AIR COMPRESSORS

To keep you oriented as we discuss pressure, the basic concepts are treated in this sequence: generation, transmission, storage, and utilization of compressed air in a pneumatic system. This section covers air compressors, the devices that generate air pressure.

Pressure Generation: Compression

The pressure exerted by a confined gas results from rapid and repeated bombardment of the container walls by the enormous number of gas molecules present. The pressure can be increased by increasing the number or force of the collisions. Increasing the temperature does this by speeding up the molecules (Charles' Law). Another way is to increase the average number of molecules in a given volume. This is compression. It can be done by either decreasing the volume (Boyle's Law) or increasing the amount of gas.

Liquids and solids can be compressed only with difficulty. But gases are easily compressed because their molecules are relatively far apart and move freely and randomly within a confined space.

Compression decreases the volume available to each molecule. This means that each particle has a shorter distance to travel before colliding with another particle or the wall. Thus, proportionately more collisions occur in a given span of time, resulting in a higher pressure.

Compression Work Requirements

An air compressor does most of its work during the compression stroke. This adds energy to the air by increasing its pressure. Compression also generates heat, however, and the amount of work required to compress a quantity of air to a given pressure depends on how fast this heat is removed. The compression work done will lie between the theoretical work requirements of two processes:

- Adiabatic–a process having no cooling; the heat remains in the air, causing a pressure rise that increases compression work requirements to a maximum value.
- Isothermal–a process that provides perfect cooling; thus, there is no change in air temperature and the work required for compression is held to a minimum.

The difference in the amount of work required to compress air to 100 psi by these two processes is about 36 percent. Most industrial air compressors are near adiabatic, since the process is too fast to allow much heat to escape through the compressor casing.

Air Compressors: Basic Operation

An air compressor operates by converting mechanical energy into pneumatic energy via compression. The input energy could come from a drive motor, gasoline engine, or power takeoff.

The ordinary hand bellows used by early smelters and blacksmiths was a simple type of air compressor. It admitted air through large holes as it expanded. As the bellows were compressed, it expelled air through a small nozzle, thus increasing the pressure inside the bellows and the velocity of the expelled air.

Modern compressors use pistons, vanes, and other pumping mechanisms to draw air from the atmosphere, compress it, and discharge it into a receiver or pressure system. Table 2 summarizes the capabilities of various compressor types.

The most basic types of air compressors are designated as .positive displacement" and "nonpositive displacement" (sometimes called "dynamic"). The characteristic action of a positive displacement compressor is thus a distinct volumetric change-a literal displacement action by which successive volumes of air are confined within a closed chamber of fixed volume and the pressure is gradually increased by reducing the volume of the space.

The forces are static-that is, the pumping rate is essentially constant, given a fixed operating speed. The principle is the same as the action of a piston/cylinder assembly in a simple hand pump.

Positive Displacement Compressors

Positive displacement compressors generally provide the most economic solution for systems requiring relatively high pressures. Their chief disadvantage is that the displacing mechanism provides lower mass flow rates than nonpositive displacement compressors (see pages 29-33).

Pressure Characteristics - A compressor with a positive displacement pumping mechanism has these important pressure characteristics:

- The pressure against which the compressor works rises to higher and higher values as pumping continues. It must be limited by some external pressure control device.
- The rate of free air delivery is highest at 0 psig and very gradually drops to lower values as pressure increases.
- The amount of heat generated progressively rises as pressure increases, causing substantial increases in temperature of both the air handled and the compressor structure.

Types of Positive Displacement Compressors

Positive displacement compressors are divided into those which compress air with a reciprocating motion and those which compress air with a rotary motion. The principal types of positive displacement compressors are the piston, diaphragm, rocking piston, rotary vane, lobed rotor, and rotary screw.

Reciprocating Piston -This design (Fig. 11) is widely used in commercial air compressors because of its high pressure capabilities, flexibility, and ability to rapidly dissipate heat of compression. And it is oil-less.

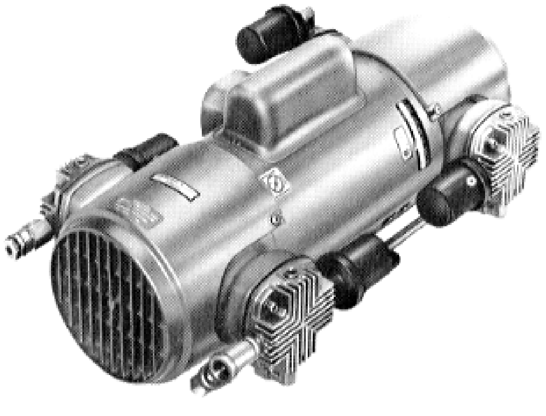
Compression is accomplished by the reciprocating movement of a piston within a cylinder (Fig. 12). This motion alternately fills the cylinder and then compresses the air. A connecting rod transforms the rotary motion of the crankshaft into reciprocating piston motion in the cylinder. Depending on the application, the rotating crank (or eccentric) is driven at constant speed by a suitable prime mover. Separate inlet and discharge valves react to variations in pressure produced by the piston movement.

As Fig. 12 shows, the suction stroke begins with the piston at the valve side of the cylinder, in a position providing minimum (or clearance) volume. As the piston moves to a maximum volume position, outside air flows into the cylinder through the inlet valve. The discharge valve remains closed during this stroke.

During the compression stroke, the piston moves in the opposite direction, decreasing the volume of air as the piston returns to the minimum position.

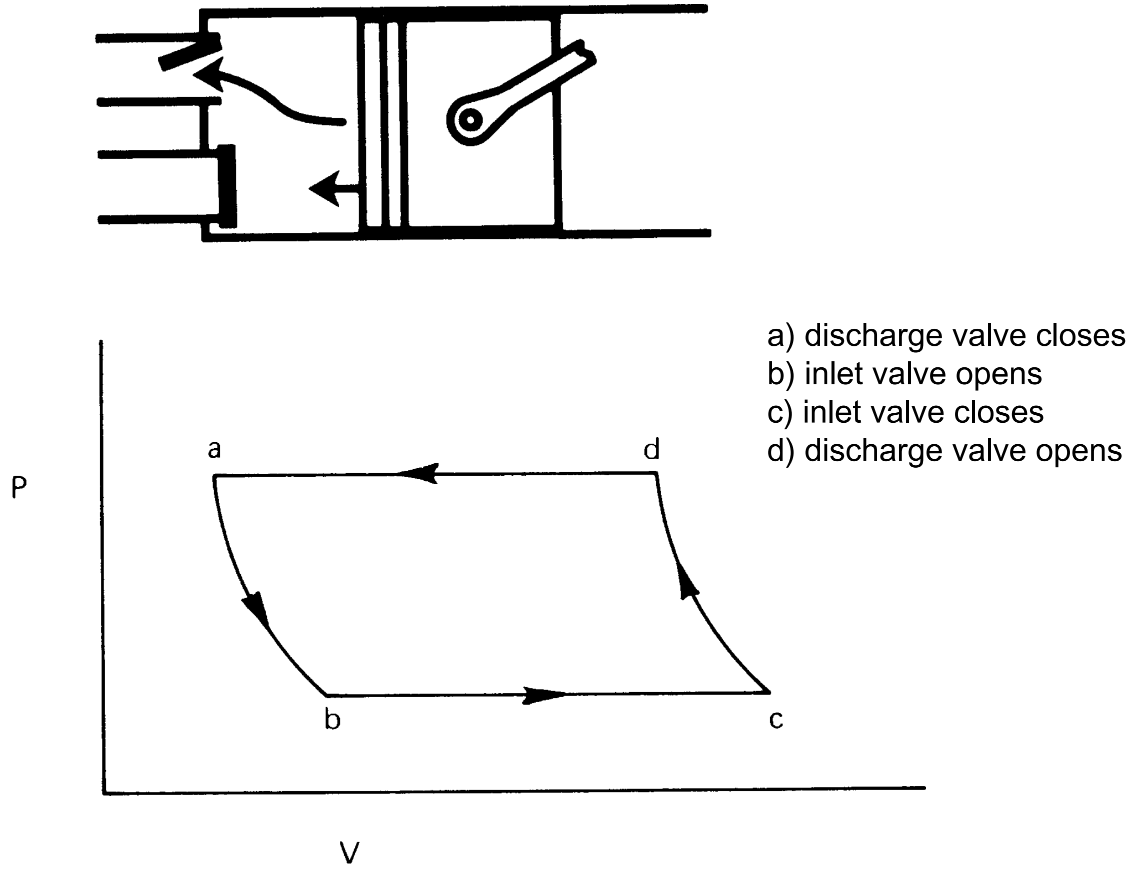
During this action, the spring-loaded inlet and discharge valves are automatically activated by pressure differentials. That is, during the suction stroke, the piston motion reduces the pressure in the cylinder below atmospheric pressure. The inlet valve then opens against the pressures of its spring and allows air to flow into the cylinder.

Figure 11



Typical reciprocating piston air compressor

Figure 12



Reciprocating motion of the piston compresses air with each revolution of the crankshaft.

When the piston begins its return (compression) stroke, the inlet valve spring closes the inlet valve because there is no pressure differential to hold the valve open. As pressure increases in the cylinder, the valve is held firmly in its seat.

The discharge valve functions similarly. When pressure in the cylinder becomes greater than the combined pressures of the valve spring and the delivery pipe, the valve opens and the compressed air flows into the system.

In short, the inlet valve is opened by reduced pressure, and the discharge valve is opened by increased pressure.

Some piston compressors are double-acting. As the piston travels in a given direction, air is compressed on one side while suction is produced on the other side. On the return stroke the same thing happens with the sides reversed. In a single-acting compressor, by contrast, only one side of the piston is active.

Single-acting compressors are generally considered light-duty machines, regardless of whether they operate continuously or intermittently. Larger double-acting compressors (usually watercooled) are considered heavy-duty machines capable of continuous operation.

Sizes of reciprocating piston compressors range from less than 1 hp to 6000 hp. Good part-load efficiency makes them very useful where wide variations in capacity are needed.

