Compressed Air Systems

CEU 246

Continuing Education from the American Society of Plumbing Engineers

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Note: In determining your answers to the CE questions, use only the material presented in the corresponding continuing education article. Using information from other materials may result in a wrong answer.

Air compressors play a vital role in hospitals, laboratories, and industrial buildings by providing air to serve various functions at pressures above atmospheric.

As the Hydraulic Institute is to pumps, the Compressed Air and Gas Institute (cagi.org) is to the air compressor industry. Compressed Air Best Practices (airbestpractices.com) is an excellent resource as well.

COMPRESSOR ACTION

An air compressor compresses air into a smaller volume and increases its pressure. The compressor utilizes the molecular energy of the air and converts it into a usable form. It does not increase the energy of the air; it simply concentrates it similar to the way a magnifying glass concentrates the sun's rays.

Theoretically, air could be compressed with perfect cooling or with no cooling whatsoever. *Isothermal compression* involves perfect cooling; the air always remains at its initial temperature while being compressed. *Adiabatic compression* involves no cooling; the initial temperature of the air is allowed to rise steadily throughout the compression process. The heat of compression helps raise the pressure under adiabatic compression, and the required pressure is attained much sooner than under isothermal compression. The drawback is that the air pressure is greater throughout the process, and more input work is required to obtain the same outlet pressure. Various methods are employed to cool the air during compression to bring the compression process closer to isothermal to reduce the power consumption.

EQUIPMENT SELECTION FACTORS

Many factors must be considered when selecting an air compressor and its accessories for a particular installation. Generally, the factors that merit consideration are:

- Required quantity of compressed air
- Required pressure
- Load characteristics (load variation, duty cycle, intermittent or continuous)
- Space conditions
- Costs (capital, operating, and maintenance)
- Compressed air quality (oil-less, oil-free, dry)
- Availability of cooling water
- Type of drive

COMPRESSOR TYPES

The two basic types of air compressors are the positive displacement and the dynamic. Reciprocating and rotary (sliding vane, screw, and scroll) compressors fall under the positive-displacement category. The centrifugal compressor is the dynamic type.

Although the laws of thermodynamics are applicable to all types of air compressors, the basic types exhibit different operating characteristics. The positive-displacement compressor is essentially a constant-volume, variable-pressure machine capable of operating over a wide range of discharge pressures at a relatively constant capacity. Dynamic compressor characteristics are the opposite, operating over a relatively wide range of capacities at a relatively constant discharge pressure.

When a compressor is referred to as *oil-less,* the compressor's lubricating oil never touches the air stream. *Oil-free* means that the oil leaving the compressor is minimized by a high-efficiency oil-removal filter located at the compressor discharge.

Single and Multistage Compressors

In a single-stage compressor, the air is compressed from the ambient condition to the required final pressure in one thermodynamic and mechanical step. It is generally accomplished without a lot of cooling and is most practical up to approximately 100 pounds per square inch (psi) at relatively low flows. Some compressors are designed to introduce cooling within the single stage of compression to raise these limits.

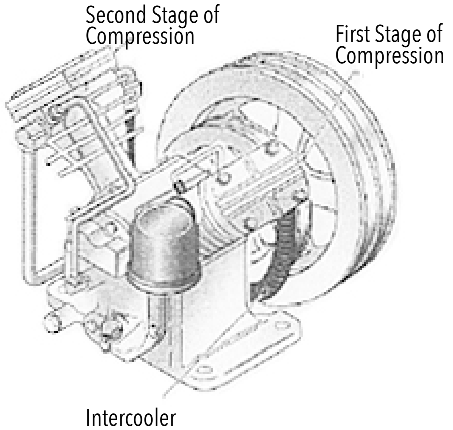

Figure 14-1 Multistage Compressor

In a multistage compressor (Figure 14-1), a portion of the required final pressure is attained in one stage, and the air is then cooled (by an intercooler) and sent to another stage to be raised to a higher pressure. This multistage compression can be repeated several times to attain higher pressures at excellent efficiencies.

Reciprocating Compressor

A reciprocating compressor is a positive-displacement machine that increases the pressure of a specific volume of air by decreasing its volume. This is accomplished by a piston moving back and forth in a cylinder. When the air is compressed in one end of the cylinder only, it is called a single-acting cylinder, and when air is compressed in both ends, it is called a double-acting cylinder (see Figure 14-2).

Cooling of the air in reciprocating compressors is accomplished with air, water, or both. The cylinders can be sealed and lubricated with oil when traces of oil in the discharge air won't cause problems. When the discharge air must be oil-free, a cylinder with a piston with Teflon rings and a coalescing discharge filter is available.

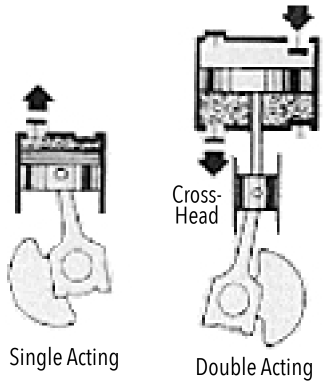

Figure 14-2 Single- and Double-Acting Cylinders

A water-cooled reciprocating compressor is generally more effective than an air-cooled compressor and uses less power, but the initial and operating costs are higher. A two-stage compressor consumes less power than a single-stage unit for the equivalent output.

Reciprocating compressors, as compared to other types, offer the highest efficiency at full load or partial load. Water-cooled two-stage compressors also provide the benefits of multi-step capacity control when desired.

Reciprocating compressors can have several cylinders. They also can have a variable-frequency drive in some applications.

Sliding Vane Compressor

Sliding vane compressors (Figure 14-3) utilize a rotor mounted eccentrically in a cylindrical housing. The vanes are free to slide in and out of slots cut into the rotor. The vanes move out and are held against the cylinder wall by centrifugal force as the rotor rotates. Air enters at the point where the vanes are at maximum extension. The space between the rotor and the cylinder casing decreases as the eccentrically mounted rotor turns, and the air is progressively compressed. At the point of maximum compression (the least space between the rotor and the casing), the air discharges through the discharge port.

Compressors of this type often spray cooling oil into the cylinder to absorb the heat of compression to keep the air temperature relatively low. This improves efficiencies and also acts to seal and lubricate the vanes. An oil-separation system removes most of the entrained oil from the discharge air. Special air filters are available to remove the remaining traces of oil when oil-less air is a requirement.

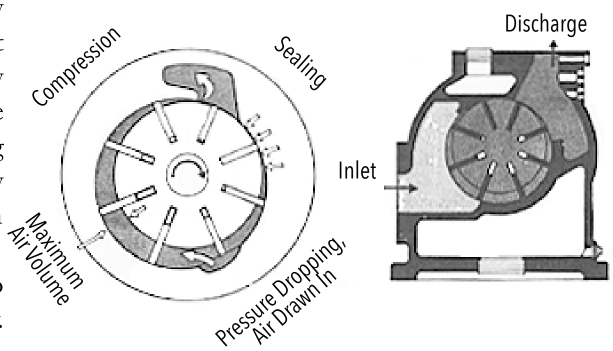

Figure 14-3 Sliding Vane Compressor

The sliding vane compressor is a compact unit and generally finds its greatest application in the lower horsepower ranges. Its efficiency is good, but not quite as good as the reciprocating type of compressor.

