Generally all compressors are fitted with some form of control system that varies the volume of air delivered to suit demand. The control system, which governs the running of the compressor, should be matched to its duties and may require re-matching with duty changes.

Compressor operation: Where more than one compressor is supplying a common header, they must be operated in such a manner that one compressor only, can handle the load variation while the other compressor operates at approximately full load. Generally the smaller capacity compressor is allowed to modulate.

Loading of compressor: If the load can be matched more closely with the compressor size, loading on the motor will be maximized and the compressor efficiency will be higher, resulting in less energy waste associated with motor inefficiency. Idle operation of the compressor should be avoided when the desired pressure is reached. Use energy efficient motors, variable speed drives, and soft starter features to minimize starting currents and surge currents.

Effectiveness of inlet & aftercoolers: Fouled intercoolers will allow high temperature air to the second stage which will reduce the efficiency of the second stage, and ultimately the overall efficiency. Fouled aftercoolers will cause more water condensation in air receivers and distribution lines, resulting in an increase of corrosion. Periodic cleaning of both the exchangers is necessary.

Compressor maintenance: Follow the supplier instructions. A routine check of driving belts for tightness and other housekeeping measures recommended in the equipment manual maintenance section should be adopted.

Compressor control assessment: Compressor capacity is expressed in terms of quantity of free air delivered at a particular pressure. Various factors such as poor maintenance, fouled heat exchangers, and local operating altitude will lead to reduced free air delivery.

Dryers: For energy conservation, consideration should be given to air driers whose operation relies on the use of a portion of the heat of compression. If chiller a plant is used for a refrigerant dryer, an attempt must be made to chill the inlet air to the compressor. This will not only increase the compressor efficiency but also removes all moisture. Oil and dirt can be removed in a later stage. A careful assessment is recommended.

Receiver: At points of sudden high demand, an extra receiver near the point of take-off should be considered.

Hunt for air leaks: A hole of 1.6mm can cause 3.2 liters per second of compressed air to leak, amounting to 2,128 kWh of energy per year. For a hole equivalent of 6.4 mm diameter, 51.2 liters/second of air is lost, wasting 34,040 kWh of energy each year at a cost of $3,404.

Check or install shut-off timers: Make sure that the compressor and any associated refrigerated air-drying equipment is switched off when it is not needed. Automatic time switching can accomplish this. If a small quantity of equipment requires air during off-hours, consider supplying them from a small compressor.

It is very easy to save energy and operating costs on your compressed air system.

Follow this checklist to insure an air compressor system is more energy efficient.

1. Check for leaks and pressure losses throughout the system monthly;
2. Insure the entire system is maintained through the use of good housekeeping practices;
3. Insure condensation can be removed quickly from the distribution network, or better still, that it does not occur at all;
4. Where possible reduce pressure settings to the minimum;
5. Always use high efficiency filters and dryers where required;
6. Reduce the compressor intake air temperature by conveying outside air via duct work to the compressor inlet;
7. Check receivers for proper sizing to store air for short heavy demands;

8. Check that the size of your compressor is matched to current demands only;
9. Select the size of the compressor so that it operates as closely as possible to full load;
10. Choose suitably sized receivers to act as a buffer between output and demand;
11. Most importantly, do not install an oversized compressor to meet anticipated future demand. It is usually more economical and more efficient to install an additional, appropriately sized compressor, when future need develops.

Equipment selection and system design play an important role in lowering the costs of compressed air production. Insuring that installed systems are running as efficiently as possible can allow for large gains.

To learn more about the energy efficiency, refer to a separate course titled "Energy Audit and Management of Compressed Air Systems".