Their disadvantages? Reciprocating piston compressors inherently generate inertial forces that shake the machine. Thus, a rigid frame, fixed to a solid foundation, is often required. Also, these machines deliver a pulsating flow of air that may be objectionable under some conditions. Properly sized pulsation damping chambers or receiver tanks, however, will eliminate such problems.

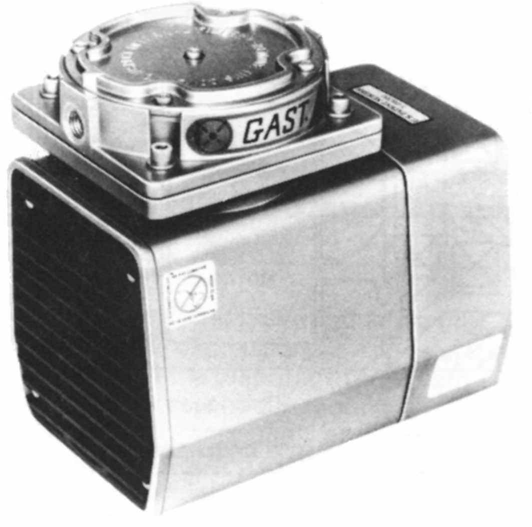
In general, the reciprocating piston compressor is best suited to compression of relatively small volumes of air to high pressures.

Diaphragm - The diaphragm design (Fig. 13) is a modification of the reciprocating piston principle. An outstanding characteristic of the diaphragm design is that the basic compressing mechanism does not require a sliding seal between moving parts. A diaphragm compressor is also oil-less and it is therefore often selected when no oil contamination of the line or atmosphere can be tolerated.

Compression is performed by the flexing of a diaphragm back and forth in a closed chamber. Fig. 14 indicates how this flexing action is generated by the motion of a connecting rod under the diaphragm. Only a short stroke is required to produce pressure effects similar to those produced by a reciprocating piston in a cylinder.

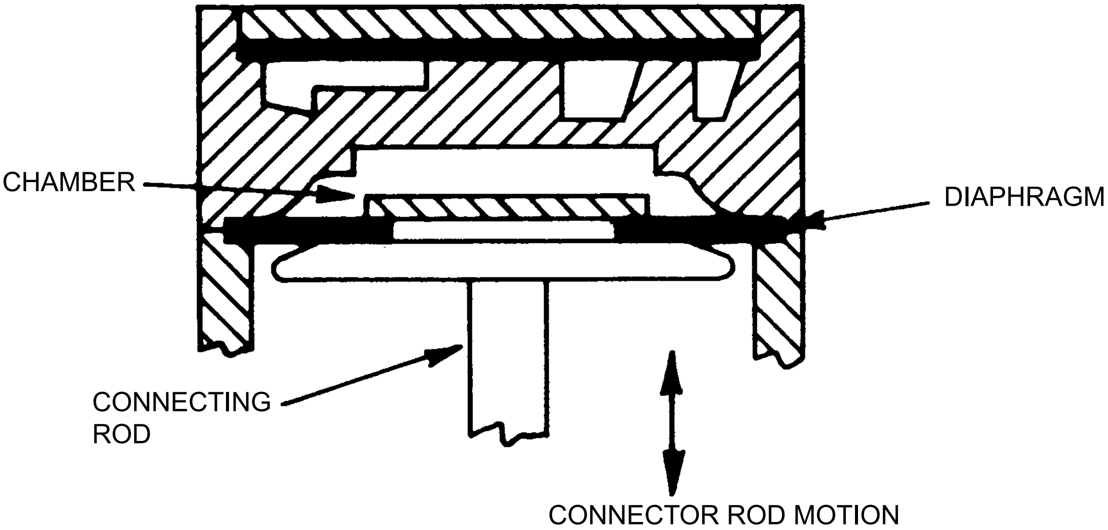
Intake and discharge valves convert the volume changes produced by the reciprocating movement into pumping action. The reed-type valves work like those in the piston design.

Figure 13



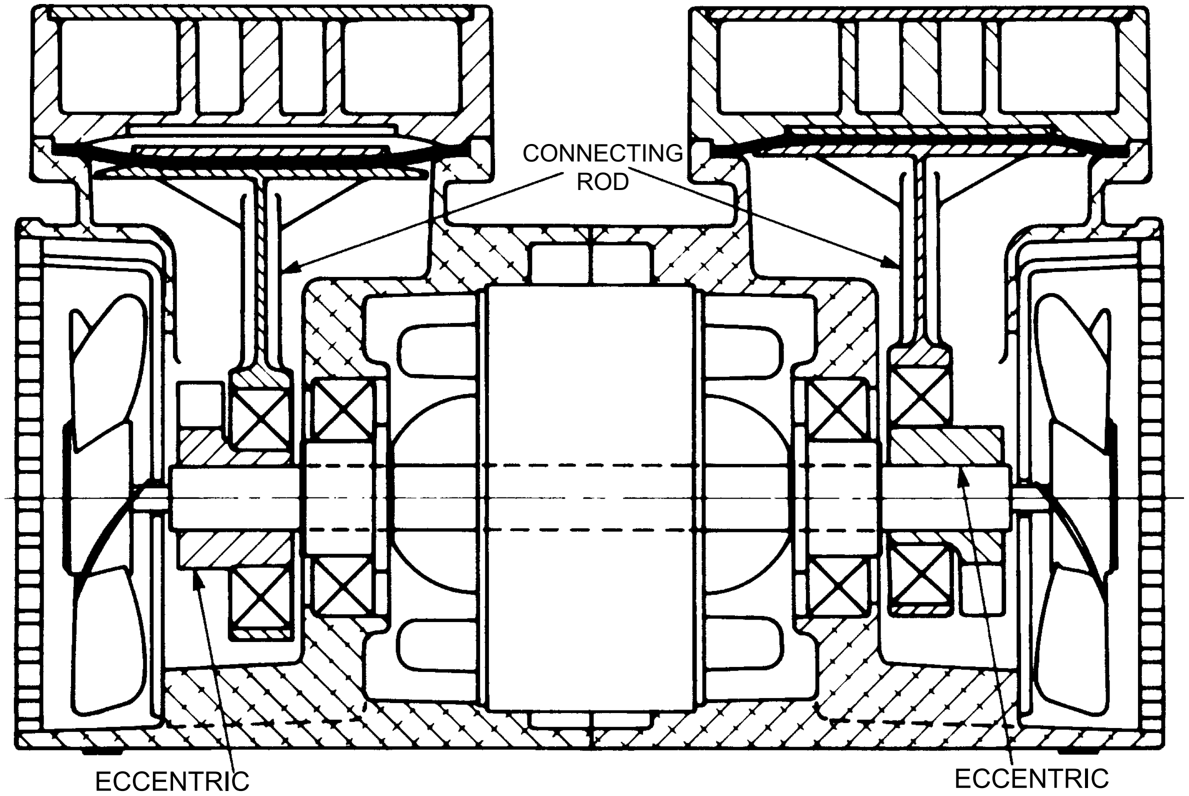
Typical diaphragm compressor. The heavy-duty diaphragm is made of heat-resistant elastomer with fabric reinforcement.

Figure 14



Cross-section shows diaphragm flexing in response to up/down motion of connecting rod.

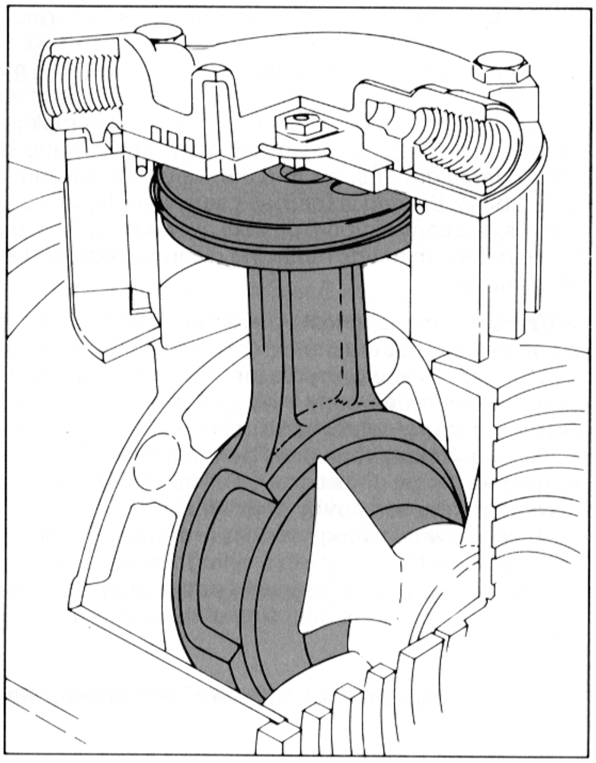
Figure 15



Dual-chamber diaphragm compressor.

Fig. 15 shows a dual-chamber machine. The contour of the diaphragm in the separate chambers indicates different stroke positions at the same instant.

The pressure capabilities of the diaphragm compressor are less than those of the piston type, but usually exceed those of the rotary vane type.



The rocking piston principle can be viewed as a combination of the reciprocating piston and diaphragm Ideas.

Rocking Piston - The rocking piston principle (Fig. 16) is another variation of reciprocal compression. In fact, it can be viewed as a combination of the diaphragm and piston principles.

The rocking piston pump essentially mounts a piston rigidly (no wrist pin) on top of the diaphragm unit's eccentric connecting rod. This piston is surmounted by a cup made of Teflon , for instance. The cup functions both as a seal-equivalent to the rings of a piston compressor-and as a guide member for the rod. It expands as the piston travels upward, thus maintaining contact with the cylinder walls and compensating for the rocking motion.

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The rocking piston compressor not only combines the mechanical features of the reciprocating piston and diaphragm types, but it also combines many of their best performance features. Like the diaphragm type, it is quiet, compact, and oil-less. Like the reciprocating piston unit, it can provide pressures to 100 psi.

