6

METAL DIAPHRAGM COMPRESSORS*

6.1 INTRODUCTION

Gas compressors are mechanical devices that convert energy from one form to another. Energy conversion can be accomplished by the use of different types of machines, but the net result is the same. The pressure of the gas is increased, and therefore the energy level of the gas is increased. All compressors have an element that increases the energy level of the gas. It can take the form of a volume reduction element as in the case of positive displacement compressors or a velocity element as in the case of dynamic compressors.

Metal diaphragm compressors are positive displacement machines in which the compressing element is a metal diaphragm or diaphragm group. The displacing element is a piston having a reciprocating motion within a cylinder. The metal diaphragm reduces (compresses) the volume of the gas causing the gas pressure to be increased. Thermodynamically, this type of compression is considered flow-type work, and it is an adiabatic or polytropic process of a nonideal gas.

6.2 TERMINOLOGY

Metal diaphragm compressors share many basic elements with positive displacement piston compressors. Some terms unique to metal diaphragm compressors are defined below.

- *Cavity*: a contour of either single or multiple radii machined in a flat plate or disk. Contours are machined in both the process and hydraulic cavity plates and are usually

* Developed and contributed by Pressure Products Industries, Inc., Warminster, Pa.

mirror images. The sum of the volume of these two cavities is the displacement of the diaphragm group.

- *Cavity plate*: the plate in which the cavity is machined. Cavity plates are either *process* or *hydraulic.* Process cavity plates also contain cooling passages for removing the heat of compression.
- *Clearance volume (dead volume)*: the volume present in one compressor cylinder or head in excess of the net volume displaced by the piston or diaphragm during the stroke.
- *Diaphragm*: a thin metal membrane that isolates the gas from the hydraulic fluid.
- *Diaphragm group*: a group of three metal diaphragms that isolates the gas from the hydraulic fluid. This group consists of a process, middle, and hydraulic diaphragm. The middle diaphragm contains either grooves or slots radiating from the center of the diaphragm to the circumference of the diaphragm to channel gas or hydraulic fluid to the leak detection groove in the event of a diaphragm failure.
- *Displacement*: the net volume displaced by the piston or diaphragm at the rated machine speed, generally expressed as a volumetric flow rate. For a single-stage compressor, it is only the displacement of the compressing end. For multistage compressors, it is the displacement of the first stage.
- *Head assembly*: the metal diaphragm compressor subassembly containing the cavity plates, support heads, diaphragms, process check valves, O-ring seal sets, and hydraulic piston. Various types of head assemblies are used, depending on the pressure and size of the cavity.
- *Hydraulic injection pump*: a pump attached to an extension of the power frame crankshaft that injects a measured amount of hydraulic fluid into the hydraulic pulsing system at a predetermined time during the suction portion of the compressor cycle.
- *Lock ring*: a threaded member designed to retain the forces (pressure and seal loads) in the metal diaphragm compressor inserted head assembly. The lock ring contains thrust bolts that provide the preload on the head assembly seals.
- *Lower head*: a structural element in which the hydraulic cavity plate sits and the hydraulic piston reciprocates. The part is used on high-pressure diaphragm compressors with intensifier assemblies.
- *Main nut*: a threaded member designed to retain the forces (pressure and seal loads) in the metal diaphragm compressor intensifier head assembly.
- *Pressure limiter*: a device that is used to control hydraulic system volume and pressure so that volumetric efficiency of the metal diaphragm compressor is maximized. *It is not a safety device to protect the compressor or the process system.*
- *Stuffing box*: the main structural member used in inserted and intensifier head assemblies.
- *Support head*: a structural element similar to a flange that supports either the process cavity plate or the hydraulic cavity plate. The upper support head supports the process cavity plate; the lower support head supports the hydraulic cavity plate.