Rotary Screw Compressor

The rotary screw compressor (Figure 14-4) is composed of two intermeshing helical rotors (screws) that roll together smoothly, squeezing the air to reduce its volume and increase its pressure. The air reaches the end of the screw at high pressure and flows out smoothly at the discharge port.

The majority of rotary screw compressors in use today are of the oil-flooded type. Oil is injected at the inlet end of the rotor and is entrained in the air stream. The oil forms a thin lubricating and sealing film between the intermeshing rotors and, at the same time, cools the compressor chamber, absorbing the heat of compression as it is generated. An oil-separation system removes all but traces of oil vapor from the discharge air. The separated oil is recirculated for reuse after being cooled in a water- or air-cooled oil cooler.

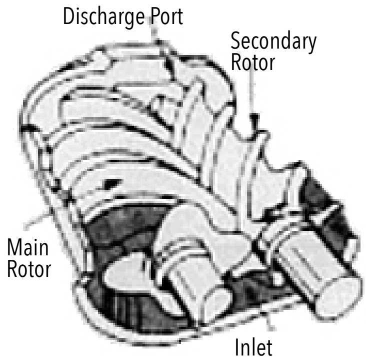

Figure 14-4 Rotary Screw Compressor

The rotary screw compressor is compact and simple in construction. Its aerodynamic stability makes it suitable for installation in practically any location. It is suitable for continuous operation, but its power consumption is higher than that for a reciprocating compressor of equivalent output.

Dry screws are available for oil-less air. No oil touches the air stream, but the screw runs hot. Oil-free screws have high-efficiency coalescing filters on the discharge.

A screw compressor has a slide valve to control the capacity. The slide valve controls the amount of air that can enter the screws.

Liquid-Sealed Rotary Compressor

In the liquid-sealed compressor, the functions of mechanical pistons or vanes are performed by a rotary ring of water that serves as the compressing mechanism. The circular, single-lobe style (Figure 14-5) is adequate for lower pressure requirements (5–15 psi), and the oval-shaped, double-lobe type (Figure 14-6), which has two diametrically opposed compression sectors that balance lateral forces, is preferred for higher pressures (50–100 psi). In the circular-lobe machine, the ring of water tends to center itself in the cylindrical body, which is offset from the rotor axis. In the double-lobe machine, the ring of water follows an elliptical path inside the oval-shaped body.

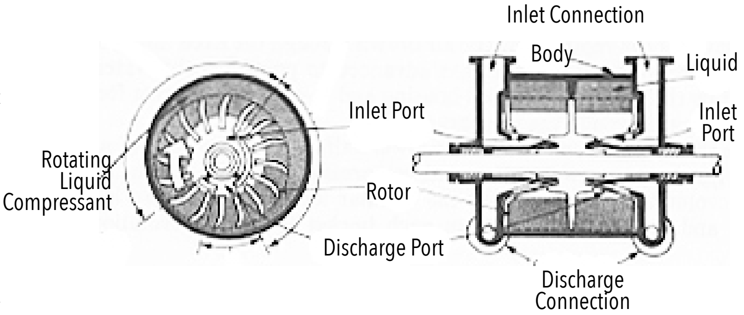

Figure 14-5 Liquid-Sealed Rotary Compressor, Circular Lobe

Although the operation of the double-lobe machine is described below, all comments are applicable to the single-lobe machine as well.

Water is introduced into the machine continuously while it is running. The water and any entrained air in the water are continuously discharged. The water is removed from the air stream by a mechanical separator. The water washes the air, removing dust and germs and discharging them to waste. Cool water also removes substantial quantities of atmospheric humidity before the air reaches the air receiver or distribution piping.

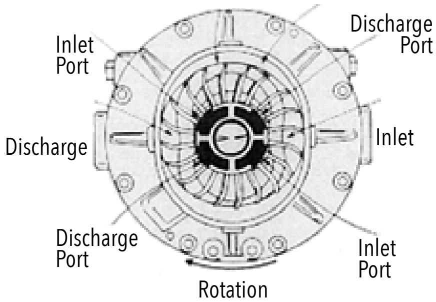

Figure 14-6 Liquid-Sealed Rotary Compressor, Double Lobe

The water is carried along as the rotor revolves, resulting in a solid liquid ring revolving in the casing at the same speed as the rotor. Because the casing is elliptic and the rotor is circular, the water alternately enters and fills the chambers and then leaves the chambers in a continuous cycle. Air is drawn through ports (connected to the inlet) in the center of the rotor at the points where the water leaves the rotor chambers. As the water is forced by the converging casing to re-enter the rotor chambers, the air in the chamber is forced out through ports connected with the compressor outlet. The bucket formed by the rotor blades is full of water, and when the bucket has moved, it is practically empty, the water having been replaced by the air drawn through the fixed inlet port in the central cone. When the bucket advances further, the water is constrained by the elliptically shaped housing and re-enters the bucket, forcing the pressurized air through the discharge port.

Since this cycle is duplicated in the lower half of the compressor in the double-lobe type, two suction and compression strokes occur in each bucket for every revolution of the rotor. In the circular-lobe machine, a single suction and compression stroke occurs in each bucket for every revolution of the rotor.

Inlet and discharge ports in the central cone are connected by cored passages with the compressor inlet and discharge connections.

Each liquid-sealed rotary compressor should be equipped with the following accessories: seal water solenoid valve, seal water adjusting valve, strainer, discharge separator with gauge glass and relief valve, inlet silencer, backflow preventer in the seal water line, and a drain funnel.

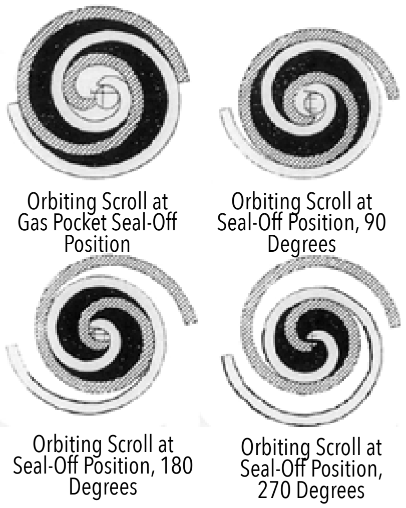

Figure 14-7 Operating Positions of Scroll Compressors

Scroll Compressor

Scroll compressors are used for small quantities of compressed air (compared to a screw). They are usually canned in a steel casing and look like a small refrigerant compressor. Figure 14-7 shows their operating positions.

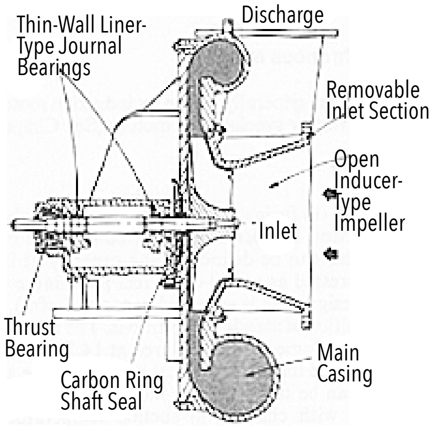

Figure 14-8 Centrifugal Compressor

Centrifugal Compressor

Centrifugal compressors (Figure 14-8) are dynamic machines that utilize impellers to impart kinetic energy to the air stream by centrifugal action. The velocity of the air is increased as it passes through each impeller. A diffuser section decelerates the high-velocity air, converting the kinetic energy into potential energy. The volute increases the pressure further and directs the air into the discharge piping.

