chapter 4

Pumps

OBJECTIVES

After studying this chapter, the student will be able to:

- Review the history and design of pumps.
- Describe the scientific principles associated with centrifugal pump operation and identify key components.
- Describe the operation and maintenance of positive displacement pumps.
- List the various types of rotary pumps.
- Describe the basic components and operation of screw pumps.
- Explain how rotary gear pumps operate.
- Describe the basic components and operation of sliding and flexible vane pumps.
- Describe the basic components of a lobe pump.
- List the various types of reciprocating pumps.
- Explain the operation of diaphragm pumps.
- Describe the operation and design of piston pumps.
- Describe the scientific principles associated with the operation of plunger pumps.
- Start up and shut down a positive displacement pump.
- Start up and shut down a centrifugal pump.
- Troubleshoot typical problems associated with the operation of centrifugal and reciprocating pumps.

Key Terms

Acceleration head—the fluctuations of suction pressure created by the intake stroke of a reciprocating pump.

Axial pump—a dynamic pump that accelerates fluid in a straight line.

Cavitation—the formation and collapse of gas pockets around the impellers during pump operation; results from insufficient suction head (or height) at the inlet to the pump.

Centrifugal pump—a dynamic pump that accelerates fluid in a circular motion.

Diaphragm pump—a reciprocating pump that uses a flexible diaphragm to positively displace fluids.

Discharge head—the resistance or pressure on the outlet side of a pump.

Dynamic—class of equipment such as pumps and compressors that convert kinetic energy to pressure; can be axial or centrifugal.

Head—is described as Pressure (at suction) × 2.31 ÷ Specific gravity; 1 psi is equal to 2.31 feet of head.

Impeller—a device attached to the shaft of a centrifugal pump that imparts velocity and pressure to a liquid.

Lobe pump—a rotary pump that uses kidney-bean-shaped lobes to displace and transfer fluid.

Mechanical seal—provides a leak-tight seal on a pump; consists of one stationary sealing element, usually made of carbon, and one that rotates with the shaft.

Net positive suction head (NPSH)—the head (pressure) in feet of liquid necessary to push the required amount of liquid into the impeller of a dynamic pump without causing cavitation.

Net positive suction head available (NPSHa)—a term used to indicate the required pump suction pressure so the pump can operate properly. It is defined as atmospheric pressure (converted to head) 1 static head 1 surface pressure head 2 vapor pressure 2 frictional losses.

Net positive suction head required (NPSHr)—the minimum NPSH necessary to avoid cavitation. The NPSHa must be greater than or equal to the NPSHr, expressed as NPSHa ≥ NPSHr. It is the reduction in total head as the liquid enters the pump.

Piston pump—a reciprocating pump that uses a piston and cylinder to move fluids.

Positive displacement—class of equipment such as pumps and compressors that move specific amounts of fluid from one place to another; can be rotary or reciprocating.

Pressure relief valve—used to relieve excessive pressure on the discharge of a positive displacement pump.

Priming—becoming filled with fluid.

Pulsation dampener—a device installed close to a pump, in the suction or discharge line, to reduce pressure variations.

Reciprocating pump—a positive displacement pump that uses a plunger, piston, or diaphragm moving in a back-and-forth motion to physically displace a specific amount of fluid in a chamber.

Rotary pump—a positive displacement pump that uses rotating elements to move fluids.

Screw pump—a rotary pump that displaces fluid with a screw.

Slip—the percentage of fluid that leaks or slips past the internal clearances of a pump over a given time.

Specific gravity—is described as the ratio between the density of a given liquid to the known density of water, or the density of gases to the density of air. The specific gravity of water or air is one.

Vane pump—a rotary pump that uses flexible or rigid vanes to displace fluids.

Vapor lock—condition in which a pump loses liquid prime and the impellers rotate in vapor.

Pump Applications and Classification

Refineries and chemical plants use pumps to move liquids. Pumps are used in a variety of applications and processes, including refrigeration, automobiles, home heating systems, and water wells. The liquids moved by a pump vary from liquid sodium and liquid potassium for cooling nuclear reactors to domestic drinking water systems. In some situations, pumps are not needed to transfer liquid. In Figure 4.1, gravity transfers the liquid into tank 4.02B. In Figure 4.2, a pump is needed to move the liquid.

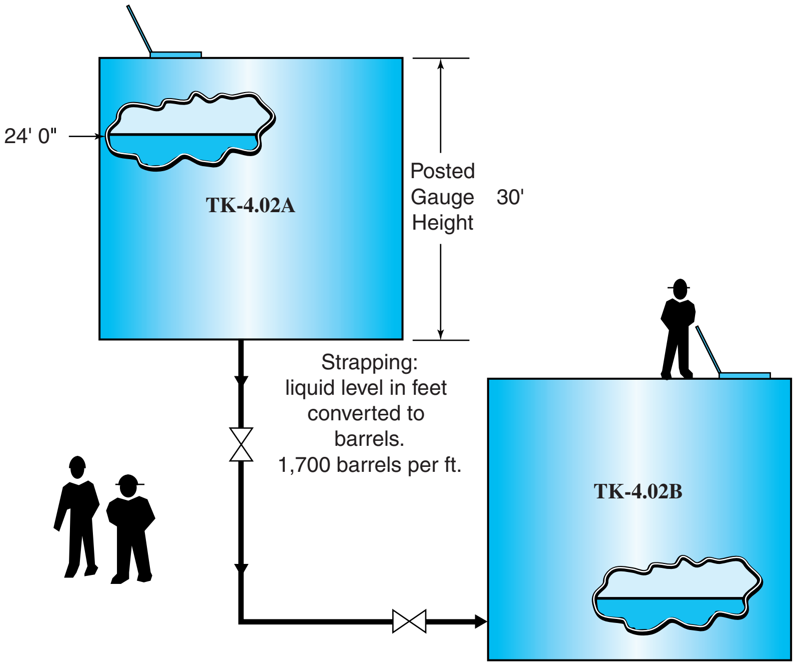
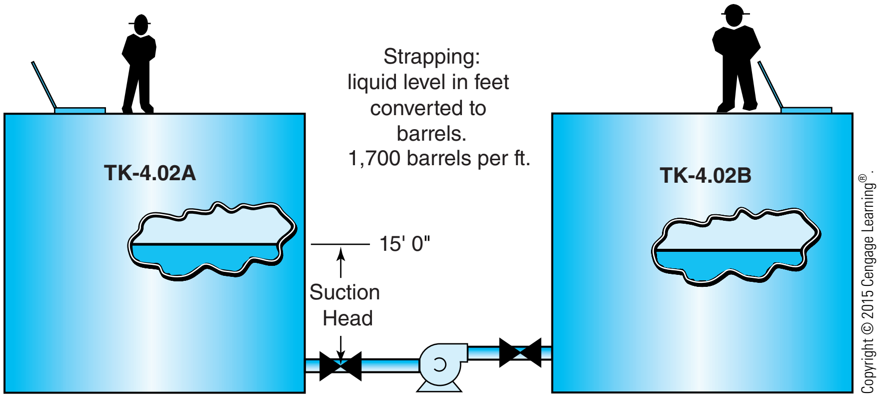