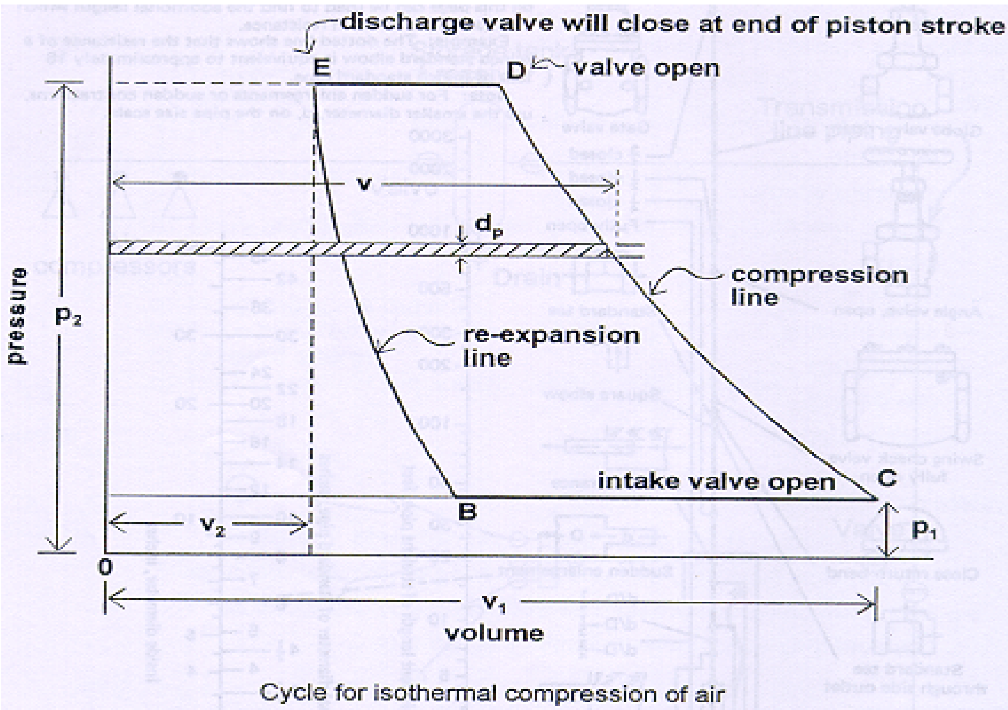
INDUSTRY CODES AND STANDARDS

Code Reference	Code Title
ANSI/ISA	S7.0.01 Quality Standards for Instrument Air
API 617	Centrifugal Compressors for Petroleum, Chemical and Gas Industry Services
API 618	Reciprocating Compressors for Petroleum, Chemical and Gas Industry Services
API 619	Rotary-Type Positive Displacement Compressors for Petroleum, Chemical and Gas Industry Services
API 672	Packaged, Integrally Geared Compressors for Petroleum, Chemical and Gas Industry Services
ASME	ASME Boiler and Pressure Vessel Code, Section VIII, Div.1
ASME/ANSI B16.5	Steel Pipe Flanges and Flanged Fittings
ASME/ANSI B31.1	Power Piping

ASME/ANSI B31.3	Chemical Plant and Petroleum Refinery Piping

A BREIF ACADEMIC SESSION

The figure below shows the compression cycle on p-v diagram.



Cycle for isothermal compression of air

1. p_1 air drawn into the cylinder at pressure
2. p_2 air discharged at pressure
3. v2 the initial volume
4. CD line that the piston follows between C and D as it compresses the air
5. DE line that forms when the discharge valve D is open, (point E being the end of the piston stroke) and the pressure is constant
6. EB line that the piston follows between E and B as it begins its return stroke and point E discharge valve closes
7. BC line that forms when the intake valve opens allowing additional air

The work done is minimum when the compression follows an isothermal law and is maximum for adiabatic compression.