Centrifugal compressors typically produce large volumes of air at relatively low pressures. Higher pressures can be attained by additional stages with intercooling between the stages. The centrifugal compressor takes up less floor space but requires more power than a reciprocating unit of equal output. Its inherently oil-free delivery of air could be a major advantage in many applications.

COMPRESSOR DUTY

Light duty can be defined as low delivery in cubic feet per minute (cfm) for several hours per day. A single-stage, air-cooled reciprocating compressor is typical for this type of service.

Medium duty can be defined as five to 10 hours of operation per day. A two-stage, air-cooled reciprocating, single-stage, water-cooled reciprocating, or screw compressor is typical for this type of service.

Heavy duty is when the compressor is required to operate 24 hours per day. Water-cooled reciprocating or scroll compressors are a must for this type of service. In the 10- to 25-horsepower (hp) range, single-stage units are satisfactory. Around 125 hp and higher, two-stage, water-cooled reciprocating compressors are usually the best choice. Generally, two-stage units are selected for ranges between 75 and 2,000 hp.

CALCULATING COMPRESSOR CAPACITY

Actual capacity is expressed as actual cubic feet per minute (acfm). Another common designation is *standard capacity* (scfm). The accepted definition of standard conditions is the volume of air measured at 14.7 psi absolute, 60°F, 0 percent humidity, and 0.24 specific heat. It is erroneous to assume that scfm is equal to acfm or free air. Under certain specific conditions this can be true, but it rarely happens in actual practice. Scfm varies with changes in altitude and temperature. The following equations are used to determine the actual capacity:

Equation 14-1a

$$\frac{PV}{T} = R$$

Equation 14-1b

$$\text{acfm} = \frac{\text{scfm} \times 14.7}{P_s - P_p(H_20)} \times \frac{T_s}{460 + 60}$$

Equation 14-1c

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

where

P_s = Suction pressure, pounds per square inch absolute (psia) (actual atmospheric pressure)

$P_P(H_20)$ = Partial pressure of water, psia (percent relative humidity x pressure of the water vapor at the suction temperature)

T_s = Suction temperature, degrees Rankin (deg. F + 460)

The following examples emphasize the problems that could arise by confusing actual and standard capacity.

- At an intake suction of 14.7 psia, 0 percent relative humidity, and 90°F, calculations show that 100 scfm equals 107.5 acfm.
- At an intake suction of 14.7 psia, 100 percent relative humidity, and 90°F, calculations show that 100 scfm equals 113 acfm.
- At an intake suction of 13.16 psia (unit is installed 3,000 feet above sea level), 100 percent relative humidity, and 90°F, calculations show that 100 scfm equals 127.5 acfm.

It is obvious from the third example that if 100 acfm were specified when in reality 100 scfm was required, the compressor would be more than 27 percent undersized. On the other hand, if 100 scfm were specified when 100 acfm was required, the compressor would be more than 27 percent oversized.

Note that the vapor pressure P_p is less than 1 up to 100°F and that the relative humidity is much less than 100 percent most of the time. This results in a number much less than 1. Also, T/t + 460 results in a number slightly more than 1. For routine day-to-day calculations, ignore the vapor pressure and the temperature correction and use the following formula:

Equation 14-2

$$\frac{P_1V_1}{P_2V_2}$$

where

P = Pressure, psia (gauge + atmospheric pressure)

V = Volume, cubic feet

Most gaseous requirements are in scfm. This holds true for many pneumatic tools as well. In general, it is safe practice to specify the required compressor capacity in scfm terms. If this is not possible, it is essential to measure conditions at the capacity and clearly state the suction pressure and temperature.

The supplier should be given the following design conditions:

- Barometric pressure in psia
- Inlet air temperature

- Relative humidity
- Cooling water temperature (if applicable)
- Discharge pressure
- Flow in acfm, acfm free air delivered (FAD), or scfm delivered—if scfm is specified, it is necessary to specify the standard pressure in psia, standard temperature, and standard relative humidity

ACCESSORIES

Air compressor accessories will improve the function of the compressed air system and in many cases are absolutely essential for proper operation. Most of the accessories discussed are not included with the compressor (unless it is a packaged unit) and must be specified separately.

Most accessories are located in the compressor room. Valving must be used for all equipment removal and/or repair. In some cases, the designer may want to bypass some equipment. In some critical uses of compressed air, dual pieces of equipment should be used if compressed air is continuously needed for industrial production. Duplex equipment is mandatory for medical air compressor systems.

Intake and Discharge Filters

An intake filter is an absolute requirement for any compressor, regardless of where the compressor is located. An open suction pipe is an invitation to costly damage. Dirt, grit, and other foreign matter will be drawn into the compressor and clog passages and abrade moving parts.

Discharge filters protect the distribution line, process equipment, and the product. Filters, singly or in series, are installed after the compressor to remove oil and oil vapor from the compressed air. Filters are used after a non-lubricated reciprocating or screw compressor to remove traces of carbon and scale.

See Table 14-1 for air filter characteristics.

Various types of filters are available to meet practically any operating condition. Viscous-impingement filters are satisfactory for average conditions. When the atmosphere is heavily laden with foreign matter, the slightly more expensive oil-bath filter should be used. Dry-type filters made of felt and wire mesh elements should be used when oil-free air is required. Combination filter/silencers, which are filters combined with a device to reduce the noise associated with the compressor air intake, are also available. The combination intake air filter and silencer shall be of the bath type, of all metal construction.

Discharge filters are usually of the coalescing type (Figure 14-9), where the oil is gathered into larger droplets that can be separated out and then captured and drained. They are essential for oil-injected screw compressors of all types. They also can be used on reciprocating compressor discharges. Packaged screws usually come with an oil filter and aftercooler in the compressor enclosure.

The intake filter should always be sized generously. If it is undersized, the compressor suction can be starved, with a resulting reduction in capacity. The intake filter is sized on the basis of the compressor's capacity, and the connection to the compressor must be equal to or larger than the inlet to the compressor.

If the filter is installed outdoors, a weather hood should be provided.

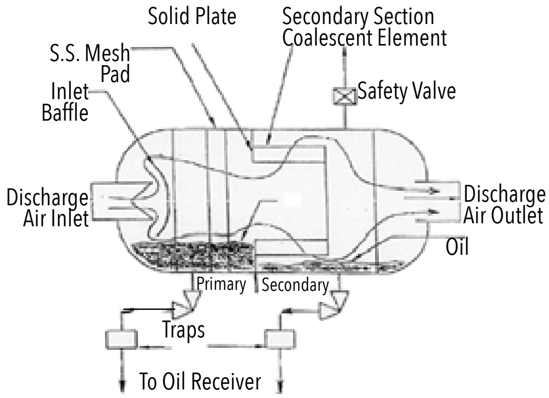

Figure 14-9 Coalescing-Type Oil Separator

Table 14-1 Inlet Air Filter Characteristics

Filter Type	Filtration Efficiency, %	Particle size, μm	Maximum Drop When Clean, wc	Comments (see key)
Dry	100 99 98	10 5 3	3–8	(1)
Viscous impingement (oil wetted)	100 95 85	20 10	¼–2	(2)(3)
Oil bath	98 90	10 3	6–10 = nominal 2 = low drop	(2)(3)(4)
Dry with silencer	100 99 98	10 5 3	5 (5) 7 (6)	

1. Recommended for non-lubricated compressors and for rotary-vane compressors in a high-dust environment
2. Not recommended for dusty areas or for non-lubricated compressors.
3. Performance requires oil to be suitable for both warm and cold weather operation.
4. Recommended for rotary-vane compressors in normal service.
5. Full-flow capacity up to 1,600 scfm.
6. Full-flow capacity from 1,600 to 6,500 scfm.

