SECTION 3.6
DIAPHRAGM PUMPS

STEPHEN D. ABLE
ROBERT BEAN
WARREN E. RUPP

Diaphragm pumps are a class of displacement pumps featuring flexible membranes in combination with check valves that are used to move fluids into and out of pumping chamber(s). These pumps are used extensively in transfer and metering applications requiring flows of up to 300 gallons per minute (1150 liters per minute). They are quite versatile, handling a wide variety of fluids including chemicals, dry powders, food additives, glues, paints, pharmaceutical products, slurries, tailings, and wastewater. A distinguishing feature of all diaphragm pumps is the absence of seals or packing, meaning they can be used in applications requiring zero leakage. There are three main categories of diaphragm pumps: 1) mechanically driven, 2) hydraulically driven, and 3) air-operated.

MECHANICALLY DRIVEN DIAPHRAGM PUMPS

Many industries are served by mechanically driven diaphragms pumps. They are used in construction, chemical, and water treatment applications.

Construction Industry Mechanically driven diaphragm pumps are widely used in the construction industry for dewatering applications where pumps may ingest rocks or other debris. A popular make of this type of pump contains a spring on the plunger rod (see Figures 1 and 2). If the operating pressure exceeds the maximum recommended pumping pressure, the spring compresses and does not move the diaphragm. The spring can compress and thus keep a rock from being pushed through the wall of the pumping chamber or cause the drive mechanism to fail.

In single-diaphragm pumps, the pumped liquid can have a lot of inertia if the suction and discharge lines are relatively long. A simple accumulator on the suction (inlet) side of the pump enables the pump to draw liquid from the accumulator while it simultaneously draws liquid through the suction line.

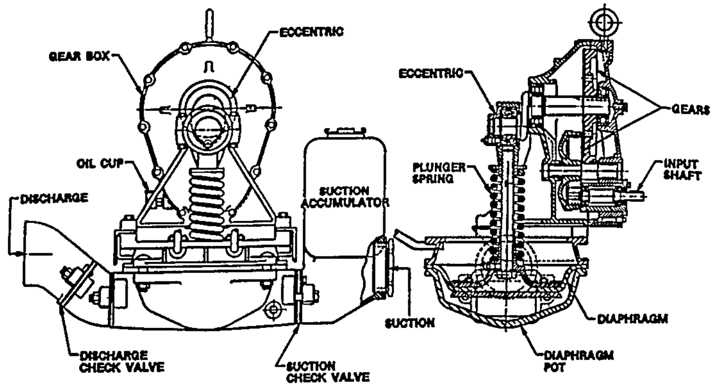

FIGURE 1 Cross-section of a mechanically driven single-diaphragm pump for the construction industry (Gorman-Rupp)

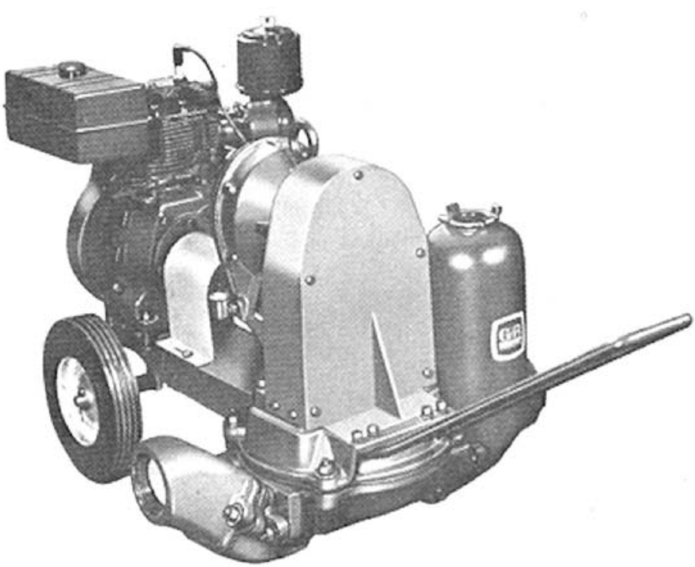

FIGURE 2 Mechanically driven single-diaphragm pump, engine-powered (Gorman-Rupp)

During the discharge stroke, the accumulator can refill with liquid from the suction line. If the discharge line from the pump is relatively long, the inertia of the liquid can be great, as mentioned earlier, and can impose severe loads on the diaphragm and drive mechanism. The spring on the plunger rod can absorb some of the drive energy early in the discharge stroke and "give it back" during the latter part of the discharge stroke, greatly reducing the inertia loading on the diaphragm and drive mechanism.

Mechanically driven diaphragm pumps in the construction industry operate by a reciprocating plunger, usually secured to plates on both sides of the diaphragm. The diaphragms are customarily fabric-reinforced elastomers (usually synthetic rubbers) similar in many ways to the fabric-reinforced materials used in pneumatic tires. The diaphragms are normally molded with a convoluted section between the central clamped area and the clamped periphery. This convoluted section permits longer strokes than would be possible otherwise.