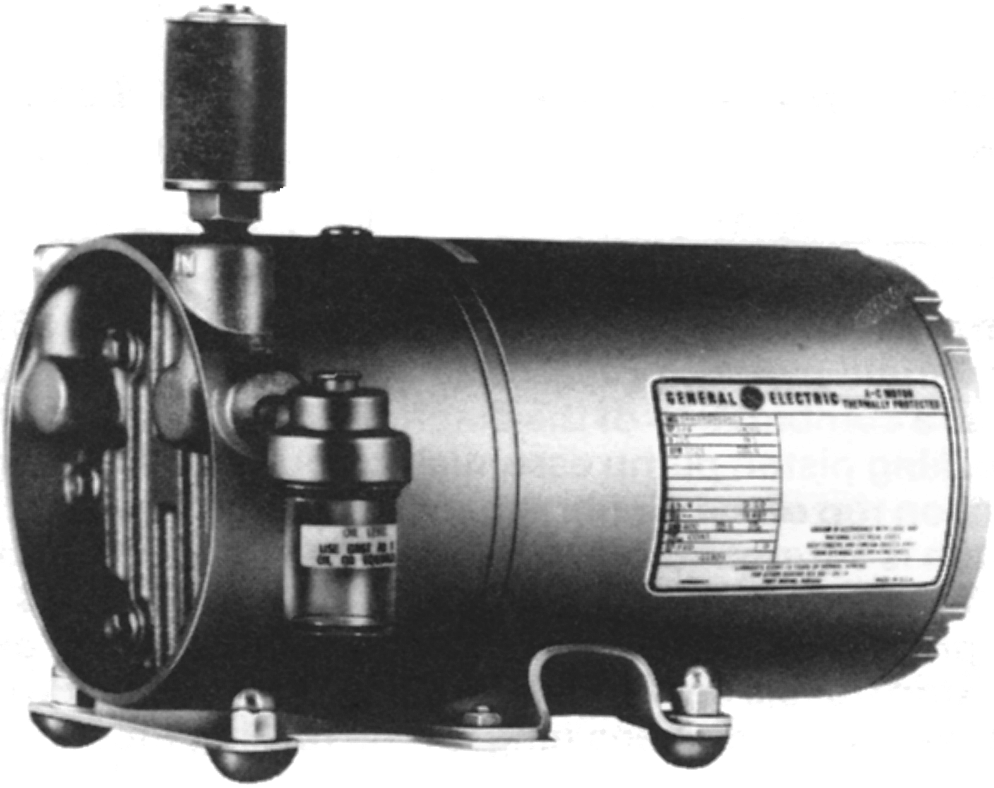
The absence of a wrist pin is the key to the light weight and compact size of the rocking piston compressor. This makes the entire piston-connecting rod assembly much shorter and sharply reduces the overall dimensions and the weight of the unit.

As for durability, the cup is (perhaps surprisingly) more durable than the rings of a conventional oil-less piston unit. And, on Gast models, when the cup needs replacing it can be removed and replaced in minutes.

Rotary Vane - Some applications require that there be little or no pulsation in the air output, and perhaps a minimum of vibration also. The rotary vane compressor (Fig. 17) provides this. It is commonly used for moderately high air flows at pressures under 30 psig, although some rotary vane designs can provide pressures of 200 psig. Rotary vane units generally have lower pressure ratings than piston units because of more difficult sealing problems and greater sensitivity to thermal effects.

Fig. 18 shows how pumping action is produced by a series of sliding, flat vanes as they rotate in a cylindrical case. As the rotor turns, the individual vanes slide in and out, trapping a quantity of air and moving it from the inlet side of the compressor to the outlet side.

Figure 17



Typical rotary vane air compressor.

There are no valves in the rotary vane design. The entire flow of air into and out of the individual compartments is controlled by the movement of the vanes across separate inlet and discharge ports.

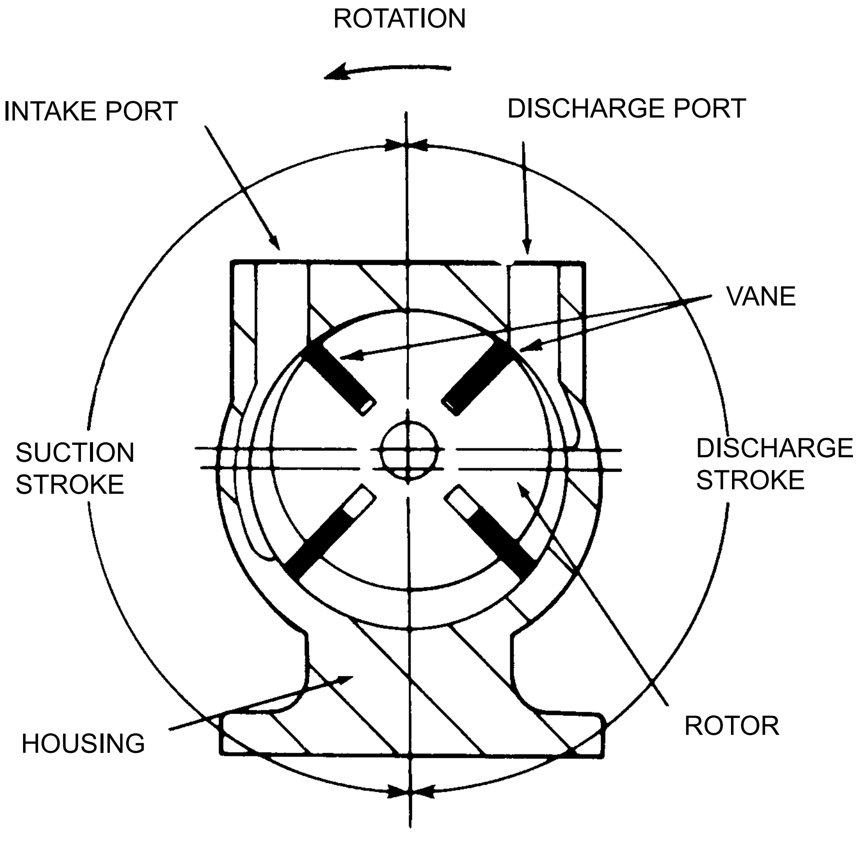
The rotor is mounted eccentrically -that is, not in the center of the casing. As the rotor rotates, the vanes are flung outwards and held against the body bore by centrifugal and pressure-loading forces. This creates a series of air compartments of unequal volume (because of the rotor's eccentricity). The compartments formed between adjacent vanes gradually become larger during the suction part of the cycle, and air is drawn into the compartment from the inlet port.

During the discharge portion of the cycle, the compartment volumes gradually become smaller, compressing the air. When a rotating compartment reaches the discharge port, the compressed air escapes to the delivery system.

The suction and exhaust flows are relatively free of pulsation because the inlet and discharge ports do not have valves, and the air is moved continuously rather than intermittently.

Rotary vane compressors have certain significant advantages. In addition to providing smooth, pulse-free air flow without receiver tanks, they are compact (or, equivalently, offer high flow

Figure 18



In a rotary-vane compressor, the eccentrically mounted rotor creates smaller compression compartments as the vanes are pushed in by chamber walls.

capacities for a given size), are simple and economical to install and operate, have low starting and running torque requirements, and produce little noise or vibration.

Rotary Screw and Lobed Rotor - Two other types of positive displacement compressors are the rotary screw and lobed rotor. Neither is as widely used, especially in smaller sizes, as are rotary vane and piston compressors.

Rotary screw compressors are used when nearly pulseless high-volume air is required. The compression mechanism is composed of two meshing rotors that have helical contours. When the rotors are driven at the same speed, air is trapped between the lobes as the screws turn. The volume between the advancing rotor helix and the endplate diminishes, forming continuous cavities until the end of the helix passes over the discharge port.

In a lobed rotor compressor, a pair of mating lobes on separate shafts rotate in opposite directions to trap incoming air and compress it against the casing. Lobed rotor units provide very high air flows at pressures between those of nonpositive displacement compressors and other types of positive displacement units.

Multistage Compression

Compression may be accomplished in one or more stages. That is, air can be compressed once or several times before it reaches the compressor outlet and is delivered to the system devices. Each stage provides a proportional increase in the output pressure.

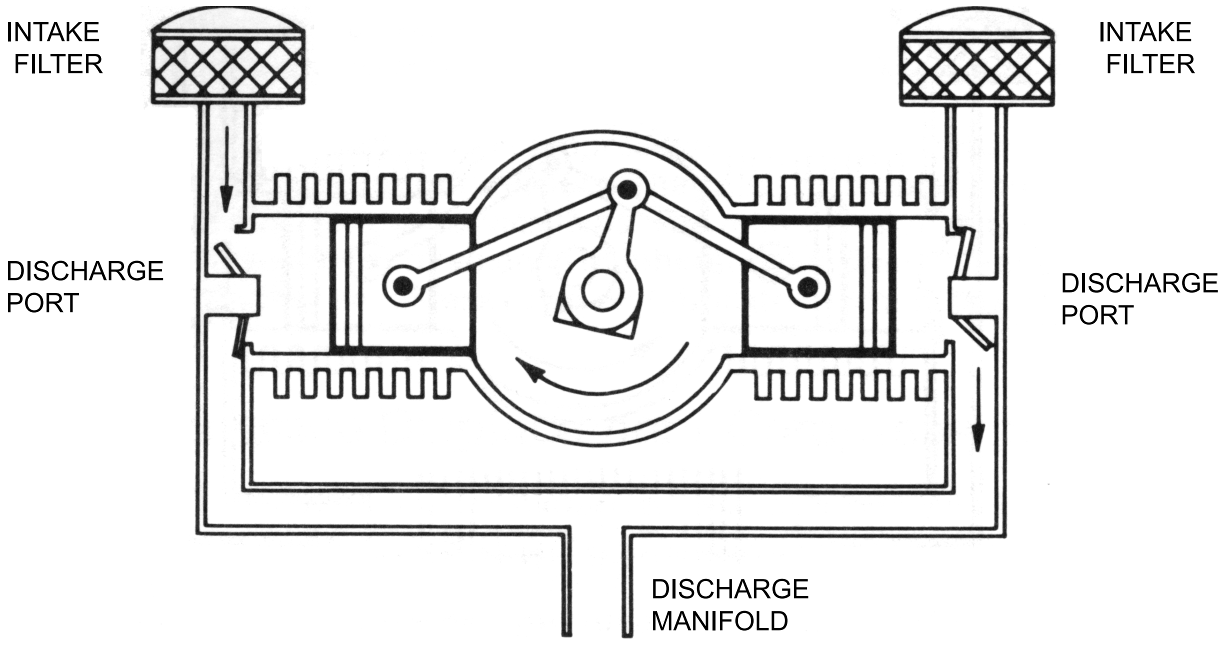
Positive displacement compressors have the advantage of providing relatively large pressure changes in a single stage, and very large pressure changes in a few stages. However, the pressure output of nonpositive displacement compressors can also be raised by staging.