Figure 4.1
Gravity Flow

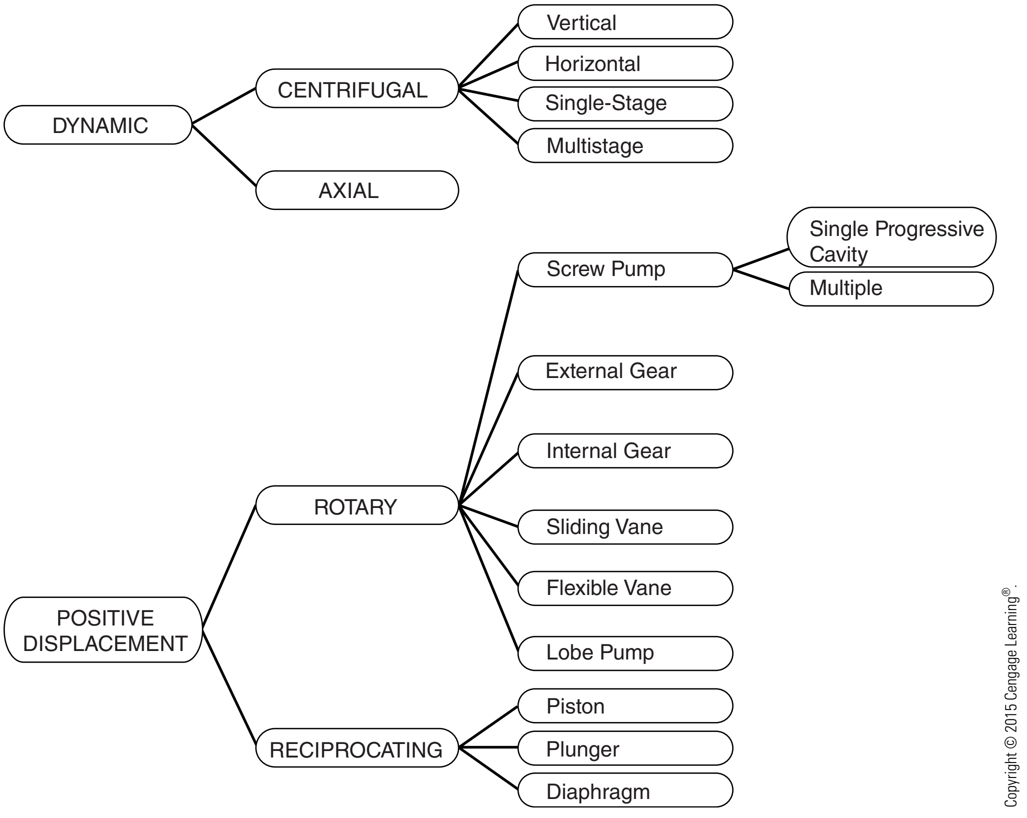
Figure 4.2
Pump Transfer



In general, pumps can be classified as **dynamic** or **positive displacement** (Figure 4.3). Both classes are designed to transfer liquids, but the way the transfer is accomplished is different.

Dynamic pumps accelerate liquids axially (in a straight line) or centrifugally (in circles). They are operated at high speeds to generate large flow rates at low discharge pressures. Pressure moves the liquid through the piping and equipment system.

Figure 4.3
Pump Family Tree



Positive displacement (PD) pumps transfer liquids by using a rotary or reciprocating motion that displaces liquid on each rotation or stroke. They are used in processes that require specific amounts of fluid to be delivered. The operation of positive displacement pumps is significantly different from that of dynamic pumps. Positive displacement pumps transfer specific amounts of fluid no matter what the discharge pressure is, whereas the amount of fluid transferred by dynamic pumps is greatly affected by discharge pressure. **Rotary pumps** deliver a specific amount of fluid with each rotation of screws, gears, vanes, or similar elements. **Reciprocating pumps** move fluids by drawing them into a chamber on the intake stroke and pushing them out of the chamber with a piston, diaphragm, or plunger on the discharge stroke.

The first reciprocating pump, invented by a Greek, Ctesibius, in about 200 BCE, was used to pump water. Around this same time, Archimedes, a Greek mathematician, invented the first screw (rotary) pump. The first true **centrifugal pumps** were not invented until the 1600s by the French inventor Denis Papin. Papin's straight-vane centrifugal pump design was improved in 1851, when a British inventor, John Appold, designed a curved-**vane pump**.

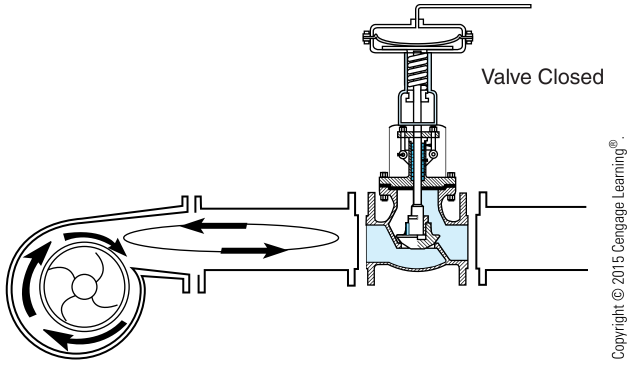
Internal Slip

Slip is defined as the percentage of fluid that leaks or slips past the internal clearances of a pump over a given time. Slip also can be defined as the difference between how much liquid a pump can move and how much it actually does move.

Because of differences in design, positive-displacement pumps and centrifugal pumps respond differently to slip. A centrifugal pump can have as much as 100% slip if the discharge valve is closed. This principle can be illustrated by following the path of liquid as it enters a centrifugal pump with an open discharge valve. As fluid moves from the suction inlet into the **impeller**, flow is accelerated into a discharge chute known as a *volute*. The volute is a specially designed chamber that widens within the pump. Shutting the discharge valve stops flow to the process unit, but circulation within the pump continues. As the impeller turns, fluid is accelerated into the large volute discharge. Circular motion (clockwise) is sustained in the volute and discharge pipe up to the discharge valve (Figure 4.4). Fluid friction within this area begins to heat up the liquid. Operators should keep this principle in mind if the liquid being pumped is close to its boiling point. When the liquid vaporizes, it expands and gets hot; this process can create tremendous pressure that will damage the pump.

Positive-displacement (PD) pumps are designed to have minimal slip characteristics. There are physical laws that state that two separate bodies