These pumps are sometimes duplexed so that the reciprocating means acts alternately on two diaphragms with one on a suction stroke, while the other is on a discharge stroke and vice versa. A connector called a *walking beam* is pivoted between two diaphragms. As one diaphragm is pushed down on a discharge stroke, the other diaphragm is simultaneously pulled up on a suction stroke. The pumping chambers with inlet and outlet check valves are manifolded together to a common inlet and a common outlet. The principle advantage of the duplex diaphragm pump is its more constant flow (two pressure pulsations per cycle).

Mechanically driven diaphragm pumps are used in the construction industry for dewatering foundations and cofferdams, as well as in sewage treatment plants for pumping lime slurries. They are normally limited to 50 ft (15.2 m) of differential head and are capable of suction lifts of as much as 25 ft (7.6 m).

Chemical and Water Treatment Industries Another type of mechanically driven diaphragm pump is used for the injection or transfer of chemicals into process streams at pressures up to 250 lb/in^2 (17 bar). These pumps are designed to enable the easy adjustment of their capacities, so precise volumes of chemicals can be injected. Typically, capacities can be adjusted through a 20:1 range. Injection repeatability is generally plus or minus 3%.

A wide range of chemicals can be handled. Wetted materials include PVC, PVDF, Polypropylene, 316SS, Alloy 20, and Alloy C22. Diaphragms are PTFE or PTFE with elastomeric backing. Ball type check valves are usually employed.

Applications for this type of pump include the injection of acids and bases for pH control, biocides, chlorination, coagulants, and fertilizers. There are two basic configurations for pumps in this class: *electromagnetic pumps* (solenoid) and *motor-driven pumps*.

Electromagnetic (electronic) pumps (see Figure 3) are used in a variety of low-power applications with flows from 0.026 to 26 gallons per hour (0.1 to 100 liters per hour) at pressures up to 250 lb/in^2 (17 bar). These metering pumps employ an electronic control circuit that pulses an electromagnet that, in turn, generates the linear motion of an armature-shaft-diaphragm assembly. Each electronic pulse results in one discharge stroke of the pump. At the end of the stroke, a set of springs returns the diaphragm assembly to its initial position, drawing more fluid into the pump chamber in preparation for the next stroke.

These pumps are inherently safe, as they can be run indefinitely in the stalled condition without damage to the pump or overpressuring most systems. An additional feature of certain electronic pumps is the regulation of pulse strength through electronic power control, which leads to smoother fluid injection. Capacity is usually controlled by adjust-

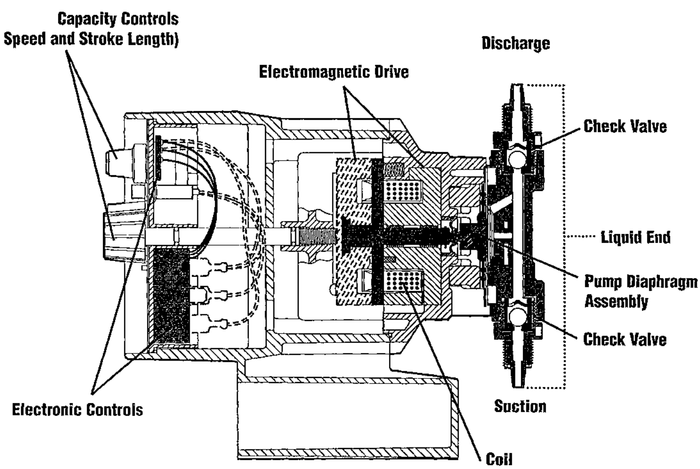

FIGURE 3 Electromagnetic diaphragm pump (Milton-Roy, subsidiary of Sundstrand Corp.)

ing the stroke rate, but the stroke length can also be adjusted. Combining these adjustments provides a wide range of outputs.

Advances in the electronic controls have led to the capability to control output manually from 4–20 mA process signals, digital pulses from external sources (such as flow meters), or serial data communications signals from computers. Yearly maintenance is recommended for low-pressure applications, but as pressures rise, diaphragms and check valves will need to be replaced more frequently.

Motor-driven, mechanically actuated diaphragm pumps are used in applications for flows from 2 to 300 gallons per hour (approximately 10 to 1000 liters per hour) again at pressures up to 250 lb/in^2 (17 bars). Since motor-driven, mechanically actuated diaphragm pumps are positive displacement pumps, capacities cannot be adjusted by the use of a throttling valve.

Three techniques are used in the industry to adjust motor-driven pump capacities. Some designs employ the use of a "mechanical lost motion" mechanism in which an adjustable mechanical stop interrupts the spring-loaded crosshead from following the cam for a portion of the stroke. This decreases the effective stroke length (see Figure 4). Other designs employ the use of an adjustable crank machined with a "variable eccentricity." The adjustment of the crank's position changes the pump's effective stroke length (see Figure 5). The third design technique is the use of AC or DC variable speed motors.