Single Stage - Fig. 19 is another way of illustrating how the compression process is carried out in a single pass through a pumping chamber. This piston-type compressor has two cylinders, but the compression action occurs in a single stage. The cylinders are connected in parallel between the atmosphere and the discharge manifold.

The normal maximum pressure rating for single-stage compressors is about 100 psig. Operation above this level increases the heat of compression (caused by leakage and recompression) to levels that could harm the compressor and the overall system.

Multiple Stage-In multiple-stage compression, the gas moves from one chamber to another. This sequential action provides the final pressure.

For general utility and process purposes, two-stage compression is usually justified when the compression ratio (R,) exceeds six. When Rc exceeds 20, compression is



SINGLE STAGE TWO CYLINDER COMPRESSOR

Basic operation of a single stage/two cylinder air compressor.

usually accomplished in three stages. To put this in pressure units, the upper limit for utility two-stage compressors is between 280 and 300 psig. A gauge pressure of 500 psi has an R_C value of 35.

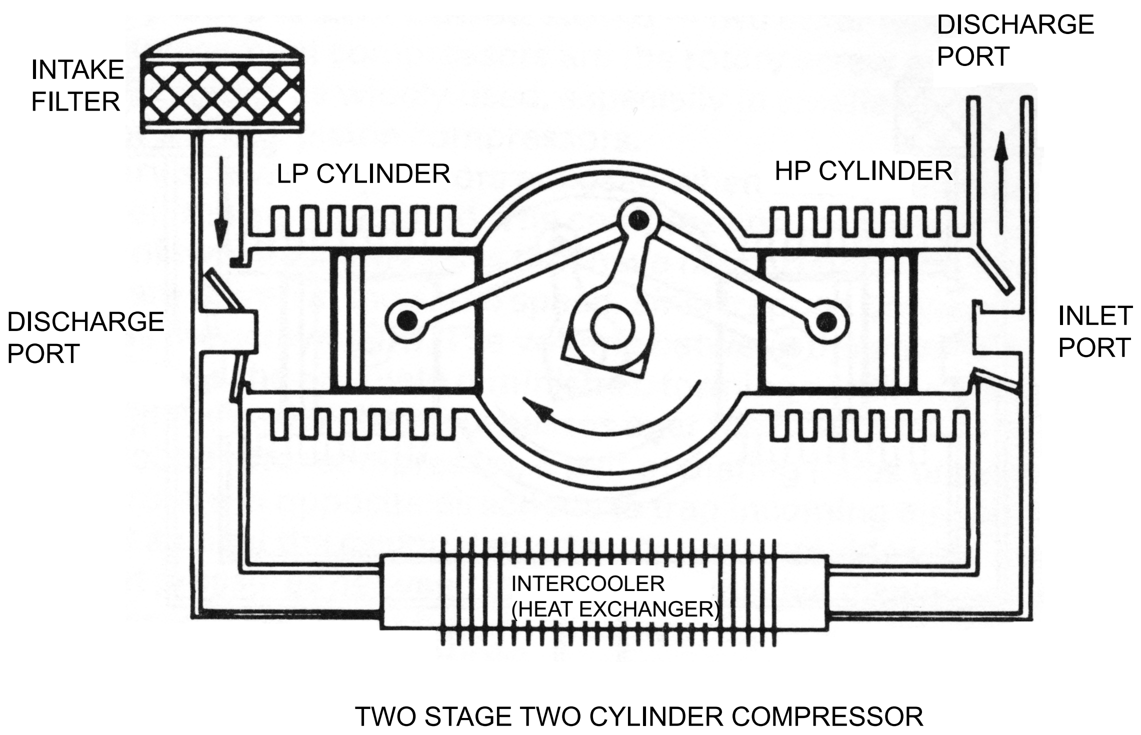
Some multistage compressors eliminate the problem of increased heat of compression above 100 psig. This is done by:

- Compressing the air to an intermediate pressure in the large-diameter low-pressure cylinder.
- Removing a portion of the heat of compression before the air is fed to the next stage (this is known as "intercooling" and is normally done by an air-cooled or water-cooled heat exchanger).
- Further compressing the air to final pressure in a smaller high-pressure cylinder.

As Fig. 20 shows, these two cylinders are connected in series through the intercooler (compare with Fig. 19). Intercooling greatly decreases both the total temperature rise of the compressed air and the amount of work required for its compression. But the added cost of an intercooler cannot always be justified on a small compressor.

Some two-stage compressors have three cylinders: two low-pressure cylinders connected to one high-pressure cylinder through an intercooler.

Figure 20



Basic operation of two stage/two cylinder air compressor

Lubrication and Exhaust Air Quality

Contamination in the air can affect many applications. A laboratory process, for example, powered by compressed air may be extremely sensitive to moisture, oil, or dust particles. Or in such places as food processing plants, even the air exhausted from the pneumatic system may have to be entirely free of oil vapor and contaminants.

A variety of filters, generally expensive, have been developed to solve such problems. An alternative is to use an oil-less air compressor.

Oil-Less Compressors - Compressors designed with "dry" self-lubricating materials, such as graphite or Teflon, produce oil-free air both in the line and at the exhaust. They effectively eliminate the presence of air/oil vapors in applications where even a very fine oil mist can cause contamination, stains, deterioration, or a safety hazard.

Oil-less pneumatic systems are particularly useful in the food, textile, paper, pharmaceutical, and chemical industries. And since no maintenance lubrication is required, these units can be mounted in the best, rather than the easiest to reach, location.

Oil-Lubricated Compressors - if, for some reason, an oilless air compressor is not practical in an application where contarnination is prohibited, then an oil-lubricated unit must be used and equipped with appropriate filters to remove the oil after the air is compressed.

In an oil-lubricated compressor, a thin film of oil is maintained between the walls of the pumping chamber and the pistons, vanes or other moving parts. Siphon or wick-type lubricators are used in light-duty operations. Pressure type lubricators are used in heavy-duty or continuous-duty applications.

In general, oil-lubricated compressors have higher pressure ratings than oil-free compressors. They also run cooler and may therefore have longer service lives. The relative value of these factors versus the convenience of inherently oil-free operation dictate whether an oil-less or an oil-lubricated compressor should be used.

Nonpositive Displacement Compressors

Also called "dynamic," "continuous-flow," and "velocity-type" compressors, this category comprises machines that use changes in kinetic energy to create pressure gradients.

Kinetic energy is the energy that a body possesses by virtue of its motion. A fluid's kinetic energy can be increased either by rotating it at high speed or by providing an impulse in the direction of flow.

Unlike the positive displacement compressor, in which distinct volumes of air are isolated and compressed, a nonpositive displacement compressor does not provide a constant-volume flow rate over a range of discharge pressures. This is because the compartments are not isolated from each other and leakage between them increases as pressure rises.

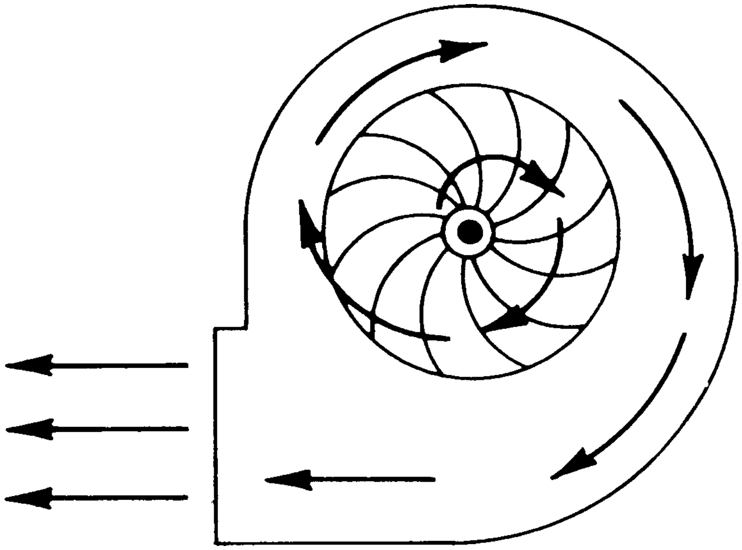
Initial acceleration of the air produces a negative (suction) pressure at the inlet port, drawing air in. Partial deceleration of air at the discharge port converts some of the kinetic energy to pressure. Speed of the rotating impeller determines the pressure change. Higher pressure differences require either faster impeller speeds or additional stages.

The most important advantage of nonpositive displacement machines is their ability to provide very high mass flow rates. On the other hand, multiple stages are required to provide pressures above 4 or 5 psi and such machines are cost effective only for flow rates above 80-100 cfm.

Nonpositive displacement devices are sometimes called fans or blowers rather than compressors. By some definitions, a fan provides less than 0.5 psi pressure and a blower between 0.5 and 10 psi. The distinction is frequently blurred in common use, however.

The three common types of nonpositive displacement compressors are centrifugal, axial, and peripheral (or regenerative). These names derive from the direction of air flow through their compression chambers.

Figure 21



In a centrifugal blower, a rotating impeller sweeps air radially along the casing to the outlet.

Centrifugal- Centrifugal compressors a re best suited to the continuous movement of large air volumes through small pressure ranges. Fig. 21 shows the basic operation. Air leaving a rotating impeller passes radially outward to the casing. Centrifugal action builds up velocity and pressure levels.

In its simplest form, a centrifugal compressor consists of a high-speed rotating impeller that receives air through an inlet nozzle at the center. The impeller vanes are fixed (unlike those in the rotary vane design). They throw the air centrifugally outward toward the casing, increasing its velocity and energy. Here, an outlet discharges the air into a stationary passageway known as a "diffuser." The diffuser reduces the air velocity, thus raising the pressure. Beyond the diffuser, the velocity may be further reduced and pressure increased by a "collector."