Compressor efficiency = Isothermal work done / Indicated work done

Mechanical efficiency = Indicated hp / B.H.P of motor

Adiabatic efficiency = Adiabatic hp / B.H.P of motor

The figure above shows a theoretical cycle. In practice, throttling of air at the intake causes the suction to fall; throttling of air at the outlet causes the discharge pressure to rise. Clearance causes expansion on the outstroke thereby reducing the capacity of machine. It is important to note that,

1. Throttling the low-pressure suction increases the temperature range in successive stages;
2. Increasing the clearance at one stage causes more work to be done in the lower stage;

Note clearance ratio = clearance volume / swept volume

$= v_2 / (v_1 - v_2)$

Power demand for compression

When describing changes in the state of air (compression, expansion, cooling) thermodynamically, air can be regarded as a perfect gas in the temperature and pressure range relevant for compressed air. The perfect gas equation describes the relation between the pressure (p), volume (V) and temperature (T) of a gas.

The following applies:

$p. V = m * R * T$

With R as the universal gas constant with the value R = 8.3144 J/(mol K). It is then valid that the product from the pressure and volume of the air is proportional to the temperature. The perfect gas equation can be used to describe the changes in state occurring.

The two most important kinds of state changes are the isothermal (pressure change at constant temperature) and the adiabatic (isentropic) (pressure change without heat exchange with the surroundings).

For isothermal changes, the following applies:

$p_1V_1 = p_2V_2$

With R and T = constant

The specific work for compression results from the work for changing the volume

$$w_{12} = -\int_1^2 p \cdot d\upsilon = -p_1 \cdot \upsilon_1 \cdot \ln\frac{\upsilon_2}{\upsilon_1}$$

The following applies to adiabatic changes:

$$\frac{p_1 \cdot V_1}{T_1} = \frac{p_2 \cdot V_2}{T_2}$$

With R = constant

For temperature:

$$\frac{T_1}{T_2} = \left[\frac{\upsilon_2}{\upsilon_1}\right]^{(\kappa-1)} = \left[\frac{p_1}{p_2}\right]^{\frac{\kappa-1}{\kappa}}$$

And for the specific work

$$w_{t,12} = \int_1^2 \upsilon \cdot dp = \int_1^2 c_p \cdot dT = c_p \cdot (T_2 - T_1)$$

For air in the relevant range for compressed air the adiabatic exponent k has a value of k = 1.4kJ/ (Kg K).

The theoretical energy demand for compressing air is thus dependent on the compression ratio and the type of change of state. Whereas the isothermal compression results in the lowest specific work, the actual state characteristics during compression (polytropic compression) are closer to reversible adiabatic compression.

These optimum values are not achievable in practice, since the compression process is afflicted with losses. Good compression air systems are characterized by specific capacities which are approx 45% above the theoretically possible ones of adiabatic compression. It should be noted that the specific energy required decreases with increasing system size. The specific performance data given incorporate all electrical and mechanical losses during compressed air production. They are not directly comparable with the rated power listed on the name plate of the drive motor of the compressor. The specific power consumption of a compressed air system should lie within the good range. The lower limit of the good range is described by the adiabatic compression which represents an ideal case and therefore cannot be achieved by real compressors.

This is just a brief description. Those interested in further study may refer to a book on mechanics and thermodynamics.

GLOSSARY OF TERMS

A

Absolute Pressure:

The sum of the gauge pressure and the atmospheric pressure (PSIA). (Example: 50 PSIG equals 50 plus atmospheric pressure, 14.7 at sea level, so 50 PSIG is the same as 64.7 PSIA at sea level

Absolute Temperature:

The temperature of a body referred to the absolute zero, at which point the volume of an ideal gas theoretically becomes zero. On the Fahrenheit scale this is minus 459.67°F; on the Celsius scale it is minus 273.15°C. Engineering values of minus 460°F and minus 273°C are used herein.

ACFM:

Actual Cubic Feet per Minute. Refers to a volume of air (one cubic foot) at ambient conditions, no matter what those conditions are. Changes in pressure, temperature, and relative humidity do not change these ratings. Therefore, ACFM is a measure of volume, regardless of weight. (See corrections for altitude chart)

After-Coolers:

Heat exchangers for cooling air or gas discharged from compressors. They provide the most effective means of removing moisture from compressed air and gases.