At higher flow rates, attention should be paid to the system design to ensure the proper handling of pressure pulsations, due to the acceleration and deceleration of the process fluid in the lines. This is especially true for pumps having a mechanical lost motion configuration, due to the diaphragm's rapid starts and stops. In the higher flow systems, pulsation dampeners are frequently employed in the discharge lines and occasionally need to be used in the suction lines to control pulsations. When discharge pressures are low, backpressure valves are employed to provide a system pressure sufficient to decelerate the fluid in the suction line at the end of every suction stroke. If the flow of the process fluid in the suction line has not stopped by the beginning of the discharge stroke, the accuracy of the injection is diminished. Yearly maintenance is recommended for low-pressure applications, but as pressures rise, diaphragms and check valves will need to be replaced more frequently.

Other Mechanically Driven Diaphragm Pumps Automotive fuel pumps are usually of the diaphragm type. The diaphragm is moved mechanically by a cam on a suction stroke

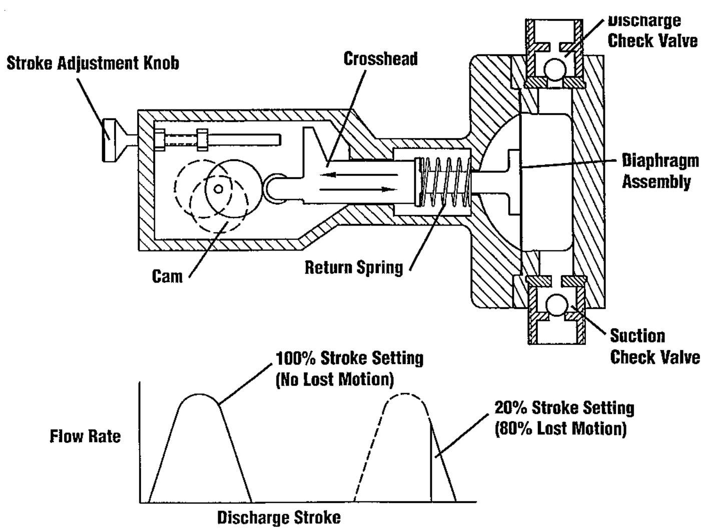

FIGURE 4 Diaphragm of a typical mechanical lost motion mechanism (Milton-Roy, subsidiary of Sundstrand Corp.)

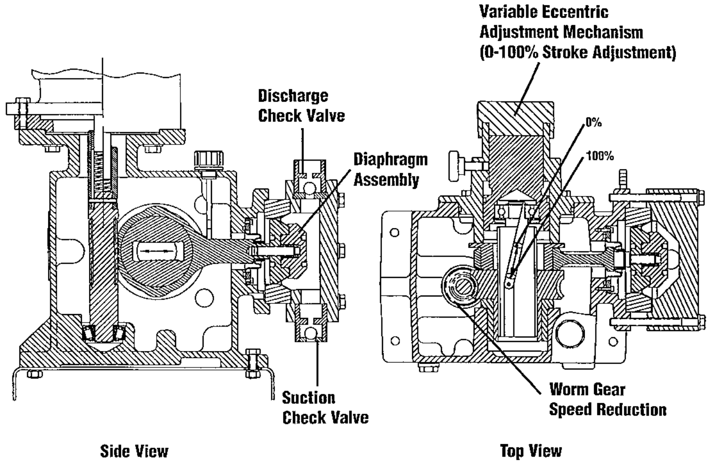

FIGURE 5 Cross-section of a variable eccentric mechanically driven diaphragm pump (Milton-Roy, subsidiary of Sundstrand Corp.)

and is returned by a spring for the discharge stroke. Thus, the spring determines the discharge pressure and provides a nearly constant pump pressure to the carburetor regardless of the pump (engine) speed or the rate of fuel consumption. Hand-operated diaphragm pumps are used extensively as bilge pumps on sailboats where the loss of power is a major concern and hand operation is essential.

HYDRAULICALLY DRIVEN DIAPHRAGM PUMPS

Hydraulically driven diaphragm pumps are used in applications for the transfer or injection of chemicals into process streams at pressures up to 7500 lb/in^2 (approximately 500 bar). Because the diaphragm is pressure-balanced, the stresses in the diaphragms are low. Therefore, these pumps tend to require minimal maintenance. The pump's capacities can be adjusted to match the specific process requirement by adjusting the effective stroke length or stroking speed of the pump. Effective stroke lengths are adjusted by either a hydraulic lost motion, a mechanical lost motion, or by varying the eccentric's offset. The repeatability of the injected flow is plus or minus 1% or better.

Applications range from 0.26 to 26,000 gallons per hour (1 to 100,000 liters per hour). At flows above 26 gallons per hour (100 liters per hour), most pump models employ capacity adjustments based on variable eccentric or variable speed technology to avoid significant pressure spikes due to the rapid acceleration and deceleration of the fluid in the pipes.