Staging can yield higher pressures. Staging is accomplished by directing the output from the diffuser of one stage into the nozzle of the next.

Because the flow from the impeller is continuous, a smooth, surge-free output is obtained. Furthermore, discharge pressure depends only on impeller speed. It is nearly constant, despite variations in flow, over the stable operating range.

But this can be a drawback if the demand falls far enough below the rated flow, allowing system pressure to build up. The compressor continues to deliver air at about the same pressure until the back-pressure exceeds that developed by the compressor. The result is "surge"-a reversal of flow. This reversal immediately allows the back-pressure to go down, and regular compression is resumed.

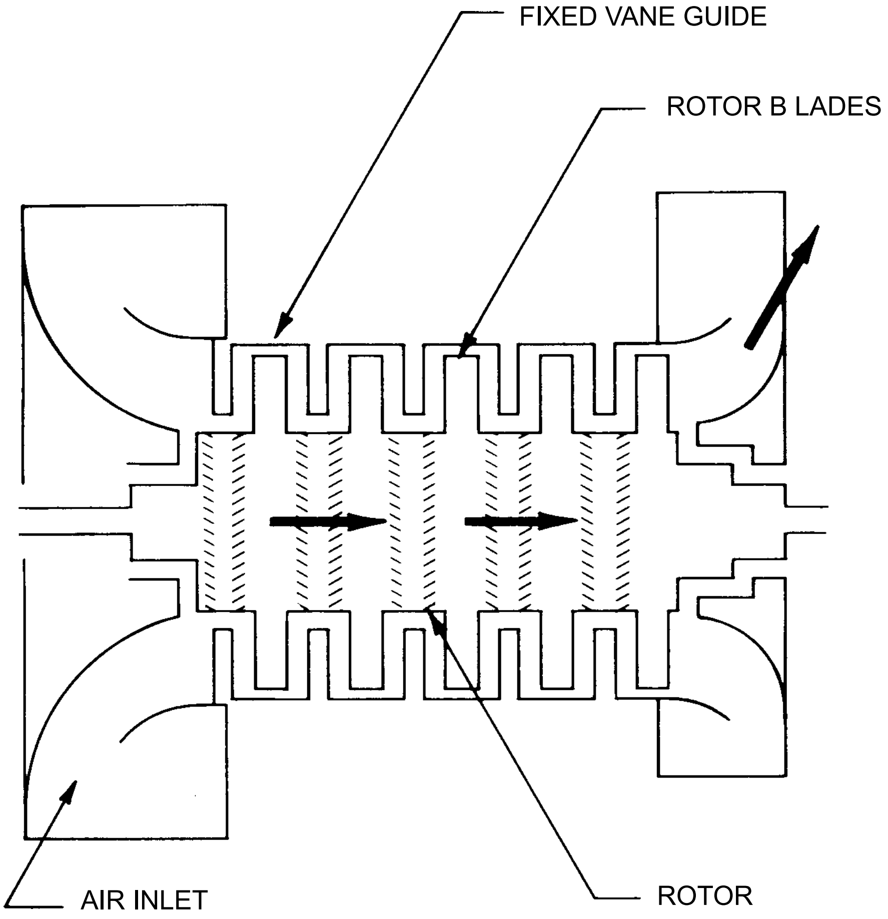
Surge can be prevented if flow remains above a limit established for each design. Various models have minimum operating flows between 45 and 90 percent of rated capacity.

Centrifugal compressors are available in both small and very large sizes. Units with up to six stages and supplying 30,000 cfm of air are commercially available. Operating speeds are very high compared with other types-up to 20,000 rpm in standard applications.

Axial Flow -This category is generally used for ultrahigh flow applications (30,000 to 1,000,000 cfm). Air flow is through a duct, primarily in a direction parallel to the axis of rotation. In multistage versions, this flow channeling is provided by the fixed guide vanes or stator blades positioned between each stage (Fig. 22).

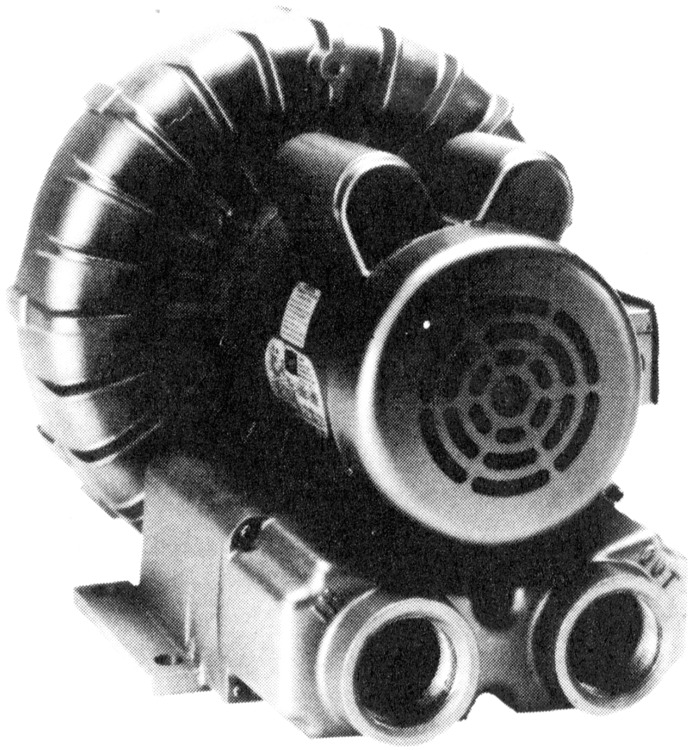
An axial flow compressor requires about a third the floor space of a centrifugal design, and it weighs about a third as much. Below capacities of 100,000 cfm, though, the axial design is seldom competitive in price.

Figure 22



Air flows (arrows) through multistage axial flow blower. The fixed guide vanes between each stage keep air flow parallel to the axis of rotation.

Figure 23



Typical peripheral (regenerative) blower provides equivalent of multistage compression in a single revolution of the impeller.

Peripheral (Regenerative) -These units (Fig. 23) provide somewhat higher pressures than do the other dynamic designs. With some units, a single-stage regenerative action provides pressures similar to those obtained with multistage centrifugal compressors.

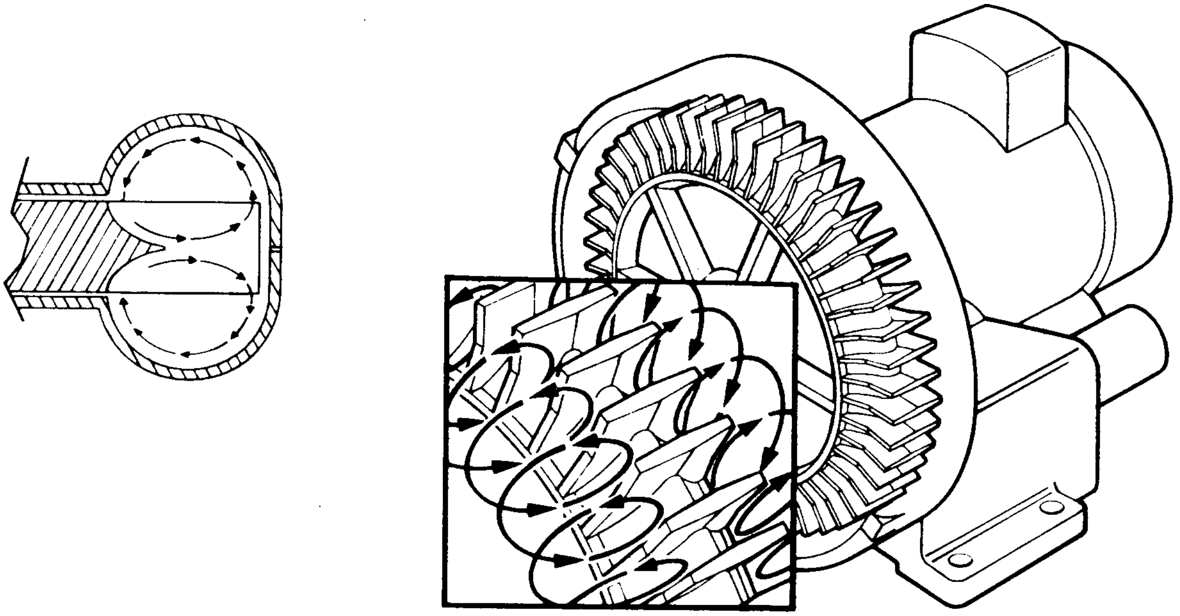
The compression space consists of a hollow, circular ring between the tips of the impeller blades and the walls of the peripheral passage. See Fig. 24. In operation, the rotating impeller draws air from the inlet port into the compression space. The air moves radially outward to the curved housing by centrifugal force.

The action is called "regenerative" because a certain amount of air slips past each impeller blade during rotation and returns to the base of a succeeding blade for reacceleration. The effect is like the pressure buildup in a multistage blower, and higher pressures can be generated.

Single-stage peripheral blowers are available in capacities up to several hundred cfm and can generate pressures close to 5 psig. Multistage versions are also available.

A significant advantage for peripheral blowers is that they are highly immune to operating conditions that might otherwise cause blockage of inlet and discharge flows. They also provide oil-less operation and continuous pulse-free flow.

Figure 24



The arrows show the route air takes through a regenerative blower.

Compressor Controls and Cycling

Before we discuss compressor selection, it is necessary to look at how pressure is regulated in a pneumatic system.

One way is to use a pressure relief valve between the compressor and the receiving tank. In this case, the compressor runs continuously against the system pressure.