Air-cooled compressors:

These are machines cooled by atmospheric air circulated around the cylinders or casings.

Altitude:

The elevation above sea level.

Atmospheric Pressure:

The pressure of the atmosphere at any location that will decrease as the elevation above sea level increases. Sea level atmospheric pressure is 14.7 PSAI, or 29.92 inches of mercury absolute. At 2500 feet, the pressure is 13.41 PSIA, or 27.32 inches of mercury.

Atmosphere:

A pressure measurement obtained by dividing absolute pressure by atmospheric pressure. (Example: 114.7 PSIA/14.7 PSIA equals 7.8 atmospheres)

Auto Drains:

Auto Drains discharge water and oil from collection points within the air system.

B

Barometric Pressure:

The absolute atmospheric pressure existing at the surface of the earth. It is the weight of a unit column of air above the point of measurement. It varies with altitude and, at any given location, with moisture content and weather.

Base plate:

A metallic structure on which a compressor or other machine is mounted.

Boolean logic:

The logic of binary systems, such as control systems in which all operations may be reduced to on/off, open closed, or some similar dichotomous basis.

Booster Compressors:

Machines designed for compressing air or other gases from an initial pressure, which is above atmospheric pressure, to a higher pressure.

Brake Horsepower:

The actual horsepower output to the drive motor.

C

Capacity:

Capacity of a compressor is the actual volume rate of flow of gas compressed and delivered at conditions of total temperature, total pressure, and composition prevailing at the compressor inlet.

Capacity (Actual):

Quantity of gas actually compressed and delivered to the discharge system at rated speed of the machine and under rated pressure conditions. Actual capacity is usually expressed in cubic feet per minute (cfm) at first stage inlet gas conditions.

Check Valve:

A valve that permits flow in one direction only.

Clearance:

When referring to a reciprocating compressor cylinder is that volume contained in one end of the cylinder which is not swept by the movement of the piston. It includes space between piston and head at the end of the compression stroke, space under the valves, etc., and is expressed as a percentage of the piston displacement per stroke. Clearance may be different for the two ends of a double-acting cylinder. An average is generally used.

Clearance pocket:

An auxiliary volume that may be opened to the clearance space to increase the clearance, usually temporarily, to reduce the volumetric efficiency of the compressor

Coalescing Filter:

Removes small particles, dirt, and oil from the compressed air.

Compressibility:

The factor of a gas or a gas mixture that causes it to differ in volume from that of a perfect gas when each is under the same pressure and temperature conditions. Occasionally it is called deviation. It must be determined experimentally.

Compression, adiabatic: This type of compression is affected when no heat is transferred to or from the gas during the compression process

Compression, isothermal: isothermal compression is a compression in which the temperature of the gas remains constant. For perfect gases, it is represented by the equation PV is a constant, if the process is reversible,

Compression Efficiency:

The ratio of the theoretical work requirement (using a stated process) to the actual work required to be done on the gas for compression and delivery. Expressed as a percentage, compression efficiency accounts for leakage and fluid friction losses, and thermodynamic variations from the theoretical process.

Compression Ratio:

Ratio of absolute discharge pressure to the absolute intake pressure (CR).

Compressors:

Machines designed for compressing air or other gases from an initial intake pressure to a higher discharge pressure.

Constant Speed Control:

Unit runs continuously but matches air supply to demand by "loading" or "unloading" the compressor.

Critical pressure:

The limiting value of saturation pressure as the saturation temperature approaches the critical temperature.

Critical temperature:

The highest temperature at which well defined liquid and vapour states exist. It is sometimes defined as the highest temperature at which it is possible to liquefy a gas by pressure alone.

D

Density:

The weight of a given volume of gas, usually expressed in lb/cu ft at specific temperature and pressure.

Desiccant Air Dryers:

A device that will remove moisture for dew-point requirements to -40 or a -100 degrees F.