6.3 DESCRIPTION

A metal diaphragm compressor (Fig. 6.1) is a positive displacement compressor. Gases are isolated from the reciprocating and hydraulic parts of the compressor by three thin flexible metal disks called *diaphragms.* The motion of the reciprocating piston is transmitted to the

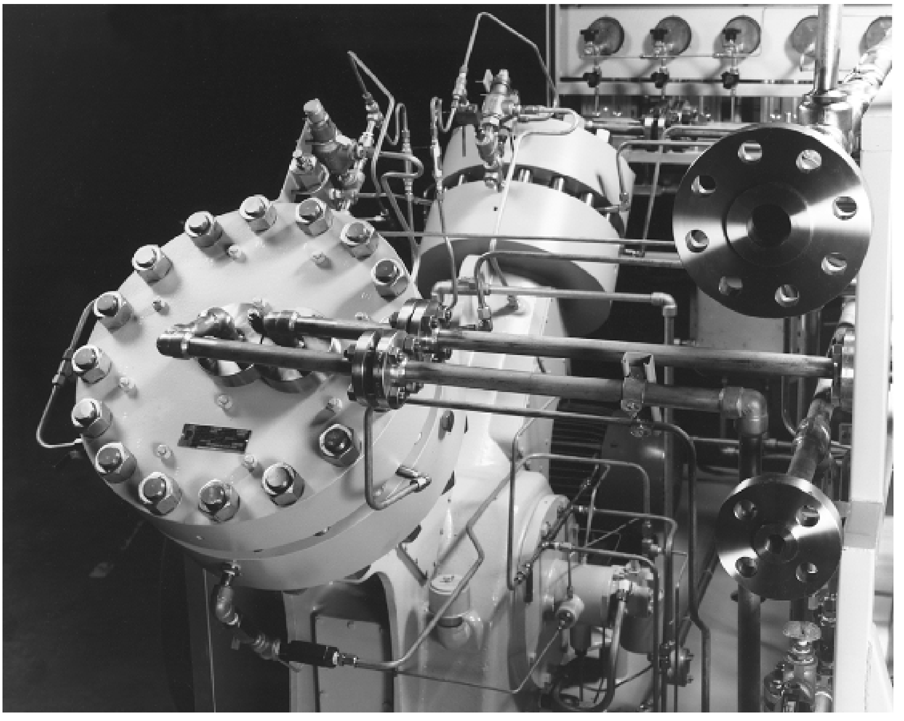

FIGURE 6.1 Metal diaphragm compressor. *(Pressure Products Industries, Inc., Warminster, Pa.)*

diaphragms by the hydraulic fluid. This motion causes the diaphragms to move into the process cavity, thereby reducing the volume and increasing the gas pressure.

The compression cycle of the metal diaphragm compressor is not unlike the positive displacement piston compressor. Both use a reciprocating piston to convert mechanical energy to flow work in the gas. Both use spring-loaded check valves that open only when the proper differential pressure exits across the valve. In each design, the clearance volume (dead volume) influences the volumetric efficiency of the compressor. However, diaphragm compressors differ in the way the compression cycle is managed, although a *p–V* diagram for the two types of compressors would be virtually identical.

The *p–V* diagram for positive displacement piston compressors was shown in Figs. 1.1 through 1.5. Point 1 is the *start of compression,* and the cylinder is filled with gas at the suction pressure. The check valves are closed and the piston is at bottom dead center of its stroke.

On the *compression* portion of the stroke, the piston has moved, reducing the volume in the cylinder with an accompanying rise in pressure (point 1 to point 2). The valves remain closed and the cylinder pressure has reached the upstream piping pressure.

Point 2 to point 3 is the *discharge* or *delivery* portion of the stroke. Compressed gas is flowing out of the discharge check valve and into the discharge piping. When the piston reaches point 3, the discharge valve will close. The piston is at top dead center of its stroke. Gas at pressure P_2 is still in the cylinder.

From point 3 to point 4, the piston is in reversal, the suction and discharge valves remain closed, and the gas trapped in the clearance volume begins to expand, resulting in a pressure reduction. This is the *expansion* portion of the cycle.

The cylinder pressure eventually drops below the suction pressure, P_1 at point 4. The suction valve will then open and gas will flow into the cylinder until the piston reaches the reversal point of its stroke, point 1.