Figure 4.4
Internal Slip



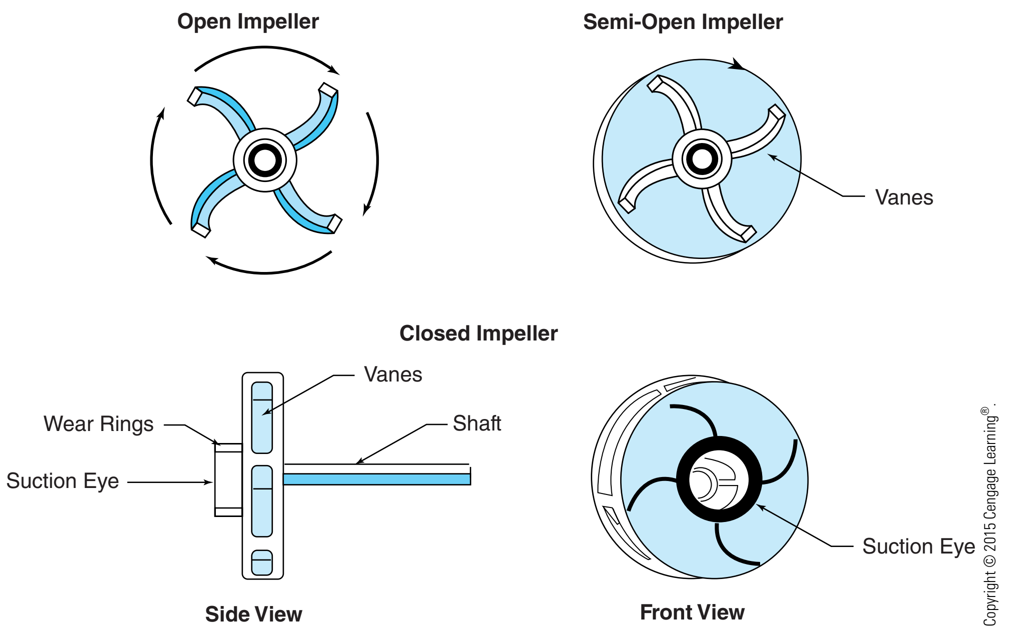
cannot occupy the same space at the same time. Positive-displacement pumps are designed to displace exact fluid volumes with solid objects, such as pistons or gears. When the discharge valve is closed on a PD pump, the following conditions exist:

- Very little (if any) slip is occurring within the body of the pump.
- Fluid pressure increases with every stroke.
- Fluid pressure is transferred equally to all isolated parts.
- The pump or discharge pipe can be damaged if a relief valve is not provided.

Dynamic Pumps

Dynamic pumps are classified as centrifugal or axial. Centrifugal pumps operate on the principle of centrifugal force. A spinning impeller inside a shell casing propels liquid outward. Fluid velocity is accelerated inside the shell of the pumps and liquid quickly moves toward the discharge port. Figure 4.5 illustrates the different types of impeller arrangements in a centrifugal pump.

Figure 4.5
Impeller Arrangements



The **axial pump** utilizes a similar spinning motion to propel liquid, but the liquid moves in a straight line. This motion is directionally different from the centrifugal pump's outward movement.

Centrifugal Pumps

Centrifugal pumps are used widely in chemical processing plants and refineries. The primary principle used by centrifugal pumps is centrifugal force. As liquid enters the suction eye of a centrifugal pump, it encounters the spinning impeller (Figure 4.6). The liquid is propelled in a circular rotation that forces it outward and into the volute. Centrifugal force and volute design convert velocity energy to pressure. As the liquid leaves the volute, it slows down, building pressure. Diffuser plates also can be added to the impeller and volute area to slow down or change the velocity of the liquid.

Basic Components

The basic components of a centrifugal pump are shown in Figure 4.6. The outer casing is designed to enhance fluid flow. It contains the fluid, forms a volute, and holds external and internal parts together. Typically, it comes in two parts separated by a gasket and bolted together. An axially split casing is split parallel to the pump shaft. A radially split casing is split perpendicular to the pump shaft. A drain on the bottom of the casing allows liquid to be drained from the pump. The volute is a gradually widening cavity inside the casing of a pump. The inlet is sometimes referred to as the *suction eye*. Fluid comes into the center of the impeller and is spun toward the outside of the volute. The inlet line is designed to run when primed (full of liquid). The outlet line receives the discharge from the pump volute. Because the discharge line is wider than the inlet volute, fluid velocity slows,

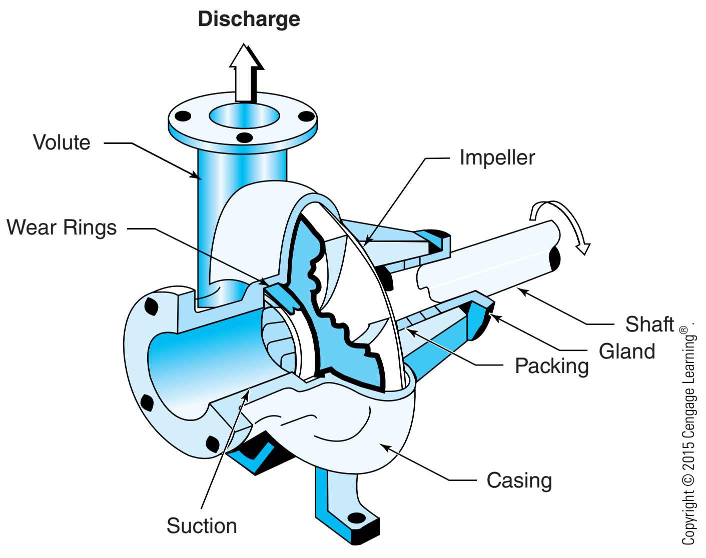


Figure 4.6 *Centrifugal Pump Components*

creating pressure. The impeller is a circular device attached to the shaft. The impeller resembles a wheel of curved blades that rotates around the shaft, spinning liquid from the eye (center of the pump) to the outer casing of the pump. This liquid enters the tapered neck of the volute before exiting the pump into the discharge line. The driver is an electric motor (fixed speed or variable speed) or a steam turbine. A manufacturer's nameplate lists the important information specific to the motor: phase, horsepower, manufacturer, and type. Radial bearings along the shaft minimize side-to-side movement. Thrust bearings eliminate axial movement along the shaft. Between the bearings and seals, a loose-fitting flinger ring mounted on the shaft conveys lubricant onto the bearings. The ring rotates on the shaft but at a lower speed. **Mechanical seals** installed where the rotating shaft enters the casing minimize or stop leakage from the internal components of the pump. Mechanical seals are composed of a stationary face and rotating face that fit closely. Seal faces may require lubrication or cooling. They require very low maintenance, have a reasonably long life, and have very little product leakage.

The stuffing box and packing gland hold packing firmly against the shaft and casing. A slight bit of internal leakage keeps the packing lubricated and cool. The packing material, located between the casing and the shaft, consists of rings composed of flexible material coated in graphite or Teflon®. The packing needs to be replaced frequently. Wear rings minimize leakage between the internal discharge and suction of the pump. Because the rotating impeller does not come into contact with the stationary casing, a void exists between the suction and discharge areas. Properly positioned wear rings minimize this leakage. If the wear rings are mounted on the pump's impeller, they turn with the impeller and are referred to as *impeller wear rings*. If the wear rings are mounted to the casing, they are stationary and are referred to as *casing wear rings*.

Pump Design

Centrifugal pumps come in a variety of designs and applications: vertical or horizontal (refers to shaft position); single stage or multiple stage (refers to the number of impellers); single or multiple suction inlets; volute or diffuser; axial flow, radial flow, or mixed flow; and open, semi-open, or closed impeller design.

Horizontal pumps are the most common type found in industry; however, vertical pumps are more compact, winterize better, and have a lower installation cost. Vertical pumps work well with liquids that are near their bubble point temperature. The lower impeller usually is located below ground level, which provides additional **net positive suction head available (NPSHa)**. The terms horizontal and vertical refer to the position the shaft occupies in relation to the ground (Figures 4.7 and 4.8). This direction indicates how impellers rest in the device. Another term used in the operation of a centrifugal pump is **net positive suction head required (NPSHr)**.