Coolers

The two main types of coolers are intercooler and aftercooler.

Intercooler

Every multistage compressor is equipped with an intercooler (Figure 14-10). The intercooler condenses any water vapor in the compressed air, but its main purpose is to decrease the air volume before it enters the next compression stage, thus increasing compressor capacity and efficiency.

A water-cooled intercooler is usually of the water-in-tube, air-in-shell construction, which adds some surge volume to reduce air pulsations before the air flows into the second stage. The intercooler should have a moisture separator and an automatic moisture trap to remove condensed water vapor. Two-stage, air-cooled reciprocating compressors do not have an intercooler as such. Instead of a separate intercooler, the compressor's cylinders are finned, and a fan driven off the shaft or a combination fan/flywheel circulates air around the cylinders.

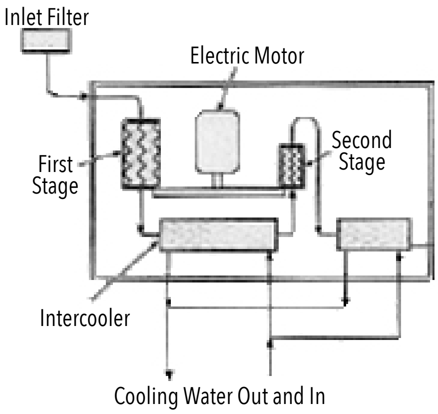

Figure 14-10 Intercooler

Aftercooler

Air in its natural state always contains a certain amount of water vapor. The water vapor in the air entering the compressor is discharged in the form of super-heated vapor. It is usually desirable to prevent water vapor from entering the distribution system. To accomplish this, the discharge air must be cooled to a temperature below saturation at the existing pressure. An aftercooler (Figure 14-11) is used to cool the discharge air to the necessary temperature to condense the vapor and remove the water. About 65 percent of the moisture is removed in the aftercooler.

The aftercooler is installed in the discharge pipeline. The most common aftercooler is the water-cooled, air-in-tube, water-in-shell pipeline type. This construction provides straight-through flow with a pressure drop usually less than 0.5 psi at rated capacity. Shells and tubes shall be packed securely to prevent leakage of either air or water. The aftercooler tube bundle shall be of the removable type. Air-cooled, fan-and-radiator aftercoolers are also available.

A separator and automatic moisture trap are integral parts of an aftercooler. The separator removes the condensed moisture from the air, and the automatic moisture trap drains the condensate periodically to preserve the separator's efficiency. In addition, the aftercooler shall be provided with an automatic solenoid-operated inlet water valve, sight flow funnel, drain cock, pressure gauge, and thermometer.

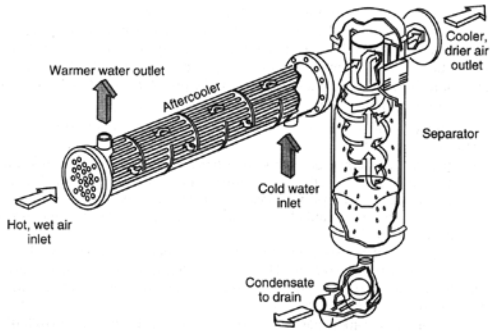

Figure 14-11 Aftercooler

One aftercooler shall be supplied with each compressor and shall be capable of reducing the compressor's air discharge temperature to within 15°F of the cooling water inlet temperature during periods of continuous operation and shall be designed for a working pressure of 200 psi. The aftercooler shall have proper provisions for expansion and contraction.

Design Criteria for Coolers

Intercoolers and aftercoolers are constructed to the industry standard of a 20°F and 15°F approach respectively. This means that the outlet air of an intercooler will be 20°F higher than the cooling water temperature, and the outlet air of an aftercooler will be 15°F higher. The air leaving an aftercooler is saturated with water vapor, so its temperature should be far enough below the ambient temperature to prevent further condensation of the water vapor. Cooling water of the lowest-possible temperature should be used to condense as much moisture as possible.

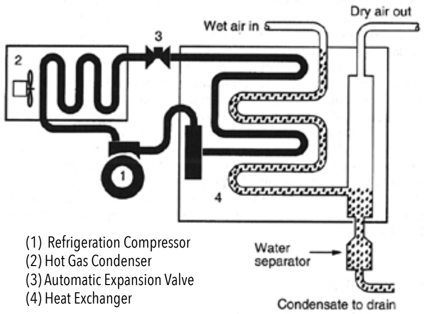

Figure 14-12 Refrigerated Air Dryer
Source: Arrow Pneumatics

Air Dryers

Aftercoolers with a 20°F approach, refrigerated air dryers (using refrigerant instead of water as the cooling medium), and desiccant air dryers are available for systems that require absolutely dry air.

Wet tanks are frequently used before the dryer to provide continuous cfm while drying. They are usually the same size as the dry tank. They also provide a dropout tank for moisture because of the slower velocity.

The refrigerated dryer (Figure 14-12) is used on almost all compressors except small units used in garages and similar areas. It will dry the air to a 35°F dewpoint, and about 90 percent of the remaining moisture is removed. To achieve a lower dewpoint (when air piping is exposed to lower temperatures), a desiccant dryer (Figure 14-13) must be used.

Air dryers are cycling or non-cycling. Both dryer types prefer a continuous flow of air and are rated at 100°F inlet air.

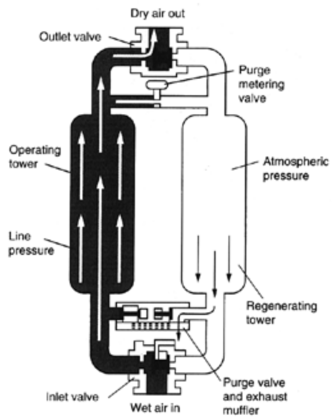

Figure 14-13 Desiccant Dryer
Source: Van Air Systems

Desiccant dryers usually have two tanks. While one is drying, the other is being regenerated to drive off moisture. Single-tank desiccant dryers are available as well, but they are seldom used for compressed air systems. They are regenerated offline by adding or replacing the desiccant.

Frequently a micron filter is used after the desiccant dryer in case some desiccant gets carried over. Desiccant dryers have a porous beaded material that causes moisture to condense as a very thin layer on the material's surface, a process called *absorption*. The desiccant material will age and must be replaced.

Desiccant dryers can go down to -100°F dewpoint, although -30°F is popular. Refrigerated and desiccant dryers are almost never used unless a very low dewpoint is needed (-60° to -100°F).