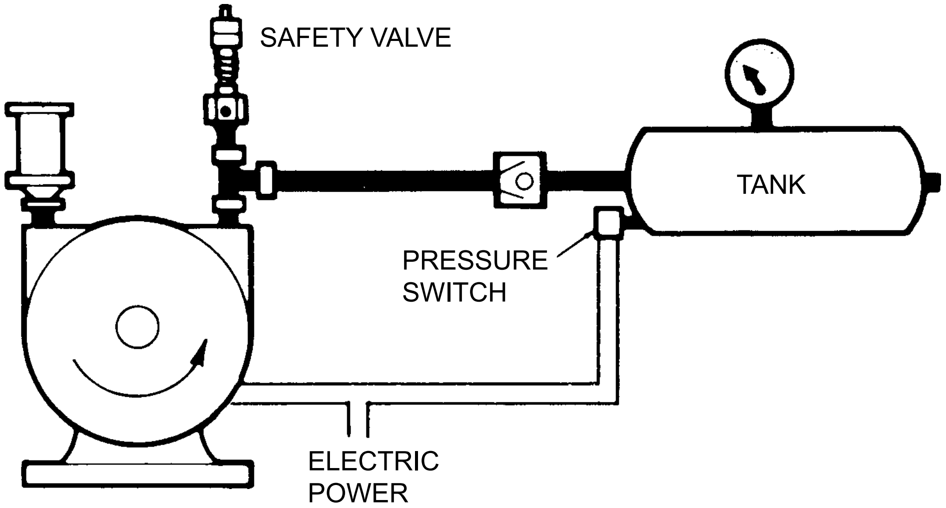
Alternatively, the compressor can be set to automatically turn off when the pressure reaches a preset maximum and on again when it reaches a minimum. This on/off cycling gives the compressor a chance to cool down and allows some models to be used at pressures higher than their continuous duty rating.

Yet another alternative, known as load/unload cycling, diverts the compressor output to the atmosphere when the set pressure is reached. This limits the work the compressor must do and the resulting heat buildup without imposing high starting torques on the motor.

On/Off Cycling - Fig. 25 shows how an electrical pressure switch, installed on the receiver tank, provides on/off cycling of the compressor. The switch starts and stops the drive motor as the pressure reaches preset levels. The normal range between .cut-out" and "cut-in" levels is 15 to 20 psi. The compressor in this type of system is said to have an intermittent duty cycle. As mentioned elsewhere, pressure ratings of many compressors are higher for intermittent than for continuous duty.

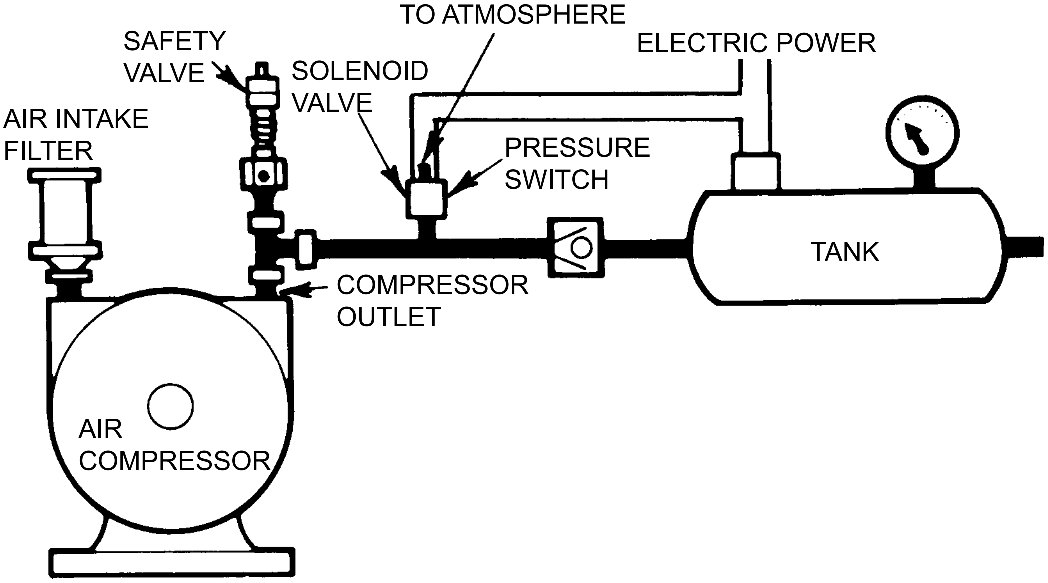
A safety valve is always used with this type of control to provide independent protection against overpressure.

Figure 25



A pressure switch can control receiver tank pressure by on/off cycling of compressor drive motor. This is completely independent of downstream pressure.

Figure 26



A pressure switch at the receiver tank can actuate a solenoid valve, providing automatic venting at a predetermined pressure limit.

Load/Unload Cycling - An electrical pressure switch can also be used to provide overpressure protection when it is not possible or advisable to start and stop the drive unit (Fig. 26). Examples are compressors driven by gasoline engines or power takeoffs.

As in the preceding system, the pressure switch is mounted at the receiver tank. But instead of being connected to a drive device, the switch is connected to a solenoid valve mounted in the delivery line,

At a predetermined upper ("unload") pressure limit, the pressure switch de-energizes the solenoid valve. The valve opens and vents output air to the atmosphere. The valve remains de-energized until the pressure switch senses that the pressure has dropped to a lower ("load") limit, when the valve closes.

Overpressure protection is similar to that provided by a pressure relief valve, except that the pressure control is at the receiver tank rather than at the compressor. The venting action reduces compressor work and heat to a minimal level. It also provides an internal flow of cool air through the compressor, supplementing the external forced draft provided by the fan.

A load/unload system requires the use of a safety valve to provide independent overpressure protection for the power supply system.

Selection of Compressor Type

In selecting an air compressor, the designer must determine how much pressure and air flow is required to meet specific application needs. He must also determine the drive power requirements for the compressor and how they will be met. Other considerations include cost, space, weight limitations, and possible needs for oil- free or pulseless air. Only when all these have been reviewed does the designer have enough information to select the type and size of compressor, plus the other components needed to complete the system.

Maximum Pressure Rating

The primary criterion for evaluating performance of a compressor is its maximum pressure rating. This is defined as the maximum pressure at which the compressor can deliver air to the system in commercial operation.

For any compressor, the physical design sets limits (because of such factors as air leakage and drive power limitations) on the pressure that can be generated. But in many cases, it is heat build-up that determines the actual pressure rating. The easier the compressor is to cool, the higher the pressure rating. This is also why many compressors have continuous-duty ratings that are considerably lower than their intermittent-duty ratings.

Basically, the selection of the appropriate compressor type is determined by comparing the maximum pressure requirements of the application with the maximum pressure rating of available compressor types.

As Table 3 shows, an application where the system pressure requirement is relatively low will give the designer a greater variety of compressor types from which to choose. As the system pressure requirement increases, the number of available alternatives diminishes-sometimes to a point where only a single compressor is applicable. Sometimes it may be a rather costly unit and have relatively high power requirements per cubic foot of air delivered.

The maximum system pressure required for a given application depends on the operating conditions, a requirement that isn't as simple as it sounds because several factors may be involved.

For example, if the system pressure is controlled by pressure venting through a relief valve, the valve will normally be set so that the maximum system pressure equals the highest pressure required by any operating device. Using this type of control, however, requires the compressor to work harder and longer at maximum pressure than with other control techniques.

But if system pressure is controlled by automatic on/off or load/ unload cycling, then the maximum system pressure will be the cutoff pressure of the cycling switch. This may be 15 to 20 psig higher than the highest working pressure required by any single operating device.

The working pressure requirements of individual devices can be determined from handbook formulas, performance curves, catalog data, or actual tests made with prototype systems. Normally, the working pressure needed will depend on the size of the actuator (work device) used. Sometimes system pressure requirements can be reduced when it is practical to use a larger actuator. That is, the required force can be generated by a lower pressure if it acts over a larger area. Overall system costs usually determine such decisions.

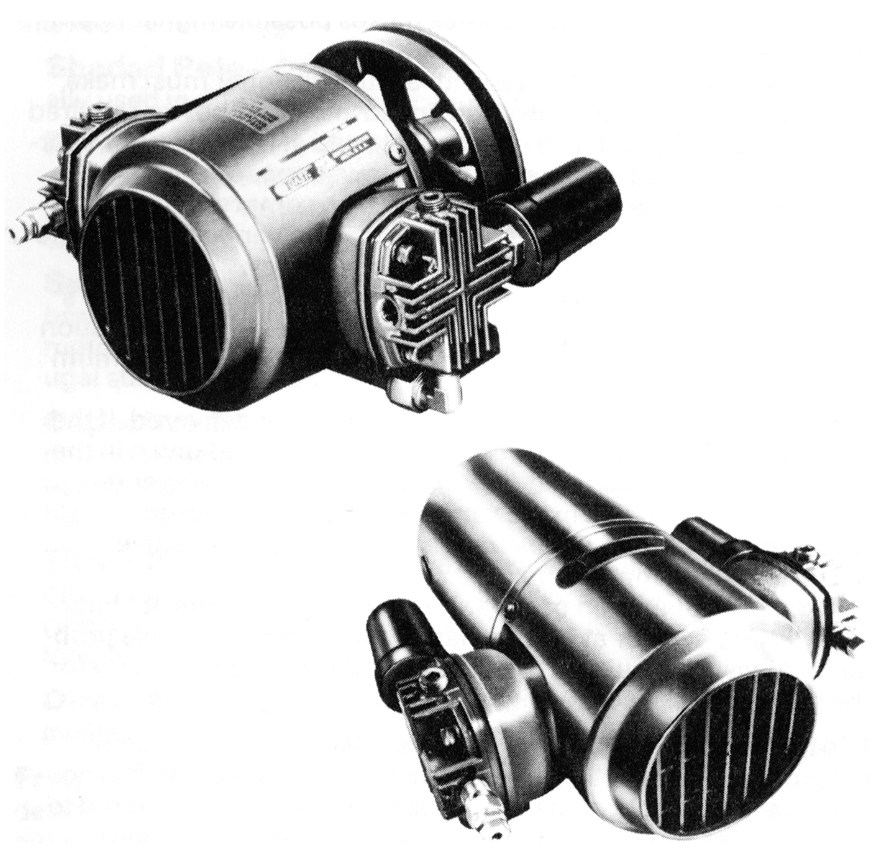
In some cases, the required working pressure may depend on the "pressure heads" needed for specific air flow velocities or rates.