Dewpoint:

The temperature at which the vapor in a space (at a given pressure) will start to condense (form dew). Dewpoint of a gas mixture is the temperature at which the highest boiling point constituent will start to condense.

Diaphragm:

A stationary element between the stages of a multistage centrifugal compressor, It may include guide vanes for directing the flowing medium to the impeller of the succeeding stage. In conjunction with an adjacent diaphragm, it forms the diffuser surrounding the impeller.

Diaphragm routing:

A method of removing heat from the flowing medium by circulation of a coolant in passages built into the diaphragm.

Diffuser:

A stationary passage surrounding an impeller, in which velocity pressure imparted to the flowing' medium by the impeller is converted into static pressure

Discharge Pressure:

The total gas pressure (static plus velocity) at the discharge flange of the compressor. Velocity pressure usually is considered only with dynamic compressors.

Note: Pressure may be expressed as gauge or absolute pressures. psig plus atmospheric pressure equals psia. Note that psig does not define a pressure unless the barometric pressure (atmospheric) is also stated.

Discharge Temperature:

The temperature existing at the discharge flange of the compressor.

Note: In a multistage compressor, the various stages will have different discharge pressures and temperatures.

Displacement:

Displacement of a compressor is the volume swept out per unit of time; it is usually expressed in cubic feet per minute

Double Acting Compressors:

Machines in which compression takes place on both strokes per revolution in each compressing element.

Double Stage Compressors:

Machines in which compression from initial to final pressure is completed in two stages.

Dry-Bulb Temperature:

The ambient gas temperature.

Dry Gas:

Any gas or gas mixture that contains no water vapor and/or in which all of the constituents are substantially above their respective saturated vapor pressures at the existing temperature. (See Wet Gas)

Note: In commercial compressor work, a gas may be considered dry (even though it contains water vapor) if its dewpoint is low at the inlet condition (say minus 50° to minus 60°F).

Dryer:

An integral part of the compressed air system that removes the heat of the compressed air and also removes the moisture from the air due to the heat loss.

Dynamic:

Machines where air or gas is compressed by the dynamic action of rotating vanes or impellers imparting velocity and pressure to the air or other gases.

E

Efficiency:

Any reference to efficiency of a dynamic type compressor must be accompanied by a qualifying statement which identifies the efficiency under consideration, as in the following definitions.

Efficiency, compression: Ratio of calculated isentropic work requirement to actual thermodynamic work requirement within the cylinder, the Inner as determined from the cylinder indicator card.

Efficiency, isothermal: Ratio of the work calculated on an isothermal basis to the actual work transferred to the gas during compression.

Efficiency, mechanical: Ratio of thermodynamic work requirement in the cylinder (a shown by die indicator card) to actual brake horsepower requirement.

Efficiency, polytropic: Ratio of the polytropic compression energy transferred to the gas no the actual energy transferred to the gas.

Efficiency, volumetric: Ration of actual capacity to displacement, stated as a percentage.

Enthalpy:

The sum of the internal and external energies. (Measure of heat content)

Entropy:

A measure of the unavailability of energy in a substance.

F

Filters:

Are devices for separating and removing dust and dirt from air before it enters a compressor.

Flange connection:

The flange connection (inlet or discharge) is a means of connecting the casing to the inlet or discharge piping by means of bolted rims (flanges).

Free air:

Free air is defined as air at atmospheric conditions at any specific location. Because the altitude, barometer, and temperature may vary at different localities and at different times, it follows that this term does not mean air under identical or standard conditions.

G

Gas:

While from a physical point of view a gas is one of the three basic phases of matter, and thus air is a gas, a special meaning is assigned in pneumatics practice. The term gas refers to any gas other than air.

Gauge Pressure:

The pressure on the gauge measured above atmospheric pressure (PSIG); that is, that measured on a given gauge, not affected by altitude or atmospheric pressure.