Air Receiver

The primary purpose of an air receiver (Figure 14-14) is to serve as a storage point for compressed air. It also functions to dampen pulsations. A receiver may not be necessary when a rotary compressor is used. The rotary's modulating control automatically supplies the demand at a constant pressure over its capacity range. However, unless the air demand is relatively constant and constantly above a minimum, some storage capacity must be provided by a receiver to improve operating efficiency and provide a pressure control point. A receiver performs the additional function of collecting condensate.

The storage amount desired can be determined by the following formula:

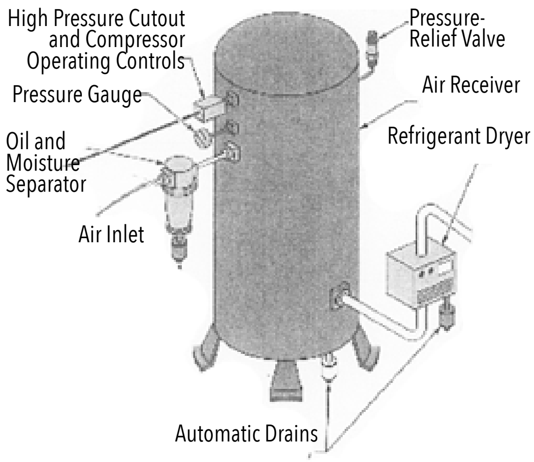

Figure 14-14 Air Receiver

Equation 14-3

$$V = \frac{TCP_a}{P_1 - P_2}$$

where

V = Tank volume, ft^3

T = Time the receiver will supply air from the upper to the lower pressure limit, minutes (determined by the designer)

P_1 = Maximum tank absolute pressure (compressor discharge pressure), psia

P_2= Minimum tank absolute pressure, psia

C = Air needed, acfm (compressor delivery)

P_a = Atmospheric pressure, psia

It is recommended that the receiver's volume be at least equal to the acfm of the compressor. Table 14-2 lists standard air receiver dimensions.

A dry tank is required unless the compressor will run for a very low air usage. This gives the compressor a pressure differential for it to stop and start. To maintain a constant pressure downstream of the dry tank, a pressure-regulating valve is required. It can be self-contained or with a remote pilot.

It is best to limit compressor starts/stops to no more than six to 10 times per hour. Running time is about 70 percent. Centrifugal, screw, and sliding vane compressors should be run 100 percent of the time. The compressor runs to satisfy pressure, and a receiver is a good part of the system control scheme.

Table 14-2 Standard ASME Receiver Dimensions

Diameter, in.	Length, ft	Volume, ft^3
13	4	4.5
14	6	11
24	6	19
30	7	34
36	8	57
42	10	96
48	12	151
54	14	223
60	16	314
66	18	428

Piping connections should be made so air flows through the receiver and does not stagnate in any part. If the receiver is piped so that it "floats" on the discharge line and the air in the receiver is not constantly changed, it becomes stagnant and may accumulate sufficient oil vapor to make the mixture hazardous. The inlet and outlet connections on a standard receiver are located at the top and bottom of the tank and at right angles to each other. If they were located directly opposite each other, the air would tend to flow directly from one connection to the other without circulating and decrease enough in velocity to allow the entrained moisture and oil to drop out.

Certain applications cause high demands for a short period. It is generally not economical to size the total system for this full demand. When this peak or surge is intermittent, it can be handled by a properly sized air receiver. The formula used to size an air receiver to handle intermittent demand is:

Equation 14-4

$$V_R = \frac{V_S P_a}{\Delta P}$$

where

V_R = Receiver volume, ft^3

V_S= Usable stored free air volume required, ft^3

ΔP = Working pressure drop in receiver, psig

P_a = Atmospheric pressure, psia

Oil Pressure Failure Switch

Each independent forced-feed lubrication system should be provided with a switch that will open its contacts when the system pressure is dangerously low. A time delay relay shall be provided to block operation of the pressure failure switch when the compressor is starting.

Water Valve
Each compressor shall be provided with an automatic modulating valve for the intercooler water supply.

Automatic Protective Devices
Compressors shall be provided with the following alarm and shutdown devices:

- High jacket cooling water temperature
- High discharge air temperature
- Excessive vibration
- High lubricant oil temperature
- Low-running gear oil pressure
- Low cylinder lubricant oil level

Alarm devices shall be set to operate well ahead of shutdown devices.

Control Devices
The following control devices shall be provided to serve the compressor:

- Air pressure switches
- Airflow switches, one for each compressor
- Temperature switches, two for each compressor, one for sensing high compressor discharge air temperature and one for sensing high aftercooler discharge air temperature

Electrical Control Cubicle
One electrical control cubicle shall be provided for the air compressor. Cable and conduit interconnections between the control cubicle and the compressor's terminal boxes will be by other trades. All other cable and conduit interconnections between the specified components shall be furnished by the plumbing contractor.

REGULATION OF COMPRESSOR OUTPUT

After the compressor has been selected, it is necessary to select the proper method to regulate the output to match the specific air demands of the system. The ideal regulating system would adjust the compressor to provide the exact volume of air required by the system at any time. To approach this ideal, a method should be employed to vary the compressor's capacity to meet varying system demands while keeping the discharge pressure relatively constant. The output capacity can be regulated by various means: start/stop, speed regulation, and unloading the compressor completely or in steps.

The discharge pressure of a compressor varies with variations in the output capacity. Pressure/capacity curves for positive-displacement and centrifugal compressors (see Figure 14-15) are available from manufacturers. The positive displacement curve slopes slightly backward from the vertical because of the decrease in volumetric efficiency at increased pressures as follows:

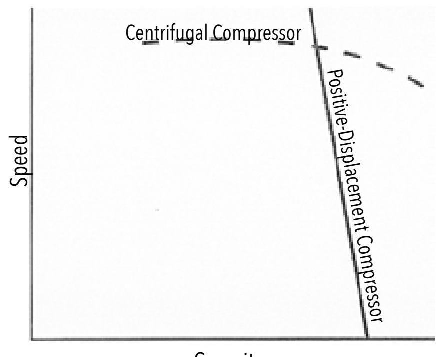

Figure 14-15 Centrifugal vs. Positive-Displacement Compressor Curves

Equation 14-5

$$\text{Volumetric efficiency} = \frac{\text{Actual inlet volume pumped}}{\text{Actual displacement volume of compressor}}$$

This measurement is higher for screw compressors than reciprocating compressors because of a loss of volume due to leakage.

As the compression ratio increases, the volumetric efficiency decreases, as shown by the following equation:

Equation 14-6

$$\text{Compression ratio} = \frac{\text{Absolute discharge pressure}}{\text{Absolute suction pressure}}$$

The centrifugal curve (Figure 14-16) results from the design of the impellers and diffusers.

The simplest control system for smaller compressors is to start and stop the compressor to satisfy the air demand at the air receiver. This is particularly advantageous when demand is intermittent, with long periods of low or no demand. This method is not desirable for high-horsepower compressors because too-frequent starts and stops cause excessive wear and tear on the motor.

To prevent frequent starts and stops, a large air compressor must be used, or the compressor must run constantly and some other means of regulating the output must be employed. The simplest method is to regulate the capacity by varying the speed of the compressor. Induction or synchronous motors are the most common drivers for most applications, and varying the speed is feasible. A common method of regulating capacity when electric motors are used as drivers is to let the motor run continuously while unloading and loading the compressor.