The *p–V* diagram of a metal diaphragm compressor is identical to a piston compressor for the *gas compression cycle.* Differences occur during the compression cycle of the hydraulic fluid. The hydraulic fluid compression cycle, often referred to as the *mechanical compression cycle,* accounts for all pressure changes in a metal diaphragm compressor. A graph of the mechanical compression cycle for a metal diaphragm compressor is shown in Fig. 6.2.

The mechanical compression cycle shown in Fig. 6.2 traces the hydraulic system pressure from the process suction pressure to the process discharge pressure and then to the hydraulic pressure limiter setting and back to the process suction pressure.

Starting at 0° of compressor crankshaft rotation (the reciprocating piston is at bottom dead center), the diaphragm group is fully deflected into the hydraulic cavity plate (Fig. 6.3). The metal diaphragm compressor head assembly is filled with gas at the suction pressure. The check valves are closed. This compares to point 1 on the *p–V* diagram (Fig. 1.5).

On the *compression* portion of the stroke, the hydraulic piston moves from bottom dead center, compressing the hydraulic fluid and forcing the diaphragm group into the cavity in the process cavity plate (Fig. 6.4). Gas volume in the process cavity plate is reduced with an accompanying rise in pressure. The valves remain closed until the process cavity pressure reaches the upstream piping pressure. This compares to points 1 and 2 on the *p–V* diagram.

Compressed gas is flowing out of the discharge check valve and into the discharge piping during the *discharge* portion of the stroke. When the diaphragm group is fully deflected or displaced into the process cavity plate, the discharge check valve will close. This compares to points 2 and 3 on the *p–V* diagram. Gas at pressure P_2 is still in the cylinder.

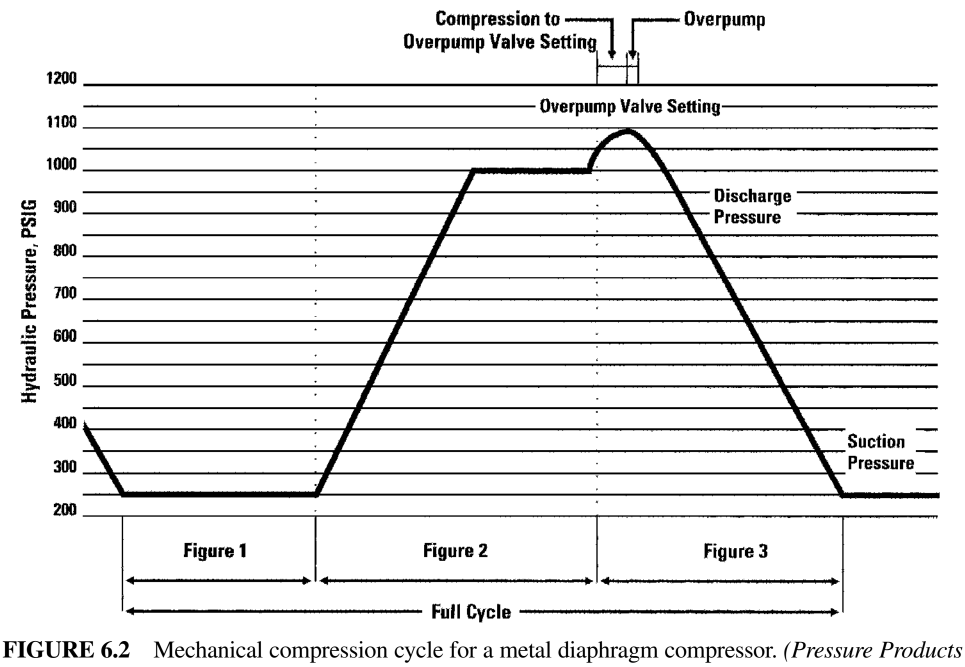

FIGURE 6.2 Mechanical compression cycle for a metal diaphragm compressor. *(Pressure Products Industries, Inc., Warminster, Pa.)*