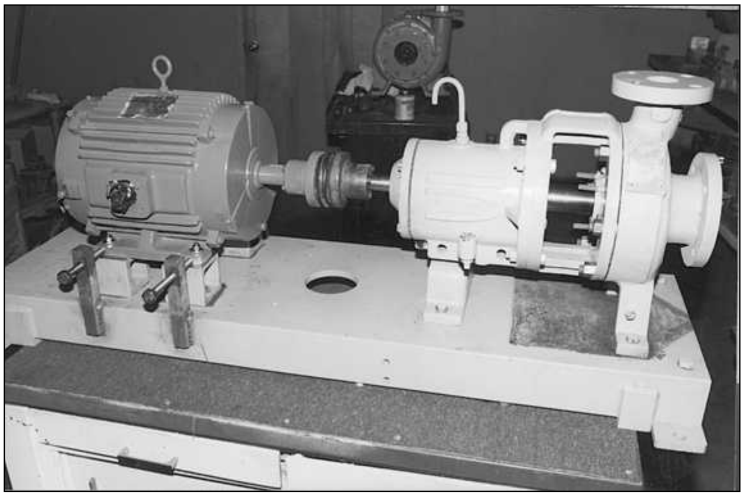


Figure 4.7
Horizontal Centrifugal Pump

Net positive suction head required is the minimum NPSH necessary to avoid cavitation. The NPSHa must be greater than or equal to the NPSHr, expressed as NPSHa $ NPSHr. It is the reduction in total head as the liquid enters the pump.

Most centrifugal pumps have a single suction inlet. In applications where the pumping volume is very high or source parameters vary significantly from destination parameters, pumps that have more than one suction inlet are used. In applications where the difference is minimal, single suction inlet pumps are used.

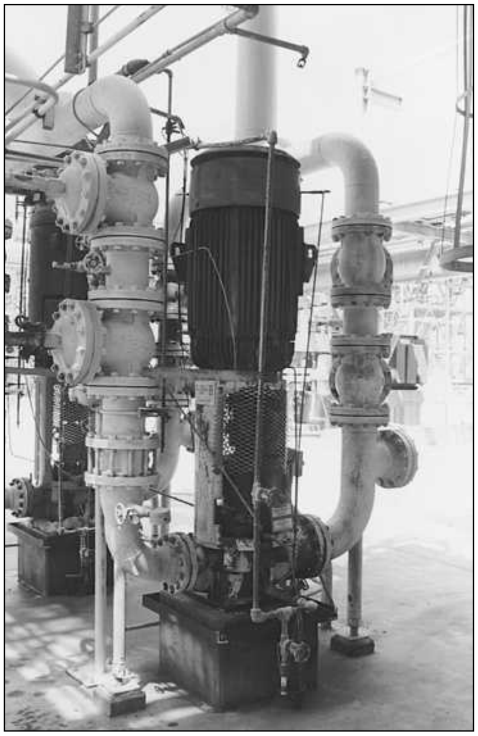


Figure 4.8
Vertical Centrifugal Pump

Impeller Design

The simplest type of centrifugal pump, a single-stage pump, has only one impeller. Multistage pumps have more than one. The impeller design comes in three basic types (see Figure 4.5). On the open impeller, vanes are connected only to the shaft. The open impeller is self-cleaning but does not have the structural support of a semi-open or closed impeller and is less efficient at producing pressure. On the semi-open impeller, the vanes are horizontally attached to a plate for structural support. On the closed impeller, the vanes are sandwiched between two plates, or shrouds. This is the strongest and most efficient design, but it is designed for use with clear liquids only. It is the most common type of impeller in industry.

Advantages and Disadvantages

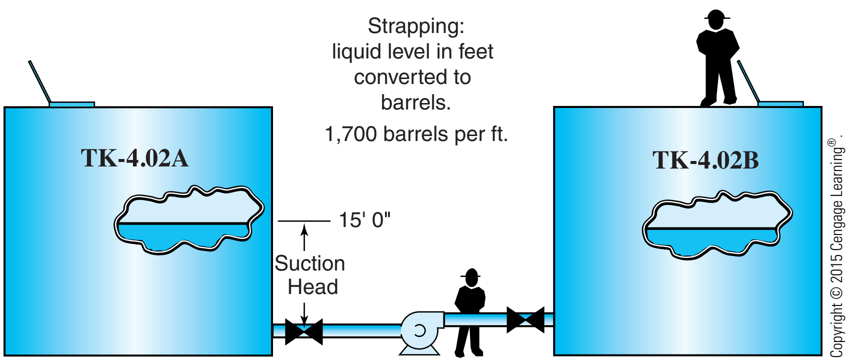
The chemical process industry typically uses centrifugal pumps that operate between 1,200 and 8,000 RPM. In modern manufacturing, centrifugal pumps are used more than positive-displacement pumps because they are cheaper and require less maintenance and space. Another attractive feature of centrifugal pumps is that they will operate with a constant head pressure over a wide capacity range. In addition, it is easier to change the element (impeller versus piston) on a centrifugal pump than on a positive-displacement pump, and it is easier to change the driver. A final advantage is the adaptability of the selected driver—variable horsepower and fixed or variable speed.

Centrifugal pumps do have some disadvantages. They are not self-**priming** and respond poorly to viscous materials or variations in suction pressures. Figure 4.9 illustrates how a centrifugal pump transfers liquid from one vessel to another.

Head (Pressure)

In a centrifugal pump, fluids must be pushed (not sucked or pulled) into the impellers. Suction **head** is a term used to describe the pressure required to force liquid into a pump. Most processes are designed so that the suction pressure is sufficient to run the pump without **cavitation** (the formation and collapse of gas pockets around the impellers). A centrifugal pump must be primed (full of liquid, or liquid full) before the pump can be started. During operation, a centrifugal pump will artificially create a low-pressure area in

Figure 4.9
Fluid Transfer



the suction eye. If the suction pressure is not carefully controlled, the low pressure could cause the liquid to boil. Boiling creates the condition called *cavitation*. Net positive suction head (NPSH) usually is calculated in feet of liquid. For example, if a pump took suction off the bottom of a 20-foot open tank with a liquid level of 10 feet, the static head would be 10 feet. This same principle can be applied to the **discharge head** on a pump. If the tank is closed, the vapor pressure of the liquid must be taken into consideration. Vapor pressure is closely related to the boiling point of a liquid. Heat affects vapor pressure by increasing molecular activity. NPSH is the minimum rating at which a centrifugal pump operates. Another problem associated with centrifugal pump operation is vapor lock. **Vapor lock** is a condition in which a pump loses liquid prime and the impellers rotate in vapor. Bled valves are located on the pump to remove air from the system. The pump must be shut down and air bled out before it will operate properly.