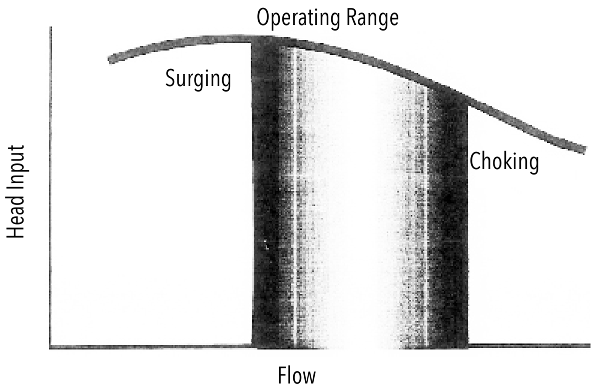

Figure 14-16 Centrifugal Curve

The fundamental operating principles of the compressor unloading/loading method of capacity control are essentially the same regardless of the type of compressor installed. The system air pressure is used to vary the compressor's capacity to match the system demand. When the system pressure approaches the set maximum (cut-out) pressure, the compressor unloads. When demand causes a reduction in the system pressure to the set minimum (cut-in) pressure, the compressor reloads.

Most compressor control systems utilize a pressure-sensing device to operate the other control components. A pressure switch is incorporated into an electronic circuit to control the compressor control program.

Rapid cycling is an undesirable condition for any type of compressor. Too-frequent cycling not only reduces operating economy, but it also results in increased maintenance because of the excessive operation of the control devices (valves, instruments, and switches). To prevent this problem and ensure the most efficient operation of the control system, the volumetric capacity of either the compressed air system or the combined compressed air system and receiver should be of sufficient size to prevent rapid cycling of the compressor.

Reciprocating Compressor Capacity Control

The suction valve unloader is the most widely used device to control reciprocating compressors. It operates by admitting suction air into the cylinder and allowing it to discharge to the atmosphere so each cylinder is operating at zero load condition.

Two-step control is used on air-cooled and single-cylinder, single-stage water-cooled compressors. This simple constant-speed control system either completely unloads the compressor to operate at zero capacity or loads the compressor to operate at 100 percent capacity. This is satisfactory for small compressors, but better control is required for higher-horsepower, two-stage double-acting units to prevent the excessive swings in capacity that occur with the two-step control.

Dual Control

When air requirements are intermittent, the start/stop control can be added to the capacity control system. Start/stop is especially advantageous when long periods of low or no demand occur or when a facility is closed on the weekends.

Dual control adds the necessary start/stop regulation. A manual selector switch places the compressor either on step control or automatic start/stop. A solenoid water valve cuts off water flow on shutdown of the compressor. A time-delay relay prevents the motor from restarting too quickly.

The compressor operates unloaded for a preselected period, and if demand doesn't increase (no drop in system pressure to the set cut-in point) during this period, the compressor will automatically shut down and will restart and return to loaded conditions when required by the system demand.

Variable-Frequency Drives

Reciprocating compressors also may be controlled by a variable-frequency drive (VFD) as can the screw and centrifugal compressors. All manufacturers have minimum desirable speeds that should not be decreased.

Rotary Compressor Capacity Control

Selecting the capacity control system for a rotary compressor requires consideration of the compressor type, number of units, and number and type of accessories.

Oil-flooded rotary compressors rely on an oil-separation system to remove all but traces of oil vapor from the discharge air. The oil-separation system can handle the discharge air volume within the normal operating pressure range. It cannot handle the increased flow volume from a compressor discharging to atmosphere. To compensate for this, oil-flooded rotary compressors have a backpressure device for minimum pressure regulation to guard against excessive oil carryover and damage to the oil-separation system.

Sliding-Vane Compressor Capacity Controls

Two types of control systems are commonly used with sliding-vane compressors. In the modulating-type suction control, a suction valve modulates to throttle the input air so the discharge air exactly meets the system demand. It operates off the system air pressure and provides a practically constant discharge pressure throughout the range of 0 to 100 percent of load. A receiver is not required (but is highly desired), and the system pressure does not have to be built up to a high cut-out pressure.

For systems with greater load variations, the automatic dual control system is often selected. With this control, the suction valve is either fully open or fully closed to control the discharge volume. Compressor operation is at full capacity until the set maximum pressure is reached. At this point, the suction valve closes and unloads the compressor. It remains unloaded until the system pressure falls to the minimum setpoint, at which point the suction valve opens and the compressor reloads to full capacity. When the compressor operates in the unloaded condition for the predetermined period, it automatically stops and then starts up again when the system pressure falls to the minimum setpoint. For effective operation, a suitably sized receiver is required.

The modulating control is generally most efficient when the average load is between 70 and 100 percent of rated capacity. The dual control is generally best when the demand is 70 percent or less of the compressor's rated capacity.

Screw Compressor Capacity Controls

Several methods are used to control the output of oil-flooded screw compressors. The simplest is to close the suction valve (slide vane) and let the compressor run at normal speed against full pressure in the oil reservoir and air receiver. However, a combination system with a VFD is the most economical.

Centrifugal Compressor Controls

Centrifugal compressors are usually controlled by a combination of valves: an inlet valve installed in the air intake ahead of the compressor and a blowoff valve installed after the compressor and ahead of a check valve.

A centrifugal compressor should never run outside its stable capacity range and must, therefore, produce its required minimum flow whenever it is running. Excess capacity is vented to the atmosphere.

Sequential Control or Multiple Compressor Operation

In all cases, the control program can mix and match compressor types and operating times and compressor unloading. Multiple unit installations frequently use sequential (lead /lag) control in which one or more units operate continuously at full capacity to handle the base load, and the additional unit, or units, load and unload to handle the peak loads.

For a two-compressor installation, one unit acts as the lead machine and runs continuously. The second unit then operates on start/stop control. This system is applicable when one unit is sized for the normal demand, and the second is sized to handle the peak demands. When the differences between the minimum and maximum demands are small and of short duration, the second unit also runs continuously, meeting the demand changes by loading and unloading.

When an industrial plant typically has a large peak load of short duration and three compressors are used, the following arrangement is very satisfactory: the lead unit runs fully loaded; the second unit loads and unloads to handle normal demand fluctuations; and the third unit operates on start/stop control to meet peak demands.

SYSTEM DESIGN

The objective of a compressed air system is to supply air to the various points of application at the required volume, pressure, and quality. Piping must be sized so the most remote outlet can deliver the required minimum volume of flow at the required minimum pressure during periods of peak demand. The air must be smooth flowing (non-pulsating) and free of dirt, oil, and moisture.

Compressed air in a plant is used to operate car lifts, spray paint, tools, and other equipment. Many air-operated devices in typical industrial plants operate continuously, while others operate very infrequently but require large volumes of air when used. The manufacturer should be consulted to determine the characteristics and requirements for the tools and equipment to be served.

The total volume of air for all requirements should be the sum of the average air consumption of each device rather than the sum of the individual maximum requirements. It's important to provide ample receiver capacity to compensate during periods of high short-term demand.