H

Head, adiabatic: The energy in four pounds required to compress adiabatically and to deliver one pound of a given gas from one pressure level to another.

Head, polytropic: The energy in foot pounds required to compress polytropically and to transfer one pound of a given gas from one pressure level to another.

Horsepower, brake:

Brake horsepower is the horsepower input to the compressor shaft, or more generally to any driven machine shaft.

Horsepower, theoretical, or ideal:

The ideal, or theoretical horsepower of a compressor is defiled as the horsepower required to compress adiabatically the air or gas delivered by the compressor through he specified range of pressures.

Humidity, specific:

Specific humidity is the weight of water vapor in an air vapor mixture per pound of dry air

Humidity, relative:

The relative humidity of a gas (or air) vapor mixture is the ration of the partial pressure of the vapor to the vapor saturation pressure at the dry bulb temperature of the mixture.

I

Ideal Compression Ratio:

In two-stage units, the square root of the total compression ratio is used to size stage compression ratio and balances the load between stages (ICR).

Ideal Gas:

Follows the perfect gas laws without deviation. Practically, there are no ideal gases, but it is the basis from which calculations are made and corrections applied.

Impeller:

The part of the totaling element of a dynamic compressor that impacts energy to the flowing medium by means of centrifugal force. It consists of a number of blades mounted so as to rotate with the shaft.

Inlet Pressure:

The total pressure (static plus velocity) at the inlet flange of the compressor. Velocity pressure is usually considered only with dynamic compressors. (See note under Discharge Pressure).

Inlet Temperature:

The temperature at the inlet flange of the compressor.

Note: In a multistage compressor, the various stages may have different inlet temperatures.

Inter-Coolers:

These are heat exchangers for removing the heat of compression between stages of a compressor. They usually condense and remove a considerable amount of moisture as well.

Intercooling:

This is the removal of heat from the air or gas between stages or stage group.

Intercooling range: The difference in air or gas temperatures between the inlet of the compressor and the outlet of the intercooler.

Intercooling, perfect: Perfect intercooling exists when the temperature of the air leaving the intercoolers equals the temperature of the air at the compressor intake.

Isentropic compression:

An adiabatic compression with an increase in entropy; a reversible-adiabatic compression.

L

Liquid piston:

A liquid piston compressor is a rotary compressor in which a vane rotor revolves in an elliptical casing, with the rotor spaces sealed by a ring of liquid rotating with it inside the casing.

Load factor:

This factor is the ration of the average compressor load during a given period of time to the maximum rated load of the compressor. It applies also to air tools, where it is the product of the work factor times the time factor.

Logic Controls:

These are control devices the operation of which may be reduced to binary operation such as an on-off, 0-1, or open-closed. They are also referred to as digital controls.

M

Mechanical Efficiency:

The ratio, expressed in percent, of the Thermodynamic Work Requirement in the cylinder to the actual shaft horsepower.

Mechanical Ratio:

Multi-Stage only. The ratio of the displacements of the low pressure and high pressure stages (MR).

Moisture Separators:

Devices for collecting and removing moisture precipitated from the air and gas during the process of cooling.

Multi-casing Compressor:

When a single motor or turbine drives two or more compressors, each with a separate casing,, the combined unit is called a multi-casing compressor.

Multi-Stage Compressors or Compound Compressors:

A machine in which compression from initial to final pressure is completed in two or more distinct steps or stages.

N

Normal Air:

The term used for average atmospheric air at sea level in a temperate zone where it contains some moisture. It is defined in the ASME Test Code for Displacement Compressors as being at 14.696 psia, 68°F, 36% RH, and weighing 0.075 lb/cu ft. The K value is 1.395.

O

Oil/Water Separator:

A device that separates the remaining compressor oil from condensate.

P

Particulate Filter:

Removes small particles and dirt from the compressed air.

Perfect Intercooling:

Is obtained when the gas is cooled to first stage inlet temperature following each stage of compression.