As with the mechanical diaphragm pumps, a wide range of chemicals can be handled. Wetted materials include PVC, Polypropylene, PVDF, 316 SS, Alloy 20, Alloy C-22, Titanium, and Inconel. Diaphragms for pressures up to 4350 lb/in^2 (300 bar) are typically composed of PTFE or PTFE with an elastomeric backing. Diaphragms above 4350 lb/in^2 (300 bar) are typically 316 SS, Alloy C, or PEEK. Optional features include fluid temperature control jackets, diaphragm rupture detection capabilities, and remote diaphragm head designs. Typical applications include the injection of acids and bases for pH control, corrosion inhibitors, methanol, coagulants, primary process blending, process slurries, and drag reducers. Three types of liquid ends are used: the disc diaphragm, shown in Figure 6, the tubular diaphragm in Figure 7, and the high performance diaphragm in Figure 8.

The disc diaphragm pump is equipped with process-side and suction-side restraining plates to prevent overdisplacement of the diaphragm during system upsets. When the

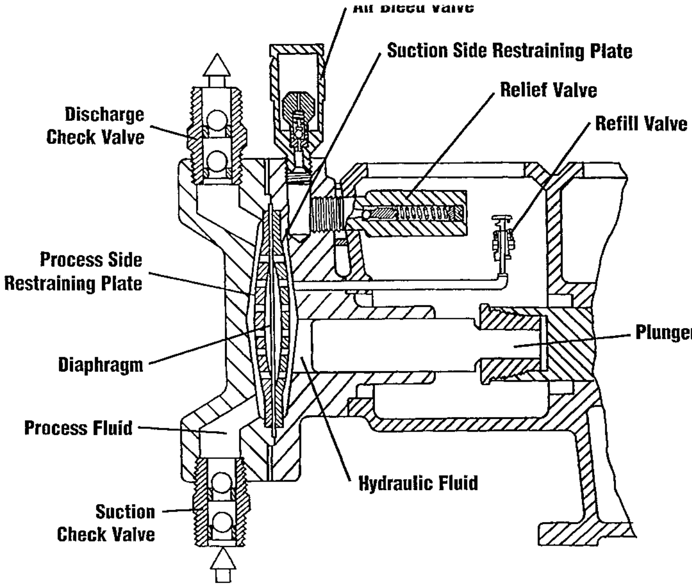

FIGURE 6 Diagram of a disc diaphragm pump (Milton-Roy, subsidiary of Sundstrand Corp.)

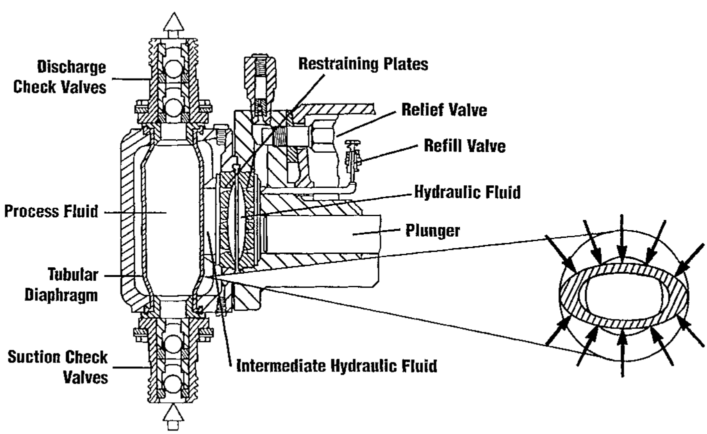

FIGURE 7 Diagram of a tubular diaphragm configuration (Milton-Roy, subsidiary of Sundstrand Corp.)

diaphragm reaches the suction-side restraining plate, the hydraulic oil pressure drops, causing the refill valve to open and replenish the oil. When the diaphragm hits the process-side restraining plate, the hydraulic pressure rises, causing the relief valve to open, venting some oil. The fluid volume between the restraining plates is typically 150% of the maximum displaced volume of the pump. Therefore, the diaphragm does not contact both restraining plates during the same stroke.

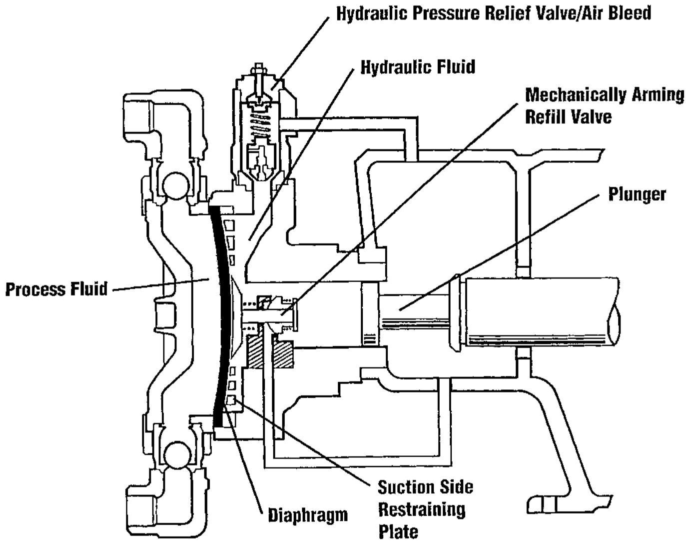

FIGURE 8 Diagram of a high performance diaphragm design (Milton-Roy, subsidiary of Sundstrand Corp.)