Air Flow

While flow capacity is the primary factor in selecting a given size compressor, it also enters when selecting a compressor type. This is because different types of compressors tend to offer trade-offs between air flow and pressure capability. Not only do dynamic compressors provide higher flows and lower pressures than do positive displacement units, but the same is often true within each group. Rotary vane compressors, for example, tend to provide more air but less pressure than do comparably sized piston compressors.

Thus, after determining the required air pressure, the usual procedure is to select the type of compressor that will provide maximum air flow at that pressure, subject to other constraints. At a minimum, it is necessary to be sure that units offering the required flow are available in the type of compressor selected. Table 4 lists typical capacities for various types of compressors.

Figure 27



Compressors are available either with an integrally mounted motor or configured for a separate drive.

If capacity is a problem, it sometimes can be solved by changing the pressure vs. flow requirement to allow use of a different and less expensive type of compressor. In any case, this potential solution should be considered before final selection is made.

Type of Drive

Air compressors are furnished with or without an integrally mounted motor (Fig. 27). This allows the compressor to utilize whatever power may be available. For example, a separate gasoline-engine drive may be required in a remote outdoor location where there is no electric power.

Separate-Drive Compressors -These units are used in applications requiring drive by variable step-down belt drive systems, or by power secured from power takeoffs, gasoline engines, or special electric motors. The drive unit and compressor are generally connected either by a flexible coupling or by a drive pulley containing a built-in cooling fan.

The most significant advantage of a separate drive model is the cost saving realized when an existing power source is available. In addition, a belt drive sometimes makes possible higher operational speeds.

If a separate drive system is chosen, the designer must make sure it can provide both the rated speed and horsepower required by the type and size of compressor selected at its maximum operating pressure. Table 5 lists the horsepower/speed ranges for Gast separate-drive piston and rotary vane compressors. The speed of the piston units, for example, can be varied from 1000 to 2000 rpm by changing the size of the drive pulley.

Power requirements listed in the compressor manufacturer's catalog should assure adequate power for rated speed operation at any pressure up to and including the compressor's maximum pressure rating.

The drive speed determines the amount of air delivered. If the compressor is operated at less than the rated speed given in the manufacturer's catalog, both air flow and the horsepower required will be reduced in the same proportion. The torque requirement will remain unchanged, but only with positive displacement compressors.

In general, operation of separate-drive compressors at abnormally low speeds or at higher than rated speeds can cause problems. Always consult the manufacturer if it will be necessary for the system to deviate considerably from the rated speed.

Motor-Mounted Compressors - Motor-mounted compressors are literally built up around the drive motor shaft. The stationary elements of the compressor are securely anchored to the motor frame. The rotor (or eccentric) that generates the pumping action is installed on the motor shaft. Therefore there is no need for base-plate mounting and power transmission components. This approach provides an extremely compact, lowcost motor/compressor package to accommodate a range of capacities.

If electric power is available, a motor-mounted compressor will quickly solve the entire drive problem at reasonable cost. The only drive system problems are those associated with supplying and controlling the electricity. In general, motor-mounted compressors are more compact and cost less than the combined cost of a separate drive, base and motor.

Table 6 summarizes some available motor-mounted compressors (Gast units are taken as typical examples). Horsepower values are included to indicate the range of power requirements.

Selecting Electric Motor Drives

Once a motor-mounted compressor has been decided on, it is necessary to select the precise motor to be used. A variety of types are available, either as standard units or on custom order.

Motor Types -Several different types of electric motors are available, each with its own advantages and drawbacks. These include the following.

Shaded Pole - offers low starting torque at low cost. Usually used in direct drive applications for small units.

Permanent Split Capacitor (PSC) -Performance and applications are similar to shaded pole motors but the PSC is more efficient, with lower line current and higher horsepower capabilities.

Split-Phase - Offers moderate starting torque but high breakdown torque. Used on easy-starting applications. Small motors may have an external relay in place of the usual centrifugal starting switch.

Capacitor Start -In many respects, the capacitor start motor is similar to the split-phase motor. The main difference is the use of a capacitor in series with the start winding, providing higher starting torque.

Three-Phase -These motors operate on three-phase power only. They offer high starting and breakdown torque, high efficiency, medium starting current, simple, rugged design, and long life.

Direct Current (DC) -These are generally used only if DC is available. They are usually used with batteries.

Frequency -most motors available in this country are designed to operate at 60 Hz. At this frequency they will run at either 1725 or 3450 rpm, depending on the number of poles wound into the motor at manufacture. Except for specialized (and relatively expensive) adjustable-speed motors, a motor's speed is fixed by its design and cannot be changed.

Some motors are dual-frequency, designed to operate either at 60 Hz or at the European standard of 50 Hz. It is important to remember that when one of these motors is operated at 50 Hz, both its speed and the pneumatic output of the unit it is driving will decline by 17 percent.

Motor Enclosures -In general, there are two classifications for motor enclosures: open motor and totally enclosed motor. These two categories are further broken down as follows.

Dripproof -This prevents liquid drops and solid particles from entering the motor at angles up to 15° from vertical.

Splashproof -This prevents liquid drops and solid particles from entering the motor at angles up to 100° from vertical.

Totally Enclosed (TE) -There are no ventilation openings in the motor housing, but it is not air tight. Totally enclosed motors are used in dirty, damp, or oil-contaminated locations

Totally Enclosed, Non-Ventilated (TENV) - Unlike regular TE motors, this is not equipped with an external cooling fan. Cooling depends on convection or on a separately driven device.

Explosion Proof -This is a totally enclosed motor designed to withstand an internal explosion of specified gases or vapors without allowing flame to escape through the housing. There are different classes of explosion proof motors. The most common is class I-Group D.

Service Factors - Fractional horsepower motors commonly have service factors between 1.0 and 1.35. That is, some motors can tolerate up to a 35 percent overload on a continuous basis. The service factor is normally stamped on the motor nameplate and can be referred to easily.

Only open motors have service factors. For totally enclosed and explosion proof motors, the implied service factor is 1.0. When substituting a totally enclosed motor for an open one, the difference in service factors may require use of the next larger size.

Temperature Rise - Most motors are provided with class A insulation, which is designed for a maximum motor temperature (measured in the windings) of 221°F (105°C). The shell temperature should normally be under 180°F (82°C). Class B insulation is designed for a maximum temperature at the windings of 266°F (130°C). If the motor's temperature consistently exceeds the maximum recommended for its insulation class, its life (normally 20,000 hours) will be halved for every additional 10°C.

Motor design generally anticipates a maximum ambient temperature of 104°F (40°C). Slightly higher temperatures can be tolerated at less than maximum load.

As a motor's internal temperature changes, the speed changes even though the load remains the same. This is because higher temperatures increase the motor winding resistance. This reduces motor current, which in turn reduces the magnetic field strength in the motor. As a result, the torque falls and the speed drops in accord with the motor speed-torque curve.

If the total winding temperature does not exceed design limits and the unit is delivering rated output, a fractional horsepower motor normally operates near its rated speed. However, where high ambient temperatures require insulation rated to 130°C (class B insulation), lower speeds are the result.

This can occasionally cause problems when the motor is operating at a service factor greater than one - that is, is running slow because it is loaded beyond the full load point. If these factors are further compounded by low line voltage (speed varies nearly as the square of the voltage), the motor may stall. Under these conditions, a higher-horsepower motor will be required.

Thermal Overload Protection - Electric motors can overheat because of high ambient temperatures, continuous stall, abnormal voltages, restricted ventilation, or an overload. To minimize motor failure, a thermal overload cut-out device is used. Two basic types are available. One type is sensitive to temperature only, the other to both temperature and current.

Some overload protectors provide running as well as locked rotor protection. These meet the requirements of Underwriters Laboratories Incorporated. Others-for instance, in permanent split capacitor and shaded pole motors-provide only locked rotor protection. All provide some degree of protection at all times. However, the protection is not always strict enough to ensure normal motor life-particularly if the motor is operating close to its limits. Tighter limits, though, could lead to an excessive number of nuisance trips.

Some thermal overload devices feature automatic reset. That is, they automatically reset themselves after a cooling period. No human intervention is required-often an advantage when compressors or pumps must run unattended. But automatic reset devices should never be used when an unexpected restart might be dangerous. And if the fault still exists at automatic restart, the motor will cycle on and off until the fault is corrected.

Other Factors

Contamination - As noted earlier, oil vapors may cause contamination or deterioration of products and materials in some applications. Oil-less compressors are generally required in such cases. They also reduce maintenance costs by eliminating periodic filling of lubricators.

Available oil-less compressors include most of the piston and diaphragm types, regenerative blowers, and some of the rotary vane designs.

Pulse-free Delivery - Applications requiring continuous, pulse-free air delivery-without the extra cost and space requirements of a receiver tank-usually dictate that the compressor use a rotary pumping mechanism, such as the rotary vane design. An additional advantage of this compressor type is that noise and vibrations are considerably below those of reciprocating designs. The regenerative blower type also has pulse-free delivery and low vibration, but the high impeller speeds can generate high-pitched noise.

Mounting Space - Very often, compressor selection is further limited by available space at the installation site. For lower pressure systems, the compact rotary vane compressors usually require less space for a given free air capacity than do piston or diaphragm designs.

Compressor Size Selection

By the time all the foregoing application needs are resolved, the choice of a particular type of compressor very often has been limited to just one or two designs. Then the next step is to determine optimum compressor size.

Like other equipment decisions, compressor size selection also begins with application needs. Each application requires a specific volume of air over a specific time at a specific pressure. Then it's basically a matter of matching these specifics against the cfm and psi ratings of available air compressors.

Determining Free Air Consumption

Free air, as already defined, is air at atmospheric pressure. The free air volume is obtained by using the gas laws (Section I and Appendix) to convert volume at the actual working pressure and temperature to volume at atmospheric pressure and ambient temperature.

Three steps are required to determine the system's rate of free air consumption:

- Identify the volume of free air required by each operating device during its work cycle. This can be done by calculations based on handbook formulas, or from free air curves, catalog data or tests made with a prototype system.
- Multiply by the number of work cycles per minute.
- Total the results for all the work devices in the system. If a receiver is not used, it is also necessary to check that possible peak demands do not exceed the average demand calculated. If they do, then it will be these peak demands that govern the capacity requirements.