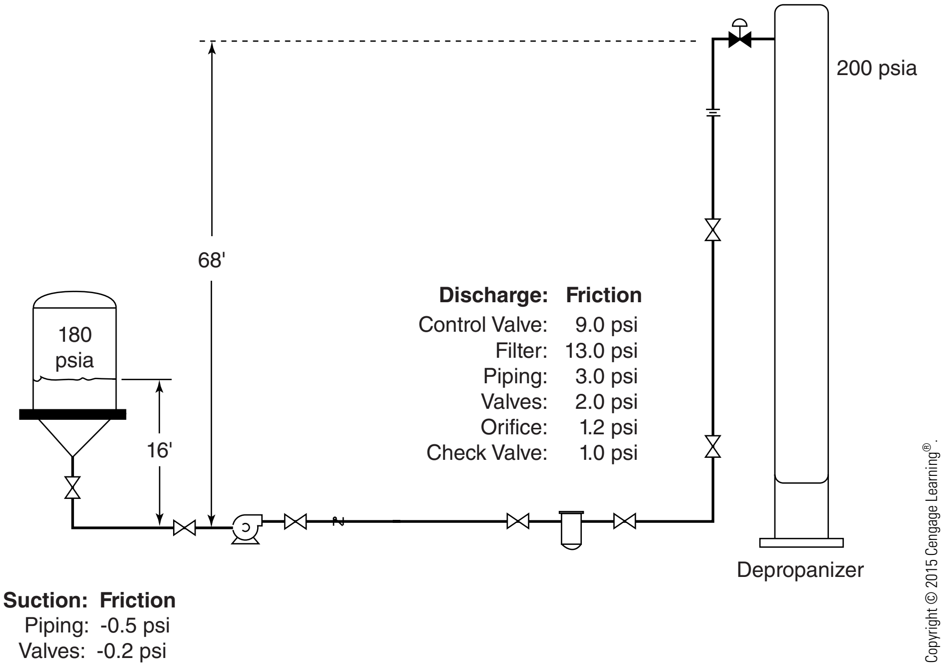
Factors that affect suction head pressure are temperature, viscosity (a fluid's resistance to flow), level of liquid in the suction system, restriction in the suction line, and flow rate through the line. Solutions to insufficient NPSH are smaller horsepower, lower speed, lower NPSH requirements, larger-diameter suction line, greater feed tank level or pressure, and cooler feed.

Determining Differential Head

A centrifugal pump requires a certain amount of back-pressure (differential head) in order to operate efficiently. The following exercise should illustrate the relationship between NPSH and the required differential head. It will also illustrate how piping changes and equipment modifications will affect the operation of a pump. A centrifugal pump should be viewed as having a set of conditions on the suction side and a wide array of variables on the discharge side. In the following depropanizer example, liquid propane is pumped from the reflux drum to the depropanizer column (Figure 4.10). On the suction side of the pump, a liquid level of 16 feet plus an operating pressure of 180 psia exists on the suction eye of the pump. The discharge of the pump is lined up through a series of gate valves, a check valve, a filter, an orifice, and a control valve. The discharge line contains a liquid leg of propane, 68 feet high. The depropanizer column operates at a pressure of 200 psia at a temperature of 90°F (32°C). The flow rates are 300 gallons per minute (GPM) normal and 340 GPM maximum. The required differential pressure of 318.7 psi takes into consideration all of the variables associated with the operation of the pump. Under these conditions, the centrifugal pump will operate efficiently. Pressure changes on the suction or discharge side of the pump will affect unit operation.

Pressure is defined as force or weight per unit area: Force (in pounds) ÷ Area (in square inches) = Pressure (in pounds per square inch). Atmospheric pressure is produced by the weight of the atmosphere as it presses down on an object resting on the surface of the earth. Pressure is directly proportional to height: the higher the atmosphere, gas, or liquid, the greater the pressure. At sea level, atmospheric pressure equals 14.7 psi. Pressure

Figure 4.10
Centrifugal Pump System



calculations are easily performed using common standards. The primary standard for liquid calculations is water. For example, the weight of water can be used to determine the **specific gravity** of a liquid. Specific gravity is the ratio of the density of a solid or a liquid to the density of water or the ratio of the density of a gas to the density of air. Density is weight per unit volume. To calculate the pressure produced by 1 ft.^{3} of water, we need to use the equation Pressure = Force ÷ Area. One cubic foot of water weighs 62.4 pounds. The surface area of 1 ft.^{3} is 12 in. × 12 in. = 144 in. For water, 62.4 ÷ 144 = 0.433 psi. For each additional foot of water, an additional 0.433 psi can be added. Expressed another way, psi × 2.31 = Head (ft.), or Head (ft.) ÷ 2.31 = psi. A common equation for determining pressure is:

$$\text{Height} \times 0.433 \times \text{Specific gravity} = \text{Pressure}$$

To calculate the required differential head (h), we need to know the specific gravity of propane: specific gravity of propane = 0.485. The unknown factor is ΔP (differential pressure). To solve for ΔP, we must pay close attention to the variables that contribute to pressure changes in a process system.

$$\text{Head } (h) = \frac{(\Delta P)(2.31)}{\text{specific gravity (s.g.)}}$$

The absolute suction pressure factors that are involved are:

Reflux drum	180.00 psia
Elevation (16 ft.)	3.36 psi (16 ft. × 0.433 × 0.485)
Friction: piping	−0.50 psi
valves	−0.20 psi
	182.66 psia − 14.7 = 167.96 psig

The absolute discharge pressure factors are:

Depropanizer tower	200.00 psia
Elevation (68 ft.)	14.29 psi (68 ft. × 0.433 × 0.485)
Friction: piping	3.00 psi
Valves	2.00 psi
Control Valve	9.00 psi
Check Valve	1.00 psi
Orifice	1.20 psi
Filter	13.00 psi
	243.49 psia − 14.7 = 228.79 psig

Now we can solve for (ΔP = 228.79 psig − 167.96 psig = 60.83 psig) and plug that value into our equation for head.

$$h = \frac{(\Delta P)(2.31)}{\text{s.g.}}$$

$$h = \frac{(60.83)(2.31)}{0.485}$$

Multiply in a standard safety factor of 1.1:

289.73 × 1.1 = 318.7 ft.

The required differential head is 318.7 feet.

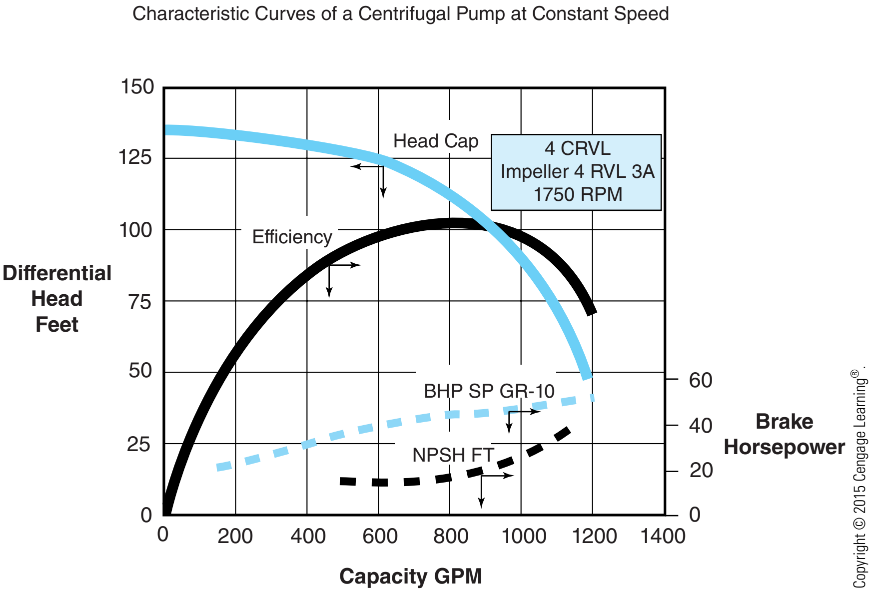
Total Head

Look again at Figure 4.2. The fluid in TK-4.02A appears to be at the same level as the fluid in TK-4.02B. The pump inlet and discharge are full, and the pump has been bled down and is liquid full. With both the suction and discharge valves open (indicated by the bow tie-shaped symbols), fluid levels equalize in the tanks. A pump is needed to transfer additional liquid into TK-4.02B. As the level increases in TK-4.02B, the discharge head (pressure in the discharge line) increases proportionally to the liquid level in the tank. Total head is equal to the discharge head minus the suction head. Operators should be aware that a centrifugal pump stops moving liquid if the discharge pressure gets too high. As discharge pressure increases, the liquid velocity slows down and even stops, and centrifugal force decreases, perhaps reaching zero.