The tubular diaphragm configuration is a variation of the disc diaphragm design. A diaphragm shaped in the form of a tube is placed in a chamber in front of the disc diaphragm assembly. This design eliminates the process fluid flowing through the front-restraining plate, reducing viscous losses and wear in case of slurries. The chamber must be filled with a precise amount of hydraulic fluid to avoid overdisplacing the tube.

The high-performance diaphragm configuration eliminates the use of a process-side restraining plate providing the throughflow performance of a tubular design while eliminating the possibility of overdisplacing the tube during startup and maintenance. With a mechanically arming, pressure-sensitive refill valve, the hydraulic fluid can only be replenished when the diaphragm is in the most rearward position. This eliminates the possibility of overfilling the hydraulic chamber and therefore overdisplacing the diaphragm during system upsets (blocked suction or discharge lines).

Most problems with hydraulic diaphragm pumps occur due to incorrect system designs. Pressures above 9 lb/in^2 (0.6 bar) should be maintained in the pump diaphragm heads during the suction stroke to stop vapor buildups in the hydraulic or process-side cavities. Pressures at 3 lb/in^2 (0.2 bar) can be handled in some applications with modified designs and special hydraulic fluids. *NPSH* calculations should include viscous losses in the check valves and contour plates (if so equipped).

In addition, since hydraulic diaphragm pumps are reciprocating machines, acceleration losses also have to be considered. Peak acceleration/deceleration losses occur at the beginning and end of the stroke, while peak viscous losses occur at midstroke. The losses are not additive. The manufacturer should be contacted to provide guidance in performing these calculations.

As with mechanically driven diaphragm pumps, at higher flows, pulsation dampeners should be considered to ensure the proper handling of pressure pulsations due to the acceleration and deceleration of the process fluid in the lines. This is especially true for pumps having a mechanical lost motion configuration due to the diaphragm's rapid starts and stops. When discharge pressures are low, backpressure valves are employed to provide a system pressure sufficient to decelerate the fluid in the suction line at the end of every suction stroke. If the flow of the process fluid in the suction line has not stopped by the beginning of the discharge stroke, the accuracy of the injection is compromised.

AIR-OPERATED DIAPHRAGM PUMPS (AODPS)

In general, diaphragm pumps of all types are sealless, have no dynamic seals or packing, are self-priming, and have an infinitely variable flow rate and pressure rate within the pressure and capacity ranges of the pump. *Air-operated diaphragm pumps (*AODPs) can also run dry indefinitely, and the discharge can be throttled to zero flow indefinitely.

The most common types of AODPs are the double-diaphragm pumps (duplex pumps). These contain two diaphragm chambers and two flexible diaphragms. The diaphragms are connected to each other through a connecting rod and are clamped at the outer edges of the diaphragm. The shaft-connected diaphragms move in the same linear direction simultaneously. Compressed air directed to the back side of the left diaphragm moves both diaphragms to the left, while air is exhausted to the atmosphere from the back side of the right diaphragm. After completion of a stroke, an air distribution valve directs compressed air from the supply to the back side of the right diaphragm and exhausts air to the atmosphere from the left chamber. This continuous reciprocating motion, along with properly operating internal check valves, creates an alternating intake and discharge of pumped liquid into and out of each chamber that results in a nearly continuous pumping action from the combined chambers.

A diaphragm pump air motor contains an air distribution valve that shifts positions at the end of each stroke of the pump. The air distribution valve alternately directs supply air pressure to one chamber and exhausts the other. Air motors often use a two-stage valve to control the reciprocating motion of the pump (see Figure 11). The pilot valve supplies a pilot air pressure signal to the air distribution valve throughout the entire stroke of the pump, even though pressure oscillations in the pumping system may occur. The pilot valve is not connected directly to the diaphragm's connecting rod, which provides a "deadband" to prevent the power valve from erroneously shifting just after the end of each stoke. The two views contained in Figure 11 depict the position of the moving parts just before the pilot valve is moved by its contact with the diaphragm washer. Depending on its position, the pilot rod alternately pressurizes and exhausts the large end of the air distribution valve. Other valve design configurations pressurize and exhaust both ends of the air distribution valve.