Performance Curve:

This curve is a plot of expected operating characteristics, e.g., discharge pressure vs. inlet capacity, shaft horsepower vs. inlet capacity.

Piston Displacement:

Net volume actually displaced by the compressor piston or rotor at rated machine speed, generally expressed in cubic feet per minute (usually CFM) For multi-stage compressors, the piston or rotor displacement of the first stage only is commonly stated as that of the entire machine.

Polytropic Head:

An expression used for dynamic compressors to denote the foot-pounds of work required per pound of gas.

Positive Displacement:

A machine where successive volumes of air or gas are confined within a closed space and pressure is increased as the volume of the closed space is decreased

Pressure (PSI):

Pounds-Per-Square-Inch- a rating of Air Pressure in the system. (PSIG) "Gauge" Gauge pressure shows amount of air pressure above ambient

Pressure Discharge:

Discharge pressure is the absolute total pressure at the discharge flange of a compressor

Pressure, intake:

Intake pressure is the absolute total pressure at the inlet flange of a compressor.

Pressure rise:

This is the difference between the discharge pressure and the intake pressure

Pressure static:

Static pressure is the pressure measured in a flowing stream (liquid or gas) in such a manner that no effect on the measurement is produced by the velocity of the stream.

R

Rotary Screw Compressors:

Machines that use male and female helical rotors to smoothly compress air.

Receivers:

Receivers are tanks used for the storage of air discharged from compressors. They serve also to damp discharge line pulsations.

Reciprocating Compressors:

Machines that use a reciprocating motion (piston) to compress air.

Refrigerated Air Dryer:

A device that will remove moisture for dew-point requirements no lower than 33-degrees F.

Rotor:

The rotor is the rotating element of a machine and, in the case of a compressor, is composed of the impeller (or impellers) and shaft, and may include shaft sleeves and a thrust balancing device.

Rotary Compressors:

These are machines in which compression is effected by the positive action of rotating elements. (Capable of 100% Duty)

Rotary Screw:

Machines that use male and female helical rotors to smoothly compress air

Rotary, Sliding Vane:

Such compressors are machines in which axial vanes slide radially in an eccentrically mounted rotor.

Rotary, two-impeller positive displacement:

These are machines in which two mating lobed impellers revolve within a cylinder or casing and are prevented from making contact with each other by timing gears mounted outside the cylinder.

Rotary, liquid-piston compressors:

These are machines in which water or other liquids are used, usually in a single rotating element, to displace the air or gas handled.

S

Saturation:

Occurs when the vapor is at the dewpoint or saturation temperature corresponding to its partial pressure. A gas is never saturated with a vapor. The space occupied jointly by the gas and vapor may be saturated, however.

Saturation (degree of):
The ratio of the weight of vapor existing in a given space to the weight that would be present if the space was saturated at the space temperature.

Saturated Air-Vapor Mixture:
Is one in which the space occupied by the mixture is saturated with water vapor at the mixture temperature.

Saturated Vapor Pressure:

The pressure existing at a given temperature in a closed vessel containing a liquid and the vapor from that liquid after equilibrium conditions has been reached; it is dependent only on temperature and must be determined experimentally.

Saturation Pressure:
Another term for Saturated Vapor Pressure.

Saturation Temperature:
The temperature corresponding to a given saturated vapor pressure for a given vapor.

SCFM:
Standard Cubic Feet per Minute. At "standard conditions" (see above) will one standard cubic foot of air actually occupy one cubic foot of volume. Another way to express one standard cubic foot of air is .075 of a pound of air. A standard cubic foot varies in volume as it deviates from standard conditions, but it always weighs .075 of a pound. Therefore, SCFM is a measure of weight, regardless of volume. (See corrections for altitude chart)

Seals:
Seals are devices used between rotating and stationary parts to separate, and minimize leakage between, areas of unequal pressures.

Single-Acting Compressors:
Machines in which compression takes place on one stroke per revolution in each compressing element.