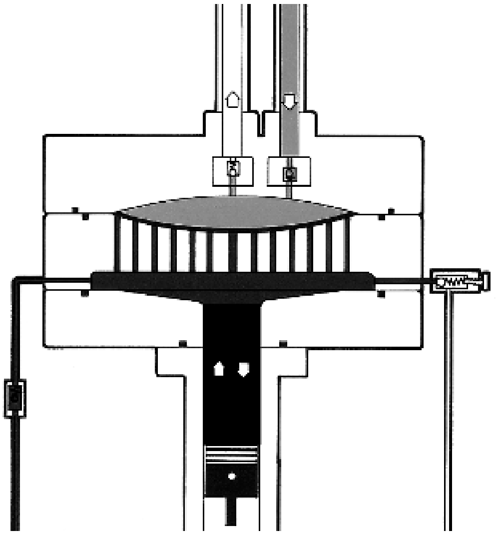

FIGURE 6.3 Diaphragm compressor reciprocating fluid piston at the 0° position. The hydraulic piston is at bottom dead center. The hydraulic system has just been filled with fluid by a single stroke of the automatic injection pump. The process gas, entering through the inlet check valve at suction pressure, has moved the diaphragm group to the bottom of the cavity. The cavity is now filled with the process gas. *(Pressure Products Industries, Inc., Warminster, Pa.)*

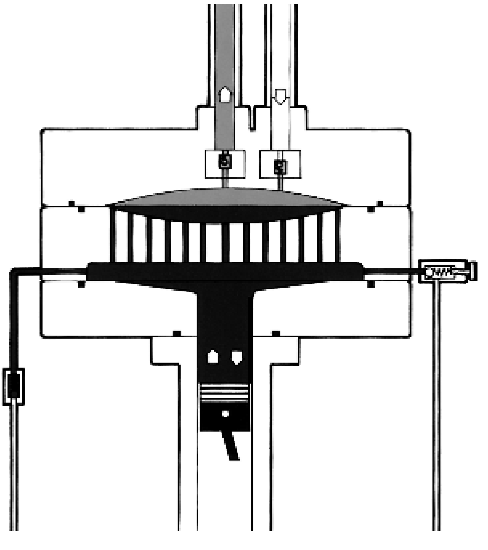

FIGURE 6.4 Diaphragm compressor reciprocating fluid piston advancing. As the crankshaft rotates, the piston moves from bottom to top dead center, and the hydraulic pressure increases. As the hydraulic pressure reaches the pressure level of the process gas in the cavity, the diaphragm group moves toward the top of the cavity, compressing the gas. When the pressure of the process gas within the cavity reaches the pressure level downstream of the discharge check valve, the check valve opens and the gas is discharged. Pressure in the hydraulic system continues to increase, which moves the diaphragm group completely through the cavity, thereby ensuring maximum gas displacement and efficiency. *(Pressure Products Industries, Inc., Warminster, Pa.)*

Differences occur between the metal diaphragm compressor and the positive displacement piston compressor at this point in the cycle. The positive displacement piston compressor would now start its reversal and go into the expansion portion of the cycle. On the other hand, the metal diaphragm compressor hydraulic piston still has a distance to travel since the volume of the hydraulic system is slightly greater than the volume of the process system (Fig. 6.5). The hydraulic system has received extra volume during the suction portion of its stroke from the *hydraulic system injection pump.* This extra volume is required to ensure that the diaphragm group is fully deflected or displaced into the process cavity plate. Without this extra volume, the diaphragm group would never attain full deflection or displacement and therefore would not reach maximum discharge pressure. The volumetric efficiency of the compressor would be reduced because of an increase in the clearance volume. The extra volume is discharged through the hydraulic pressure limiter once the hydraulic system reaches the pressure limiter setting. The extra volume discharged through the hydraulic pressure limiter is called *overpump*.

The expansion cycle of the metal diaphragm compressor begins once the hydraulic pressure limiter has closed and the hydraulic piston has started its reversal. The suction and discharge valves remain closed, and the gas trapped in the clearance volume begins to expand, resulting in pressure reduction. This compares to points 3 and 4 on the *p–V* diagram.