The two common types of liquid check valves that are used in a diaphragm pump are the *flap valve* and the *ball valve*. A flap valve pump (see Figures 9 and 10) can handle nearly marble-sized solids. Because the discharge is from the bottom of the diaphragm chambers, the pump is ideally suited for pumping solids in suspension that may tend to settle out, particularly when the pumping rate is reduced or when the pump is shut down. The bottom outlet enables foreign matter to be easily pumped out of the chambers.

The popular air-operated, double-diaphragm pump with ball valves (see Figures 12 and 13) features the inlet at the bottom of the diaphragm chambers, and the outlet is at the top. The top discharge arrangement has the advantage of enabling air or vapors to be easily expelled from the chambers. Trapped air or vapors in pumps having bottom outlets can reduce the volumetric displacement of the pumps as the air or vapor is alternately compressed and expanded, instead of the liquid being displaced. This can be a concern in low-flow applications requiring relatively high pumping pressure and that handle viscous liquids. In higher flow applications, a sufficient turbulence is present and air or vapors mix with the pumped liquid to purge the pumping chambers of the gases.

The performance chart of a typical 2-in (51-mm) air-operated, double-diaphragm pump (see Figure 14) is similar to that of other pump types but contains air consumption rather than horsepower consumption. With a constant supply pressure of compressed air, work and energy relationships in the air chambers, as well as liquid flow losses within the pump, result in a downward sloping head-capacity curve, similar to a centrifugal pump. The following are noteworthy features of air-operated diaphragm pumps:

- With the pump shut off, there is no power consumption. Air consumption is approximately proportional to the flow rate; there is zero air consumption at a zero flow rate and maximum air consumption at a maximum flow rate. This feature enables diaphragm pumps to be used in applications where the flow rate must be varied over a wide range or from no flow to a high flow rate.

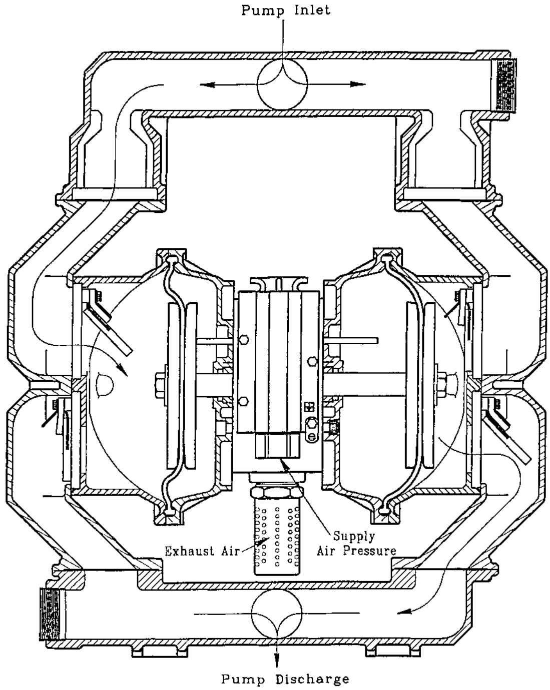

FIGURE 9 Cross-section of an air-operated double-diaphragm pump with flap check valves (Ingersoll-Rand Fluid Products)

- The pump discharge pressure remains the same for a given capacity and air inlet pressure regardless of the specific gravity of the liquid being pumped. The discharge head varies with the specific gravity of the pumped fluid, because pressure and not head is primarily maintained by the air pressure. For centrifugal pumps, the discharge pressure is directly proportional to the specific gravity of the liquid being pumped, while head is fixed at a given point on the performance curve. The supplied air pressure, pump flow rate, and *NPSH* set the discharge pressure for a given air operated pump, not the head, which is a characteristic of a centrifugal pump operated at a fixed speed.
- The *NPSH* required for an air-operated diaphragm pump is defined in the same manner as with any reciprocating pump. The *NPSH* required is determined to occur when the volumetric efficiency drops by a measurable amount (normally 3%) at a fixed speed or flow rate.

MATERIALS OF AIR-OPERATED DIAPHRAGM PUMPS

Check valves for diaphragm pumps are of three types: flap, ball, and poppet (see Figure 15). Flap valves preferably hang in a vertical position with a horizontal flow through the valves. Their principle advantage is the capability to handle large objects in suspension. Flap valves with elastomeric hinges are extensively used. Ball valves are arranged to provide a vertical flow through the valve seats. Poppet valves are usually guided by a valve stem and are spring-loaded. The poppet type of valve is not position-sensitive and can

FIGURE 10 ARO air-operated double-diaphragm pump with flap check valves (Ingersoll-Rand Fluid Products)