Pump Curves

Centrifugal pumps are designed to work in specific services at specific rates. The best operating condition for a pump usually is indicated on the pump's efficiency curve. The efficiency curve includes several values: flow rate (in GPM), total head in feet (discharge head minus suction head; sometimes called differential head), pump efficiency, required pump horsepower, and pump NPSH.

Figure 4.11
Pump Curve



Because pumps are not always operating under their optimal conditions, they are designed to work across a range of rates and liquid properties. The operating parameters (driver horsepower, impeller size, liquid properties, pump efficiency, pump capacity and head, NPSH requirements, and so on) are all shown on a graph known as the pump curve (Figure 4.11). When there is a problem with a pump's performance or a change in the service, the pump curve is one of the first documents consulted. Manufacturers typically include pump curves with their products so that engineers and operators can refer to them before changing or redesigning a pump system. If the pump is operated at higher rates, efficiency decreases and the pump could be damaged.

Cavitation

Cavitation occurs when suction pressure drops below NPSH. At this point, the liquid vaporizes and forms gas pockets inside the pump casing. As these pockets form and collapse, the pump can be severely damaged. Operators easily can identify a pump that is cavitating. The sound of a cavitating pump closely resembles the noise you would hear if steel ball bearings were dumped into a pump's suction line. The operator also can expect to see rapid swings on the discharge pressure. Cavitation sends slugs of liquid and vapor through the pump. Each slug has an impact on the internal components of the pump. Serious damage will occur if this problem is not resolved quickly.

Affinity Laws

Relationships, called *affinity laws*, exist among a centrifugal pump's speed, capacity, head, and power. The capacity of a centrifugal pump is linked directly to its speed, or RPM. Total head is proportional to the square of the speed. Consumed power is proportional to the cube of the speed.

Pump Selection Chart

Modern industrial manufacturers use a pump selection chart when they are engineering a new process. The chart is set up with a horizontal axis that identifies capacity (in GPM) and two vertical axes that identify head (in feet of liquid) on the left and pressure (in pounds per square inch) on the right.

Construction Materials

Centrifugal pumps typically are manufactured with cast iron internal components and cast steel external cases. They can be made of most alloys as needed to cope with the nature of the liquid being pumped.

Factors That Affect Suction and Discharge

Operators need to be aware of the number of process variables that exist inside a system, including upstream and downstream vessels, valves, filters, piping, discharge head, and suction head. Each of these factors affects how efficiently a pump will operate. Figure 4.12 illustrates a tank-to-ship transfer.

Single- and Multistage Pumps

The terms single-stage and multistage are used to refer to the number of impellers a centrifugal pump uses. As flow enters a multistage pump, it enters the suction eye of the first-stage impeller. As the spinning impeller accelerates the fluid, it graduates into the suction of the next stage, where it is accelerated even more. At each stage, the pressure and fluid flow increase until the fluid reaches the discharge chamber.

When a designer builds a multistage pump, the concept of thrust must be considered. The suction side of an impeller exerts a small force on the shaft. The discharge of the impeller exerts a significant amount of thrust on the rotor. Collectively, the sum of the forces along the shaft is tremendous

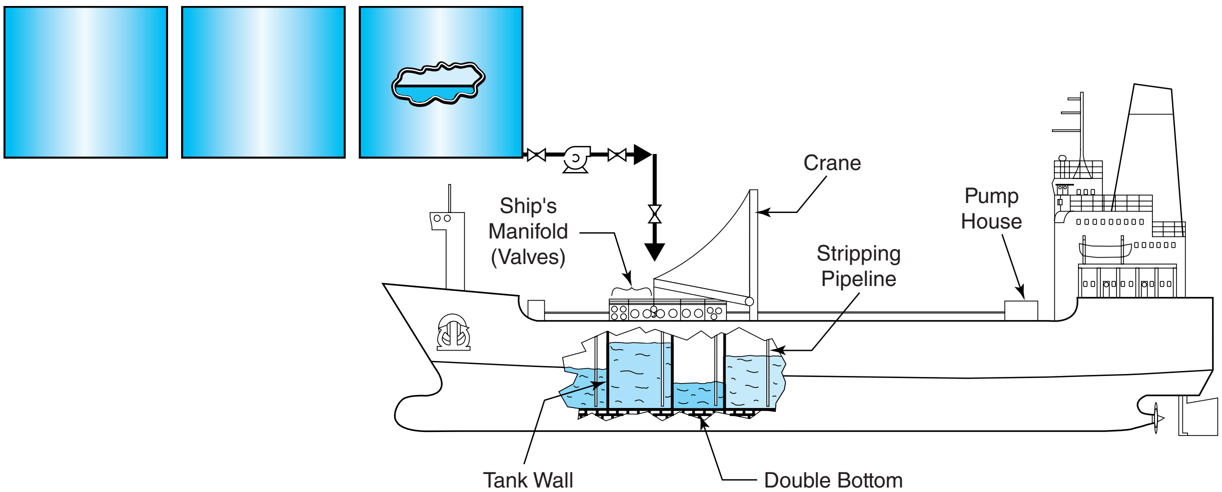


Figure 4.12 *Tank-to-Ship Transfer*

in a multistage pump. There are two ways to minimize thrust. One way is to use a balance device, a hydraulic system that connects the pump suction to the discharge end of the pump. The system is composed of a discharge side balancing drum, a balance line, and a low-pressure reservoir behind the drum. Another way is to align the impellers in opposite directions. Opposite alignment maintains even thrust along the shaft.

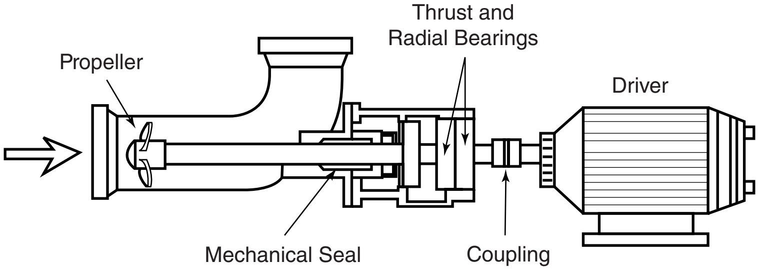
Multistage pumps must never be operated with the discharge valve closed. Usually, a minimum-flow system is designed into the piping so that there is always sufficient flow through the stages to protect them from damage.

Axial Pumps

Another way to accelerate and transfer fluid is to push it axially, or in a straight line. Axial pumps (Figure 4.13) are designed to provide this special feature. A common example of this principle is a boat motor. The motor turns a set of blades, forcing water to accelerate along a straight line. An axial pump operates using this same principle. Most axial pumps are located in an elbow on a piping run. The driveshaft extends through the elbow and into the process flow. A propeller is located on the process end of the driveshaft. The propeller is sized to fit the inside diameter of the pipe. The blading is engineered to pull fluid axially down the shaft. A mechanical seal prevents leakage where the shaft penetrates the pipe elbow. A specially designed thrust bearing prevents axial movement of the shaft. Heavy-duty radial bearings support the pump shaft and prevent radial movement. Some axial pumps have thrust-bearing oil coolers. An optional safety seal oil system or thrust-bearing lube system is available for some models. The motor is mounted just outside the elbow on a pad that allows for exact driveshaft lineup. A coupling securely connects the motor to the pump.