Single-Stage Compressors:
Machines in which compression from initial to final pressure is complete in a single step or stage.

Slip:
The internal leakage within a rotary compressor. It represents gas at least partially compressed

but not delivered. It is determined experimentally and expressed in CFM to be deducted from the displacement to obtain capacity.

Slip RPM:

The speed required of a rotary compressor to maintain a given discharge pressure, supplying leakage only (zero actual output). The factor must be established by experiment.

Specific Gravity:

The ratio of the density of a given gas to the density of dry air, both measured at the same specified conditions of temperature and pressure, usually 14.696 psiA and 60°F. It should also take into account any compressibility deviations from a perfect gas.

Specific Heat:

(Heat Capacity) The rate of change in enthalpy with temperature. It is commonly measured at constant pressure or at constant volume. The values are different and are known as Cp and Cv respectively.

Specific Humidity: (See Humidity)

Specific Volume:

The volume of a given weight of gas, usually expressed as cu ft/lb at specific conditions.

Standard Air:

Measured at 68 degrees F, 14.7 PSIA, and 36% relative humidity (.075lb/ft3 density). This agrees with the Compressed Air and Gas Institute (CAGI). The gas industries use 60 degrees F, 14.7 PSIA, and dry as conditions for standard air (SCFM).

Standard Pressure and Temperature (SPT):

Generally is 14.696 psiA and 60°F unless specifically stated otherwise.

State:

State of a system or part thereof is its condition at an instant of time as described or measured by its properties.

Suction Pressure:

Absolute static prevailing at the suction of the ejector.

Super-Compressibility:

A term used with various meanings, most frequently the same as compressibility, although this is not assured. A current ASME Power Test Code uses it as a ratio of gas densities rather than volumes. Therefore it is 1/Z in this case. Super-compressibility should never be used unless its meaning is clarified completely. Compressibility is much to be preferred and is used herein.

T

Temperature rise ratio:

This is the ration of the computed isentropic temperature rise to the measured total temperature rise during compression. For a perfect gas, this is equal to the ration of the isentropic enthalpy rise to the actual enthalpy rise.

Torque:

Torque is a torsional moment or couple. It usually refers to the driving couple of a machine or motor.

Turbine:

A turbine is a prime mover in which a stream of fluid, such as water, steam or gas, provides the impulse to drive a bladed rotor.

Two-Stage Compressors:

These are machines in which air or gas is compressed from initial pressure to an intermediate pressure in one or more cylinders or casing.

V

Vacuum Pumps:

Machines for compressing air or other gases from an initial pressure that is below atmospheric pressure to a final pressuring that is near atmospheric

Vapor Filters:

Are filters designed for the removal of vapors and odors, which still may be present, after the air has passed through the coalescing and/or particulate filters. The activated carbon element attracts residual vapors and binds them to the surface of the activated carbon grain molecules.

Vapor Pressure:

The pressure exerted by a vapor confined within a given space. The vapor may be the sole occupant of the space, or may be associated with other gases.

Volumetric Efficiency:

The ratio of the actual inlet capacity (ACFM) to the first stage displacement expressed as a percentage. Volumetric efficiency varies by clearance or blow-by, heating losses, valve losses, and specific gravity of gas being compressed.

W

Water-Cooled Compressors:

These are machines cooled by water circulated through jackets surrounding the cylinders or casings.

Wet-Bulb Temperature (WBT):

WBT is used in psychrometric and is the temperature recorded by a thermometer whose bulb has been covered with a wetted wick and whirled on a sling psychrometer. Taken together with the dry-bulb temperature, it permits determination of the relative humidity of the atmosphere.

Wet Gas:

Any gas or gas mixture in which one or more of the constituents is at its saturated vapor pressure. The constituent at saturation pressure may or may not be water vapor.

Work:

Energy in transition and is defined in units of Force times Distance. Work cannot be done unless there is movement.