It's extremely difficult to determine the actual required capacity for a plant due to the many variables involved. The plant engineer is the most valuable source of information and should be consulted for guidance.

Consult the tool manufacturer for the correct usage and pressure to use in the design of the system.

Compressed Air Leakage

Air leakage is very expensive, but the system design must allow for some leakage. An allowance of 5 to 10 percent is reasonable for a manufacturing plant, with less than half that for a hospital or laboratory. Leakage occurs through piping, fittings, joints, valves, and the equipment or its connections (e.g., air at the equipment is not turned off). For example, the leakage of air through an orifice at 100 psig is as follows:

- 1/64 inch = 0.4 cfm
- 1/16 inch = 6.5 cfm
- ¼ inch = 104 cfm
- ½ inch = 415 cfm
- 1 inch = 1,661 cfm

For about every 5 cfm of leakage, the system is losing 1 horsepower at 100 psig.

Pressure

Most tools require pressure between 100 and 125 psi, but the range for a facility can vary much more than that, which means the designer must create a system that compensates for the wide range of required pressures. For instance, the design could provide both a low-pressure and a high-pressure system or one dry tank and a separate low-pressure system with pressure-regulating valves where needed.

The total system pressure should be as low as possible, as each additional pound per square inch equals approximately 0.5 percent required additional brake horsepower, which means higher energy costs.

The system pressure must accommodate the following:

- Pressure drop of all compressed air production components up to the dry tank (approximately 10 percent of the needed pressure)
- Pressure required by the equipment needing the highest pressure
- Pressure required for the pipe and fittings after the dry tank (approximately 3 percent but not more than 5 percent of the needed pressure)

Piping

Possible pipe materials for the distribution network are:

- Schedule 40 black steel (may rust)
- Schedule 40 galvanized steel (galvanizing may flake off)
- Copper (Type K or L)
- Stainless steel (30A or 316)
- Aluminum

Piping larger than 2 inches is generally black steel pipe with welded fittings. Sizes 2 inches and smaller may be black steel with screwed fittings or copper with silver solder brazed fittings.

Plastic pipe should not be used unless it is guaranteed for compressed air.

Only mechanical-made joints (welded, brazed, screwed, flanged, or crimped) guaranteed for compressed air should be used. No slip joints shall be used anywhere in the system.

Valves

All risers and branches should be valved. Mains should be provided with sectionalized valves at strategic locations, and all stubouts for future extensions should be valved so the system is not hampered when the additional work is performed.

Each branch should have a valve rated for compressed air, and each piece of equipment should have a valve as well. Valves are usually three-piece full-port ball valves.

Valves should be bubble-tight tested for air or other gases. Ball valves and butterfly valves are the most often used. Globe valves have a higher pressure drop through them, but they have good shutoff capability.

Relief valves must be installed on all storage vessels to prevent overpressure. The relief valve should be set to 50 percent more than the normal working pressure. The discharge should be no less than ¾ inch.

Alarms and Gauges

Alarms and gauges should be provided to sense critical information such as high pressure, low pressure, high filter pressure, etc. Pressure gauges should be provided at all tanks, across all filters, across the desiccant dryer, across the compressor, and elsewhere as desired. Gauges should be easily readable, with the pressure reading in the middle range, and provided with a pulsation dampener and needle or ball valve shutoff.

Temperature gauges are useful to indicate the air temperature in and out of the aftercooler, refrigerated dryer, desiccant dryer, etc.

Sometimes temperature and/or pressure test plugs are used in place of a gauge, although gauges are preferred. The plug must be suitable for compressed air at the pressure used and must have a screw-on brass cap.

Flow Meters

Flow meters can be either of two types: electric or mechanical. The mechanical kind is called a variable-area type and uses a small ball as an indicator in a variable-area vertical tube. The type of mechanical meter most often used has an accuracy of 10 percent full scale. This means that if the flow range is from 1 to 10 scfm, the accuracy is ±1 acfm. More accurate variable-area flow meters are available.

Mass flow meters are electronically operated, using the difference in temperature that gas creates when flowing over a heated element. The mass flow meter is very accurate, but expensive.

System Sizing

Use the full demand of the connected devices to size the branches. To size mains, use a demand factor based on the percentage of use of the connected devices. Add 10 percent to the calculated total demand for future additions or equipment replacement. Allow an additional 5 percent for leakage around valve stems and hose couplings.

The total friction head loss in the longest length of run should be limited to a maximum of 3 to 5 psi.

The friction head loss in compressed air piping is determined in a similar manner to water distribution piping. Thus, it is directly proportional to the length of run. The length of run to the most remote outlet is selected to establish the permissible uniform friction head loss. If the losses in this run of piping are within the required limits, then every other run of piping will be well within the required limits. The uniform friction head loss in psi per 100 feet of run is found by dividing the total allowable friction head loss

(5 psi) by the equivalent length of run and multiplying by 100. The equivalent length of run should be taken as 1.3 times the developed (measured) length.

The flow velocity should be maintained below 4,000 feet per minute (fpm). When selecting pipe sizes for runs to individual outlets and minor branch lines, the simultaneous use factors should be ignored, and the piping should be sized for 100 percent usage. The simultaneous use factors are to be used for sizing mains and major branches.

No pipe (except the branch to an individual outlet) should be less than ½ inch, with all other piping not less than ¾ inch.

The designer must decide if the mains should be run as a single grid, multiple grid (Figure 14-17), or loop system (Figure 14-18). Loop systems are used often in industrial plants so users can shut down sections for repairs or additions and back feed from the other side of the loop.

Some designers size the mains as one continuous size, but that depends on the layout and type of the building.

Hoses should be as large as logical and not less than the tool connection size. Hoses should be as short as possible but not shorter than is convenient for the user. If the hose is more than 20 feet, increase the size to the next larger size. It is best to limit the pressure drop to 3 to 5 psi.

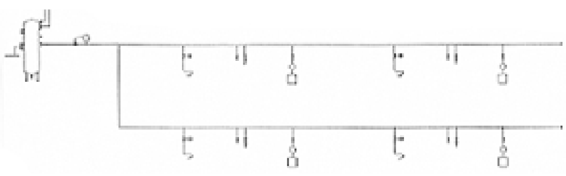

Figure 14-17 Grid System

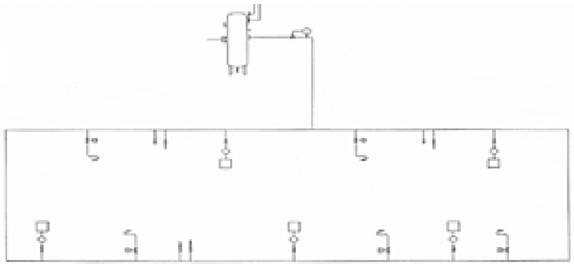

Figure 14-18 Loop System

Air inlet piping should have a low pressure drop. The pipe velocity should be not more than 1,000 fpm. See Table 14-3 for recommended air inlet pipe sizing. The intake air should be as clean, cool, and dry as possible. All piping connections to the compressor should be made with flexible, braided, high-pressure hose.

The presence of moisture in compressed air is always possible, even when dryers are used. Good engineering practice suggests that lines should be pitched, preferably in the direction of air flow, and low points drained. The amount of pitch required will vary with the size of the piping and the amount of moisture anticipated. Pitch varies from 1 inch per 40 feet to 1/8 inch per foot for an average size system.