The cavity pressure eventually drops below the suction pressure. The suction valve will then open and gas will flow into the process cavity until the diaphragm group reaches its

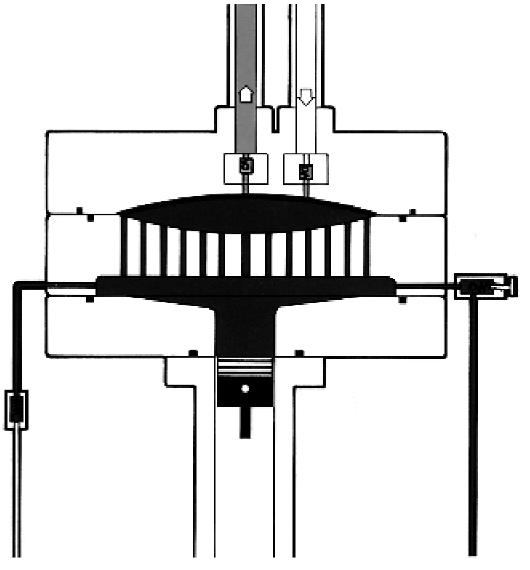

FIGURE 6.5 Diaphragm compressor reciprocating fluid piston at the limit of a stroke. When the diaphragm group has completely moved through the cavity, the piston must travel still farther to reach its top dead center position. As this takes place, hydraulic fluid is forced through the hydraulic overpump valve, which is set at a pressure level higher than the desired discharge process pressure. The compression portion of the cycle is now completed, and the piston begins to move toward bottom dead center. As the hydraulic piston moves toward bottom dead center, the expansion of residual gas combined with gas entering the cavity at suction pressure deflects the diaphragm group toward the bottom of the cavity, and the cycle is complete. *(Pressure Products Industries, Inc., Warminster, Pa.)*

maximum deflection in the hydraulic cavity plate. It is during this phase of the cycle that the hydraulic injection pump will add the extra volume that will eventually become the *overpump* at the end of the discharge portion of the cycle.

The power requirements of a metal diaphragm, it is important to note, are not based solely on the work imparted to the gas. The mechanical energy required during the mechanical compression cycle and the thermodynamic work of the gas compression cycle must both be considered to determine the power requirements of the metal diaphragm compressor.

Figure 6.6 illustrates the head components of a typical metal diaphragm compressor. The head assembly consists of the upper head (process cavity plate), diaphragm group, lower head (hydraulic cavity plate), and lower support head. Not shown is the power frame, which would include hydraulic piston, hydraulic pressure limiter, hydraulic injection pump,