Axial pumps can be mounted vertically or horizontally. Axial pumps are frequently found in pipeline service and as the primary transfer device on loop reactors. Drive options include direct, variable, and belt drive between 7.5 and 2,000 hp. Design pressures vary between 300 and 1,500 psig. Design temperatures range from −50° to 650°F (−45.55°C to 343.33°C).

Figure 4.13
Axial Pump



Jet Pumps

Jet pumps (Figure 4.14) take their name from the way they transfer liquids. A specially designed jet is engineered to utilize the venturi effect. Jet pumps are frequently used to lift water from wells over 200 feet deep. When a water well is set, a hole is drilled down to the water table. A polyvinylchloride (PVC) screen is connected to a PVC water pipe that is pushed down the open hole. The pipe is allowed to extend a few feet above ground level. Water passes through the screen and into the pipe. Pressure in the water pocket causes the water level to pass through the screen and up the pipe. The water level will typically stop before it reaches the top of the pipe. The process of lifting the water out of the pipe is the function of the jet pump. The different parts of the jet assembly and drop pipe include a foot valve, nozzle, venturi, suction, and discharge. During installation, a foot valve (check valve) is securely attached to the bottom of the jet. A leather seal is located between the check and the jet. The jet is secured to the drop pipe and lowered into the water pipe casing. A specially designed adapter is used to connect the center drop pipe to the outer casing. The adapter provides a base upon which the vertical centrifugal pump can be mounted. During operation, water is forced back down the void between the center

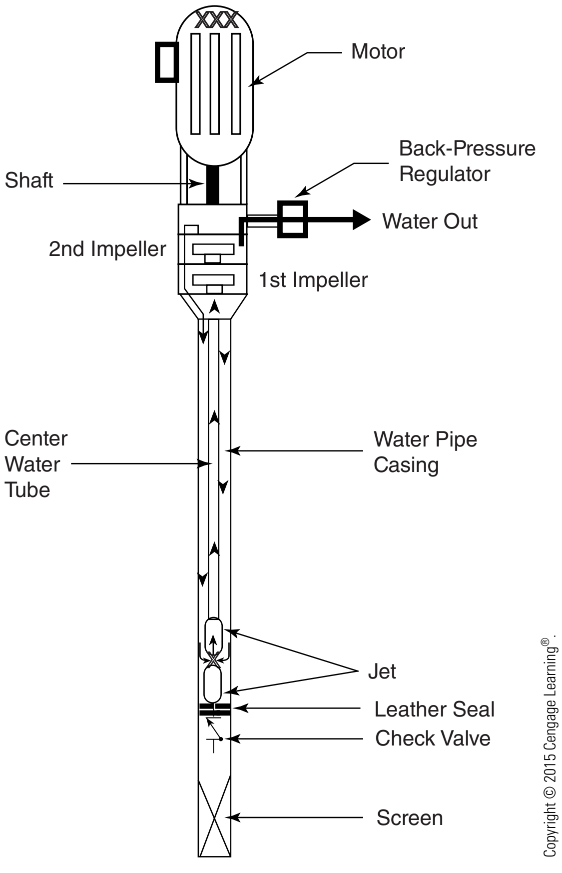


Figure 4.14
Jet Pump

drop pipe and the outer casing. As water is pumped back into the well casing, the foot valve slams shut. A small opening in the jet provides access back to the suction of the pump. A venturi effect occurs at the jet as pressure builds up in the casing. As pressure increases in the casing, velocity increases across the jet. A low-pressure zone is established inside the drop pipe as water quickly flows up toward the pump. A back-pressure regulator holds pressure inside the pump until it reaches operating conditions. When pressures reach operating conditions, water flow is divided as some water recirculates down the casing and the excess flows to a storage tank.

Another common jet pump arrangement includes a jet assembly and a centrifugal pump. The jet assembly forms a suction chamber that creates a vacuum when a stream of high-velocity water flows through a jet. The jet assembly is composed of two major parts: a nozzle and a venturi tube. The nozzle directs high-velocity water into the venturi tube or diffuser. As the high-velocity water exits the nozzle and enters the diffuser, it slows down, creating pressure. The primary purpose of the diffuser is to convert water velocity to pressure.

Positive Displacement Pumps

Rotary and reciprocating pumps are the two major classifications of PD pumps. Rotary pumps displace liquid with rotary-motion gears, screws, vanes, or lobes. Reciprocating pumps displace fluid with a diaphragm, piston, or plunger that moves back and forth.

CAUTION: *During pump operation, a PD pump should never be blocked on the discharge side until the pump is turned off. Equipment and personnel can be severely damaged if the discharge side is blocked while the pump is on. Most PD pumps are provided with pressure relief valves to prevent damage.*

Rotary Pumps

Rotary pumps are PD pumps that transfer liquids by using a rotary motion. The driveshaft turns the rotary elements inside a leak-tight chamber that has a defined inlet and outlet. Engineering design requires close running clearances between the rotating elements and chamber wall. Rotary pumps have very little internal slip. This type of pump is the most widely used positive displacement pump. Rotary pumps are used to move the more viscous type of fluids: heavy hydrocarbons, syrup, paint, and slurries. Rotary pumps combine the rotary motion of a centrifugal pump and the positive displacement feature of a reciprocating pump. Rotary pumps come in four main types: screw (single and multiple), gear (internal and external), vane (sliding and flexible), and lobe.

Figure 4.15
Progressive Cavity Pump

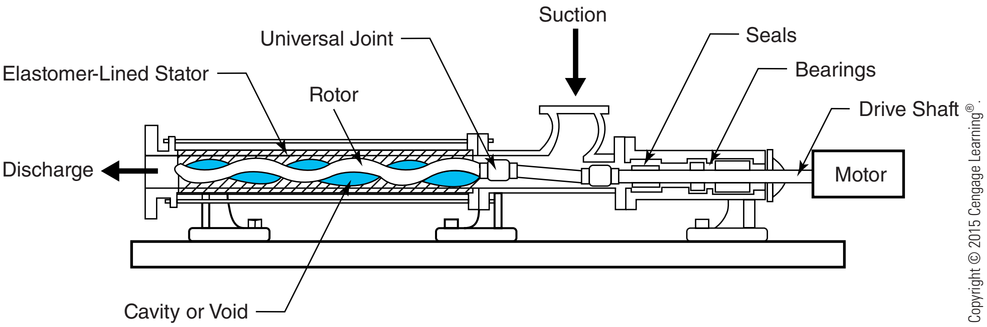


Figure 4.16
Progressive Cavity Pump Components

Single-Screw Rotary Pumps (Progressive Cavity Pumps)

A progressive cavity, or PC, pump (Figures 4.15 and 4.16) consists of only one moving part, the rotor. The rotor turns inside an elastomer-lined stator. When the self-priming rotor turns, cavities, or voids, are formed between the rotor and the stator. These voids progress axially from the suction casing to the discharge outlet. During operation, the cavities fill with fluid. Progressive cavity pumps provide high suction, extremely low shear, and smooth pulsation-free operation. These features are important where turbulence affects fluid composition. The PC pump is ideally suited for metering operations. Typically, this type of pump is used for heavy or viscous fluid service. The solid content of the process fluid does not affect the effectiveness of a PC pump. Progressive cavity pumps can be found in a variety of applications. Operating conditions include pressures up to 1,000 psi, flow rates to 950 GPM, and viscosities of over 1,000,000 cP (centipoises).