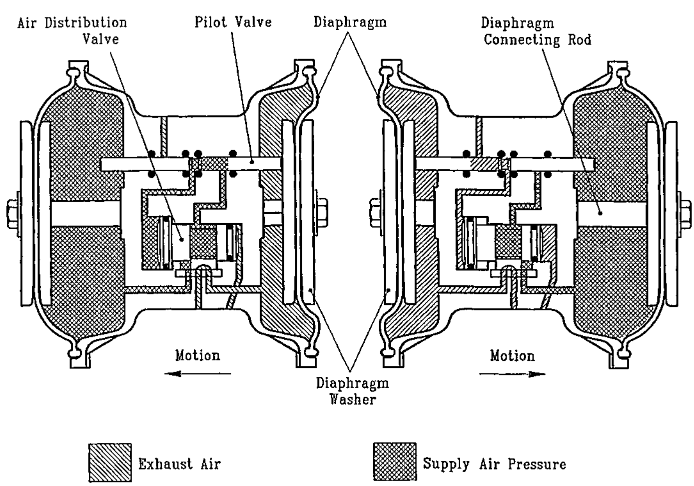

FIGURE 11 Cross-section of an air-operated double-diaphragm pump air motor operation (Ingersoll-Rand Fluid Products)

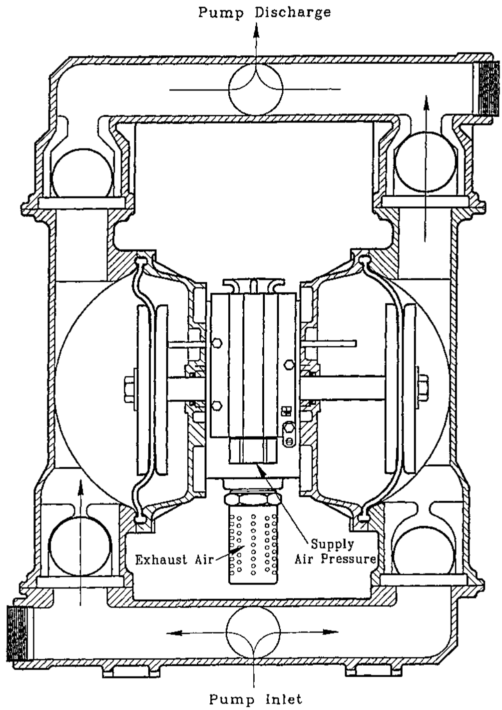

FIGURE 12 Cross-section of an air-operated double-diaphragm pump with ball check valves (Ingersoll-Rand Fluid Products)

operate in any orientation. Since many diaphragm pumps are used to pump abrasive slurries, the valves usually have elastomeric faces or are elastomeric balls. Large ball check valves may have metal cores covered by a thick wall of synthetic rubber. They may also be made of solid rubber, a thermoplastic elastomer, or Teflon®.

Diaphragms are customarily made of fabric-reinforced synthetic rubber, thermoplastic elastomers, or PTFE. Diaphragm materials include most of the synthetic rubbers: neoprene, Buna N, EPR, Viton®, thermoplastic elastomers such as Hytrel® and Santoprene® as well as Teflon®. Many combinations of pump and diaphragm materials can cover a wide range of pumped products. For some solvents and aggressive acids or alkalis, Teflon® diaphragms can be used either directly or as an overlay on the conventional diaphragm.

The diaphragms in air-operated, double-diaphragm pumps are essentially balanced and act simply as membranes separating the compressed air from the product being pumped. The only unbalance occurs during the suction stroke of one diaphragm while it is being pulled by the shaft-connected other diaphragm. When the suction lift is minimal, the unbalance may be negligible.

Pump case materials include cast iron, aluminum, stainless steel, Carpenter 20, Hastelloy C, and plastics reinforced with glass or metal fibers.

APPLICATIONS OF AIR-OPERATED DIAPHRAGM PUMPS

General Diaphragm pumps are ideally suited for handling abrasive slurries because 1) the liquid velocity through the check valves and pumping chambers does not exceed the

FIGURE 13 ARO air-operated double-diaphragm pump with ball check values (Ingersoll-Rand Fluid Products)