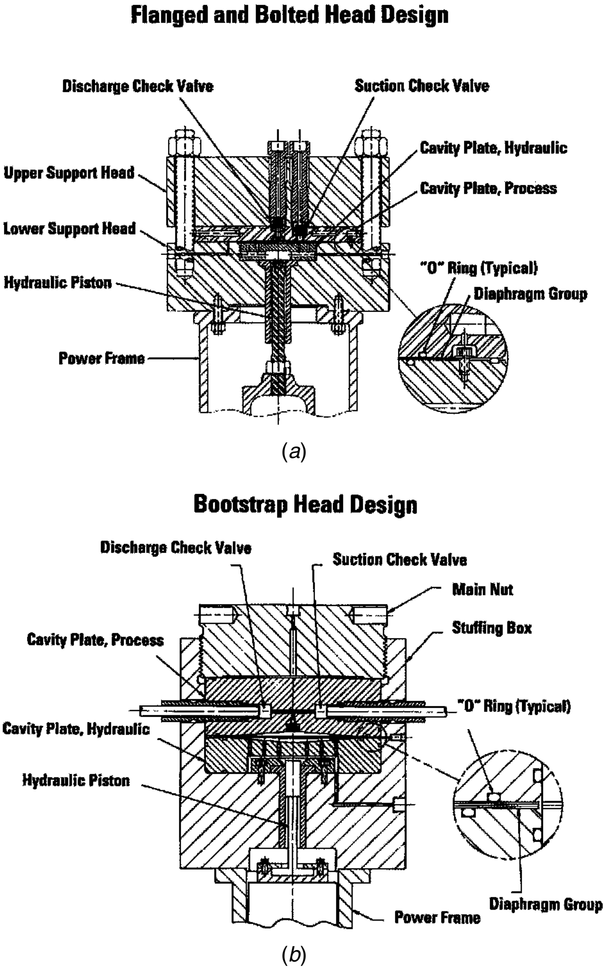

FIGURE 6.6 Diaphragm compressor head designs. (*a*) Represents the simplest and most commonly used design; this is limited to pressures of 5000 psi (345 bar) and below. (*b*) Provides a positive seal with a simple low-torque closure. This design is used when the combination of pressure and diameter make it the most efficient closure. *(Pressure Products Industries, Inc., Warminster, Pa.)*

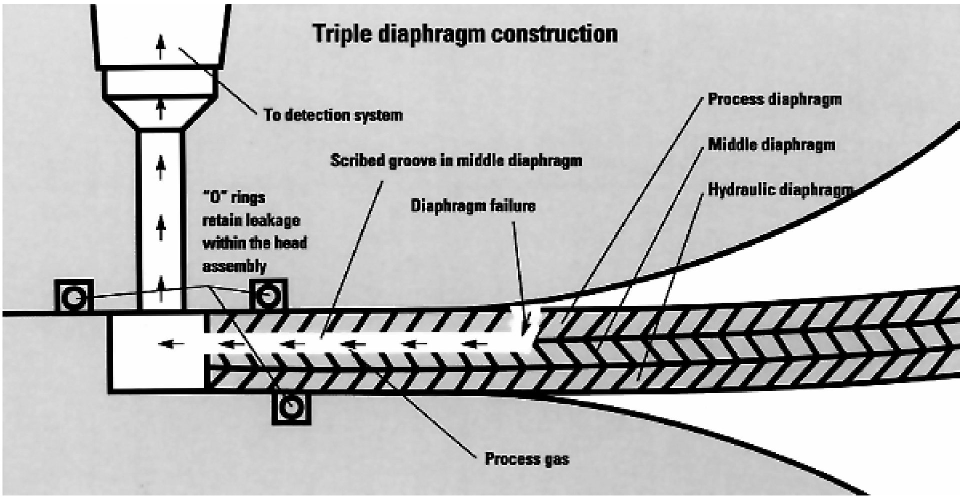

FIGURE 6.7 Triple diaphragm. This construction can be combined with suitable instrumentation to detect diaphragm failure rapidly. *(Pressure Products Industries, Inc., Warminster, Pa.)*

and suction and discharge check valves. Triple diaphragm construction and the leak detection port are shown enlarged in Fig. 6.7. Note the static O-ring seals for the process side, hydraulic side, and secondary containment seal.

Diaphragm compressors compress gas with no contamination and virtually no leakage. More specifically, leakage is less than 1×10^{-5} standard mL/s helium with O-ring seals. Rates of less than 1×10^{-7} can be obtained with metal-to-metal seals.

Under normal operating conditions, the gas is completely isolated from the hydraulic fluid by the diaphragm group. This permits toxic, flammable, pure, or expensive gas to be compressed safely, without contamination or leakage. Triple diaphragm construction ensures product purity since the three diaphragms will continue to isolate the gas from the hydraulic fluid, even under abnormal conditions such as a diaphragm or seal failure. The leak detection system retains any effluent during abnormal conditions. The system senses any diaphragm or seal abnormality and gives the operator a visual indication and shutdown or alarm capabilities by use of the system pressure switch.

Metal diaphragm compressors are usually available in single- and two-stage models. Most compressor displacements range from 0.032 to 110.8 cfm (0.054 to 188.27 m^3/h) based on an operating speed of 400 rpm. Standard discharge pressures range from 25 to 30,000 psi (172 kPa to 207 MPa).