Where runs are extensive in length, it may be necessary to rise and drip to maintain headroom. The drip points may be drained manually; however, it's preferable to use an automatic drip trap to ensure continuous drainage of the moisture.

Table 14-3 Recommended Air Inlet Pipe Size

Maximum scfm Free Air Capacity	Minimum Pipe Size, in.
50	2½
110	3
210	4
400	5
800	6

Note: 1 cfm = 0.03 m3/min
Source: James Church

Flushing and Testing the Distribution System

After the system is completely installed and before it is placed in service, the piping system must be flushed to remove all loose debris and then tested. An accepted flushing method is to allow a volume of two to five times the expected flow through each respective part of the system. This is done by connecting air under pressure to the piping system and then opening and closing all outlets and valves, starting from the closest and working to the most remote.

Testing is done by pressurizing the system to the test pressure with air. The system test pressure for low-pressure systems is 150 percent more than the working pressure. For systems with a working pressure up to 200 psig, the entire piping system is tested to 300 psig for one hour, with no leakage permitted. If a working pressure higher than 200 psig is required, the system is tested at 150 percent of the system pressure. This pressure testing should be done in increments of 100 psig, starting with 100 psig. This is done to prevent damage due to a catastrophic failure. Leaks are repaired after each increment. After final testing, it is recommended that the piping be left pressurized at the system working pressure.

WASTE HEAT RECOVERY

It pays to consider waste heat recovery for compressed air systems. Available heat that can be recovered is about 94 percent of the energy input from a water-cooled, oil-injected screw or a water-cooled dry screw and about 76 percent from an air-cooled, oil-injected screw. Water temperatures are possible to 160°F for oil-injected and to 190°F for oil-less screws. However, due to efficiencies of equipment used for the heat recovery, the designer can expect to get about 80 to 90 percent of that available.

In some cases, the availability of the saved energy and the use do not occur at the same time, and storage will be necessary. Some of the general uses for the energy saved are:

- Space heating
- Industrial process heating
- Water heating for cleanup
- Makeup air heating

- Drying processes

Plate-and-frame heat exchangers are high efficiency and are frequently used for nonpotable water systems. Shell-and-tube heat exchangers with double-wall tubes are used when potable water is being heated.

Waste heat recovery possibilities can be grouped into three categories:

- Compressors up to approximately 50 hp
- Air-cooled screw compressors (with a fan or fans)
- Water-cooled screw or reciprocating compressors

Small compressors are usually air-cooled, with the heat being given off to the ambient air surrounding the compressor by fins and/or fans.

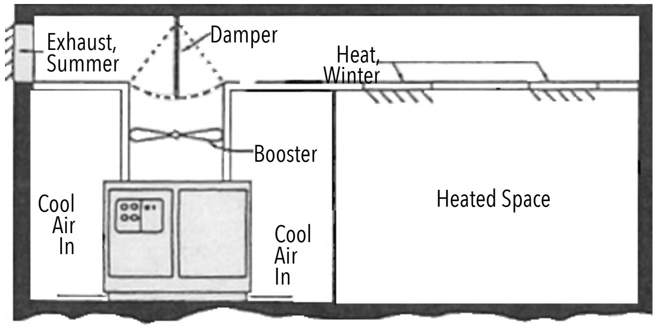

Figure 14-19 Using Air-Cooled Screw Compressor Heat

Reciprocating air compressors have heads and/or intercoolers that are water cooled. Oil-injected and oil-less screws are usually water cooled, but air-cooled, oil-injected screws can be purchased. The energy picked up by the cooling water is substantial, and rather than dumping it, a use should be found.

Air-cooled screws can use the heat from the exhaust air to heat space (see Figure 14-19), or an air-to-water heat exchanger can be used to heat water or other fluids. If the air is used directly, the fan must be able to overcome the static pressure of the ductwork, and the air stream should never be shut off to both air paths.

An approximation of the heat energy available is as follows:

Equation 14-7

$$\text{Btuh} = \frac{\text{Motor hp x Load factor x 2,545 Btuh-hp}}{\text{Motor efficiency}} - 10\% \text{ (water cooled) or } 30\% \text{ (air cooled)}$$

See Tables 14-4 and 14-5 for potential water heating and space heating quantities.

Table 14-4 Hot Water Generation Potential

Motor hp	Available Heat, Btuh	Water Quantity, gph
5	11,240	13
10	21,294	25
15	30,198	36
20	40,263	48
25	50,329	60
30	62,454	75
40	81,876	98
50	102,920	123
75	150,163	180
100	200,217	240
200	394,682	474
300	585,643	703

Source: Gardner-Denver Industrial Machinery

Table 14-5 Heating Potential from Air-Cooled Screw-Type Rotary Compressor

Motor hp	Available Heat, Btuh
30	83,952
40	111,936
50	139,920
75	209,880
100	279,840
150	419,760
200	559,680
250	699,600
300	839, 520
350	979,440
400	1,119,360
500	1,399,200

Source: Kaeser Compressors Inc.

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CE Questions — "Compressed Air Systems" (CEU 246)

1. Standard capacity (scfm) varies with changes in ________.
   a. temperature and humidity
   b. specific heat and altitude
   c. altitude and temperature
   d. altitude and humidity

2. The primary purpose of the ________ is to serve as a storage point for compressed air.
   a. air receiver
   b. aftercooler
   c. airflow switch
   d. intercooler

3. Which compressor type offers the highest efficiency at full load or partial load?
   a. rotary screw compressor
   b. reciprocating compressor
   c. sliding vane compressor
   d. scroll compressor

4. During ________, the initial temperature of the air is allowed to rise steadily throughout the compression process.
   a. adiabatic compression
   b. multistage compression
   c. isothermal compression
   d. heat of compression

5. Which of the following compressors should be run 100 percent of the time?
   a. centrifugal
   b. screw
   c. sliding vane
   d. all of the above

6. What is the recommended air inlet pipe size for a 150-scfm system?
   a. 2½ inches
   b. 3 inches
   c. 4 inches
   d. 5 inches

7. As the compression ratio increases, the ________ decreases.
   a. absolute discharge pressure
   b. volumetric efficiency
   c. absolute suction pressure
   d. actual displacement volume

8. What is the air leakage through a ¼-inch orifice at 100 psig?
   a. 0.4 cfm
   b. 6.5 cfm
   c. 104 cfm
   d. 415 cfm

9. Which of the following is typical for light-duty service?
   a. single-stage, water-cooled reciprocating compressor
   b. single-stage, air-cooled reciprocating compressor
   c. two-stage, air-cooled reciprocating compressor
   d. screw compressor

10. In a multistage compressor, the main purpose of the ________ is to decrease the air volume before it enters the next compression stage, thus increasing compressor capacity and efficiency.
    a. air receiver
    b. aftercooler
    c. airflow switch
    d. intercooler

11. Which of the following joints shall not be used in the compressed air system?
    a. screwed
    b. welded
    c. slip
    d. flanged

12. The system pressure must accommodate what?
    a. pressure drop of all compressed air production components up to the dry tank
    b. pressure required by the equipment needing the highest pressure
    c. pressure required for the pipe and fittings after the dry tank
    d. all of the above