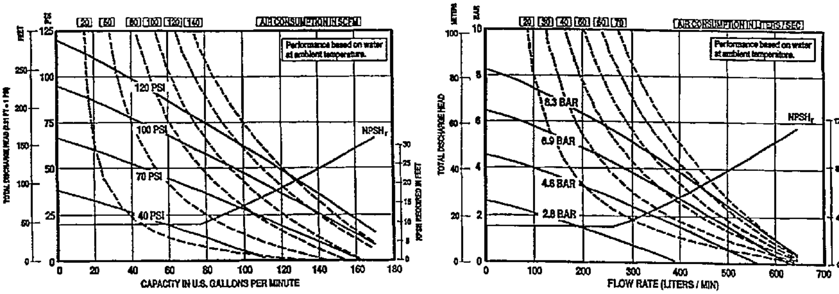

FIGURE 14 Performance curve for a 2-in air-operated double-diaphragm pump

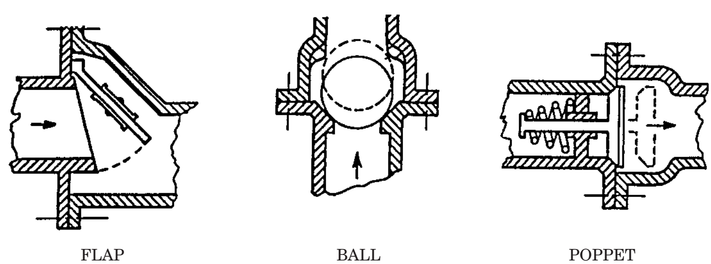

FIGURE 15 Three basic types of check valves

pipeline velocity and 2) the scouring and abrasions from the slurry are minimal. Because no close-fit sliding or rubbing parts exist and velocities are low, these pumps can be used for liquids with viscosities up to 50,000 SSU (11,000 cSt). Because the turbulence and mixing are minimal, they are ideally suited for shear-sensitive materials, such as latex.

Pumping Dry Powders Since diaphragm pumps can pump air as well as liquids, they are used successfully to pump dry powders. The air acts as a fluid medium for the powders in suspension, and the pump moves the air containing the suspended powder. Sometimes it is necessary to inject air into the powder to lower the apparent specific gravity and to get the powder into suspension.

Pump Controls An air pressure regulator in the compressed air supply line can control the pumping pressure. An air line valve can control the pumping rate. Thus, the pressure and capacity are easily controlled. Although air-operated diaphragm pumps are displacement pumps, they are not positive ones. The maximum pumping pressure cannot exceed the pressure of the compressed air powering the pumps. Table 1 describes the control of diaphragm pumps with the features inherent with each drive type.

Liquids Handled and Applications A variety of liquids can be handled by AODPs, yet the compatibility of pump case materials, valve materials, and diaphragms is the basic application limitation. Liquids and slurries handled by diaphragm pumps include ceramic slurry, paint, cement grout, chemicals, glue, resins, petroleum products, driller's mud, mill scale, ore concentrates, printer's ink, sewage, filter aids, latex, waste oils, wood preservatives, core washes, asphaltic coatings, bilge waste, radioactive waste, lapping compounds, porcelain frit, mine tailings, volatile solvents, coolants with metal fines, varnish, acids, coatings, soapstone slurries, explosives, lime slurries, yeast, chocolate, and wine. Typical applications of AODPs include tank and container loading and unloading, fluid filtration, spray painting, adhesive application, process mixing and batching, cutting oil, machine coolant, lubrication, sump pumping, dewatering, and waste water treatment.

LIMITATIONS AND ADVANTAGES OF AIR-OPERATED DIAPHRAGM PUMPS

This section outlines the pros and cons of AODPS. Table 1 also details the controls of the different types of pumps. The limitations of AODPs are as follows:

TABLE 1 Control of diaphragm pumps

Feature	Electro-Magnetically Driven	Mechanically Driven	Hydraulically Driven	Air-Operated
Can run dry:	Yes	Yes	Yes	Yes
Self-priming:	Yes	Yes	Yes	Yes
Discharge can be shutoff without damage:	Yes	No	Yes	Yes
Relief valve required:	No	Yes	Integral to pump	No
Flow controlled by:	Motor speed or stroke-length adjustment	Motor speed or stroke-length adjustment	Motor speed or stroke-length adjustment	Motor speed or discharge valve

- AODPs are not practical for pumping rates above about 300 gpm (1150 ℓ/m).
- AODPs are not manufactured for operating air pressures above 125 lb/in^2 gauge (8.6 bar). However, some versions are available that increase the pressure ratio by 2:1 or 3:1.
- Ice formation in air motors can occur (basic to the physics of operation), but the effect can be minimized by proper application and design.
- Diaphragms have a finite life. Fluids with abrasives and higher process temperatures can limit a diaphragm's life, but many material choices are available, including Teflon®, and several thermoplastic elastomers.

An AODP's advantages are as follows:

- They are self-priming from a dry start.
- The pumps have an infinitely variable flow rate and pressure-within-pressure and capacity ranges.
- AODPs have no dynamic seals or packing.
- They can run dry indefinitely.
- The discharge can be throttled to zero flow indefinitely.
- No air is used when the AODP is deadheaded. Electrically driven pumps will consume a significant portion of the rated power when no demand flow exists.
- AODPs are suited for use in hazardous environments (no electric power required).
- Power is used in proportion to the pumping rate.
- They can be used in confined areas without heat buildup.
- AODPs can pump abrasive slurries and solids in suspension.
- The pumps can handle viscous liquids up to 50,000 SSU (11,000 cSt).
- A minimal degradation of the viscosity of shear-sensitive materials occurs.
- They can pump dry powders in air suspension.
- No close-fit, sliding, or rotating parts come in contact with liquid.
- No bypass is required as in other displacement pumps.
- When properly maintained, there is zero leakage.
- They are simple to maintain and to repair.
- There is no bedplate and no coupling to align.
- AODPs can be used in handling aggressive chemical solutions.
- They can handle a wider range of materials than any other type of pump.