Effects of Receiver Recharging - if a receiver tank used in an application requires rapid on/off or load/unload cycling operations, the compressor must be sized with extra capacity so the receiver can be recharged without interrupting normal system operation.

A rule-of-thumb for determining the volume of free air required for receiver tank recharging is to multiply the receiver volume by the pressure difference (in atmospheres) between the cut-in and cut-out pressures. Then divide the result by the charging time permitted and select the compressor that will deliver that cfm at the cut-out pressure.

Effects of Initial Receiver Charging - in some intermittent systems, extra-large receivers are used to permit a longer off period. While this reduces the number of duty cycles during a given interval, the time required for initial charging of the large receiver may be too long to permit normal system operation.

A practical solution is to select a compressor with greater capacity than otherwise required simply to reduce the initial charging time. The increased capacity will also reduce the portion of the duty cycle the compressor is on.

The time required for initial receiver charging can be estimated by dividing the amount of free air to be pumped into the receiver
by an average delivery rate: rate at low pressure plus rate at high pressure divided by two.

Determining Available Compressor Capacity

In determining an air compressor's ability to meet specific system needs, rated capacity is generally determined from curves or performance tables. These show the actual free air delivery at rated speed for discharge pressures ranging from 0 psig to the maximum pressure rating. (Table 4 lists typical capacity ranges for various types of compressors.)

Keep in mind that horsepower and displacement are not suitable sizing criteria. Such factors can lead to large sizing errors because they do not provide accurate measures of the compressor's actual delivery capabilities.

For protection against problems caused by leaks, unusual operating conditions, or poor maintenance, size selection should provide some extra capacity. Generally, the compressor actually selected should have a rated free air capacity 10 to 25 percent greater than the system's actual rate of free air consumption. This precaution also allows for possible future system expansion or field modifications.

Effects of Duty Cycle - When an intermittent pressure rating is used in selecting a compressor, the restrictions on duty cycles established by the compressor manufacturer must be strictly observed. For example, intermittent pressure ratings for Gast compressors are based on a 50/50 (10-minute on/10-minute off or open) duty cycle. This 10-minute off period is a minimum necessary to allow the compressor to cool. Longer off periods can be obtained by increasing the receiver volume or by increasing the difference between cut-in and cut-out pressures of the pressure switch.

The 10-minute on period is the maximum based on temperature rise. Increasing the compressor capacity will shorten the on periods, but very short on cycles can cause problems when pressure is controlled by starting and stopping the compressor's drive motor. This is because too-frequent starts can actuate the motor's thermal overload mechanism, temporarily interrupting electrical power. This is best solved by leaving the pump on and using a solenoid valve.

Other Selection Considerations

Volumetric Efficiency -The theoretical pumping capability of a positive displacement compressor is the product of its displacement (the total volume transported by its pumping elements in one revolution) times its speed in revolutions per minute. Displacement is determined by the size and number of the pumping elements (piston chambers, vane compartments, etc.). Displacement alone should not be used as a sizing parameter, since it is a theoretical value that does not take into account pumping losses.

A pumping device's volumetric efficiency is how close it comes to delivering the calculated volume of fluid. Volumetric efficiency varies with speed, pressure, and type of pump. It is found by comparing actual delivery with computed delivery using this formula:

$$\text{Volumetric Efficiency (\%)} = \frac{\text{Free Air Delivered in cfm}}{\text{Theoretical Capability in cfm}} \times 100$$

The volumetric efficiency of an air compressor is highest at 0 psig-that is, when it is discharging to the atmosphere. Volumetric efficiency becomes progressively lower as pressure increases.

This drop reflects a loss in rated capacity at higher pressures, mainly because of increases in the pressure of air trapped in the "clearance volume" and to an increase in internal leakage or slippage. The temperature and density of the incoming air also affect the efficiency.

Drive Power Requirements - For any given compressor, the power required for compression depends on the capacity of the compressor, the pressure at which it is operated, and the efficiency of the cooling method. Additional power is needed to overcome inertia and the frictional effects of startup, as well as mechanical resistance while driving the compressor at rated speeds.

The manufacturer's drive power recommendations for a given compressor usually includes both a suggested drive speed and a horsepower requirement. The drive speed will be that at which the rated capacities are developed. The horsepower specification will be the maximum power required. This is usually the power required at maximum rated pressure but may occasionally reflect startup requirements.

The compressor manufacturer can generally provide performance curves that show the power requirements at rated speeds over a range of pressures. In some cases, curves may be available showing power requirements at different speeds for given pressures.

Adherence to these recommendations will assure satisfactory operation at any pressure within the compressor's range of operation.

Power Efficiency - Techniques to evaluate the efficiency with which a compressor uses power have been widely adopted. In general, these call for simultaneous measurements of cylinder volume and pressure, free air flow, temperatures, and input power.

Actual outputs calculated from these measurements are compared with theoretical values. This way the efficiency of the compressor, the compression process, and the overall installation can be determined.

A simple but relatively accurate comparison of the performance of different compressors is provided by the cfm of free air delivered per horsepower. This can be calculated directly from manufacturers' catalog data.

It's a simple procedure. First, find the cfm delivered at the required pressure. Divide this value by the horsepower at that pressure. This results in the actual quantity of free air per minute per installed horsepower. (Be sure to note, however, whether catalog data are based on cfm at actual pressure levels or at atmospheric pressure. The same reference level must be used for all compressors being compared.)

Since horsepower delivered is directly proportional to the product of gauge pressure and flow rate, cfm at a given pressure per input horsepower indicates power efficiency.

There is a relatively wide variation in the energy efficiency, defined as cfm of free air per horsepower, of the various compressor types, as Tables 5 and 6 indicate. This often enables the designer to reduce power requirements simply by switching to a different type of compressor.

Temperature Effects on Performance - High temperature is an air compressor's enemy. It can limit pressure capabilities, reduce delivery rates, and increase power requirements. Continued operation at high temperature accelerates wear and degrades the lubricant, causing bearing failures.

To avoid problems with high temperatures, the compressor's operating pressure should be held within the manufacturer's stated maximum pressure rating and duty cycle limitations. If the compressor must operate continuously at high pressures or temperatures, a heavy-duty water-cooled unit may be required.

Wherever possible, the compressor should be installed where its fan can draw in cool, clean air. Units powered by electric motors should not be installed where ambient temperatures are above 40°C (104°F).

In addition to the effects of a compressor's overheating, discharge of high temperature air can have a number of adverse effects on a pneumatic system: (a) reduced receiver storage capacity; (b) removal of volatile components from lubricating oil carried over into receiver and air lines; (c) increased moisture carried over into the air system. How to avoid these problems is discussed in Section III.

Table 2

Summary of Compressor characteristics

Class	Category	Type	Power Range (HP)	Pressure Range (PSI)	Advantages
Positive displacement compressors	Reciprocating	Piston Air-cooled	1/2 to 5000	10 to 15,000	Simple, lightweight
		Piston Water - cooled	10 to 5000	10 to 50,000	Efficient, heavy-duty
		Diaphragm	10 to 200	10 to 3,500	No seal, contamination-free
	Rotary	Sliding vane	10 to 500	10 to 150	Compact, high-speed
		Screw (helix)	10 to 500	10 to 150	Pulseless delivery
		Lobe, low-pressure	15 to 200	5 to 40	Compact, oil-free
		Lobe, high-pressure	7 1/2 to 3000	20 to 750	Compact high-speed
Non-positive Displacement compressors	Rotary	Centrifugal	50 to 20,000	40 to 2,000	Compact oil-free high-speed
		Axial Flow	1000-10,000	40 to 500	High-volume, high-speed
		Regenerative peripheral blower	1/4 to 20	1 to 5	Compact, oil-free high volume

Table 3

Pressure Ratings and Applicable Compressors

Required System Pressure (PSIG)		Compressor Types Available	
Continuous	Intermittent*	Preferred Type	Optional Type
100 to 175	175 to 200	Two-stage (piston) Piston (1 stage)	-
50 to 100	-	Rocking Piston (1 stage)	-
30 to 60	-	Diaphragm	Rocking Piston (1 stage)
25 to 30	25 to 30	Rotary vane (oil-lubricated)	Any of above
10 to 15	15 to 20	Rotary vane (oil-less)	Any of above
10	10	Rotary vane (oil-lubridated & oil-less)	Any of above
3.5	-	Regenerative (peripheral) blower	-

*Pressure ratings based on 10-minute or / 10-minute off duty cycle

Table 4

Capacity Ranges and Pressures

Available Compressor Types	Maximum Pressure (PSIG)		Range of Capacities (CFM Free Air at 0 PSIG)	
	Continuous	Intermittent	Smallest	Largest
Piston (1-stage)	50-100	50-100	1.3	11.0
Rocking Piston (1-stage)	10-100	10-100	0.6	3.25
Diaphragm (1-stage)	50-60	50-60	0.51	3.8
Rotary Vane (oil-lubricated)	10-25	12-30	1.3	55
Rotary Vane (oil-less)	10-15	10-20	0.35	55

Table shows pressures and range of capacities available from various types of Gast compressors

Table 5

Availability of some separate drive comrpessors

Compressor Type	Range of Capacities (CFM at 0 PSIG)	Drive Requirements	
		H.P.	Speed
Piston (1-stage)	1.3 to 4.8 cu. ft.	0.3 to 1.1	2000 RPM (minimum 1000 RPM)
Rotary vane (oil-lubricated & oil-less)	0.35 to 55 cu. ft.	1/40 to 5	Most common 1725 RPM (range, 880 to 3450 RPM)

Table 6

Availability of Motor-Mounted Compressors

Compressor Type	Range of Capacities (CFM Free Air at 0 PSIG)	Motor H.P. Requirements
Piston (1- and 2-stage)	1.3 to 11.0	1/6 to 2
Rocking Piston	0.6 to 3.25	1/8 to 1/2
Diaphragm	0.8 to 3.9	1/16 to 1/2
Rotary vane (oil-lubricated & oil-less)	0.35 to 55	1/15 to 3/4