Rotor and Stator

The rotational speed of the rotor and the total volume of the cavities determine PC pump flow rate. The rubbing velocity determines rotor and stator life. If the space between the rotor and stator is small, a high degree of rubbing velocity is created. Rubbing velocity is a major factor in the life of the stator. The stator can be replaced after it is worn out. The rotor is typically made of high-chrome tool steel that resists particle abrasion. The stator is manufactured by extruding molten elastomer under high pressure into a heavy metal stator tube with an inner rotor core. When the molten elastomer cools, the core is removed. The stator tube can be threaded on each end for easy installation over the rotor, or it can be connected with four tension rods.

Universal Joints

The universal joint (U-joint) transmits torque from the driveshaft to the rotor. The PC pump's U-joint is located in the suction housing of the pump. As process fluid flows around the U-joint, dead zones are eliminated. The rotor in a PC pump turns about three different rotation centers; that is, it has about three curves.

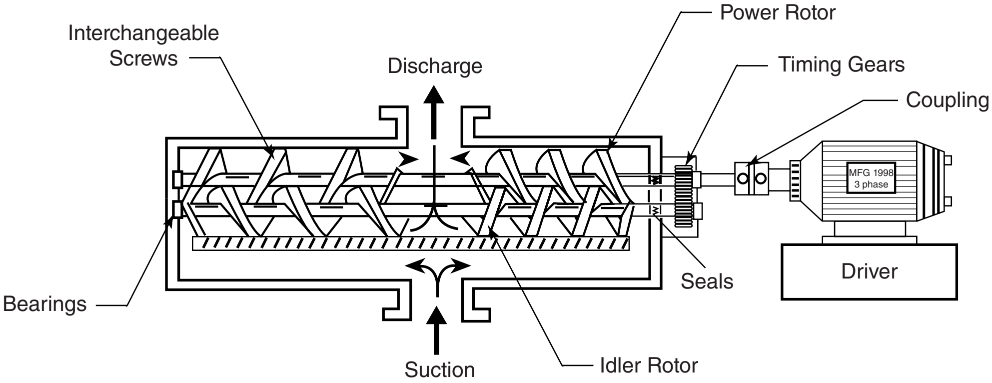
Seals and Bearings

The PC pump uses mechanical or soft packing to prevent leakage. The bearing housing is located on the driveshaft end of the pump. Large roller bearings designed to handle excessive loads protect the driveshaft as it transmits torque through the bearing housing. Because of this unique design, PC pumps can be adapted to use belt or direct drives.

Multiple-Screw Rotary Pumps

Multiple-screw rotary pumps can be used in a variety of applications. They have either two or three screws. The versatile, heavy-duty, self-priming, two-**screw pump** has been in service since 1934. The special design of the pump elements enables the two-screw pump to provide high flow rates and excellent suction and to pump virtually any fluid. A two-screw pump has two rotors: a power rotor and an idler rotor. A set of external timing gears and bearings allows the screws (the rotors) to turn in unison without making contact with each other. This feature allows the pump to transfer any fluid regardless of abrasiveness, lubricity, or viscosity. In addition, because the screws do not touch, the pump can run empty without damaging the system. This feature makes it an ideal choice in tank-stripping operations or in operations in which fluid suction pressure will vary. The twin-screw pump has a driving and a driven shaft, two screws, an external set of timing gears and heavy-duty bearings, and divided-entry flow (Figure 4.17).

Figure 4.17
Two-Screw Pump



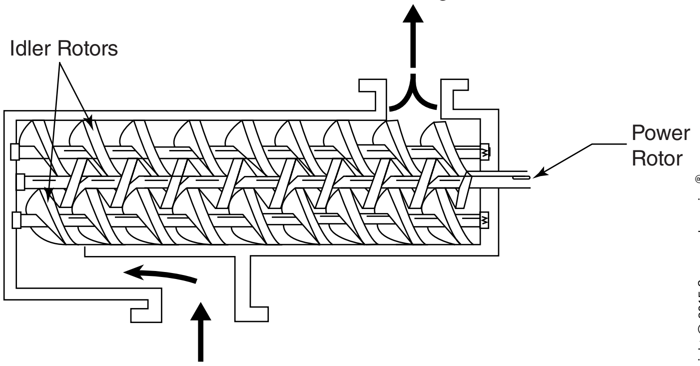


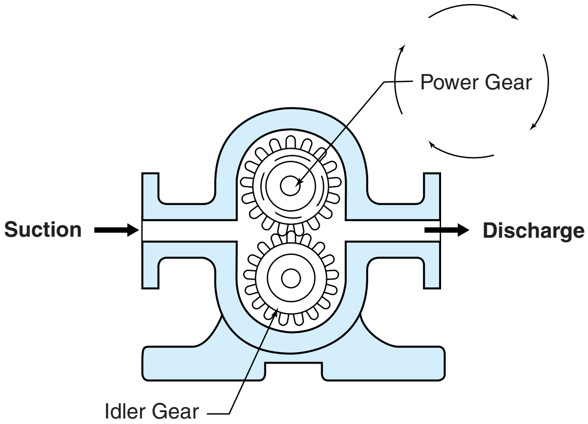
Figure 4.18
Three-Screw Pump

As fluid enters the pump, it is divided into two equal streams and directed to the two ends of the shaft. The pumping action of the screws moves the two streams of process fluid in a straight line between the closely spaced rotors until they combine at the discharge port. In a two- or three-screw design, the direction of rotation of the power rotor will determine whether the inlet and outlet ports are located on the top or bottom of the pump. Because the two streams have equal, simultaneous flow paths, the rotating rotors are balanced. This unique design reduces bearing wear. Most two-screw pumps require mechanical seals instead of soft packing on the suction side of the pump because of the large sealing area. Two-screw pumps typically operate at a speed of 3,500 RPM, flow rate of 8,800 GPM, inlet pressure up to 100 psi, discharge pressure up to 725 psi, and temperature up to 500°F (260°C).

The three-screw pump consists of a power or driver rotor and two idler rotors (Figure 4.18). The power screw meshes with the idler screws during operation. The three-screw pump is unlike the two-screw pump in that the three screws touch. Each screw rotates easily on a set of heavy bearings. During operation, the self-priming screws rotate, creating voids that transfer fluid in a continuous, pulsation-free flow. A typical three-screw pump does not need thrust bearings because of the balanced system. The engineering specifications allow this type of pump to be operated at speeds of up to 6,000 RPM, with pressures up to 750 psig, and flow rates around 600 GPM.

Gear Pumps
Gear pumps are similar to screw pumps in that they can be used in viscous service. Gear pumps typically can be found in two common types: external and internal.

External Gear Pumps
External gear pumps have two interesting gears that rotate parallel to each other, allowing fluid to be picked up by the gears and transferred out of the pump (Figure 4.19). One of the gears is an idler gear; the other is attached



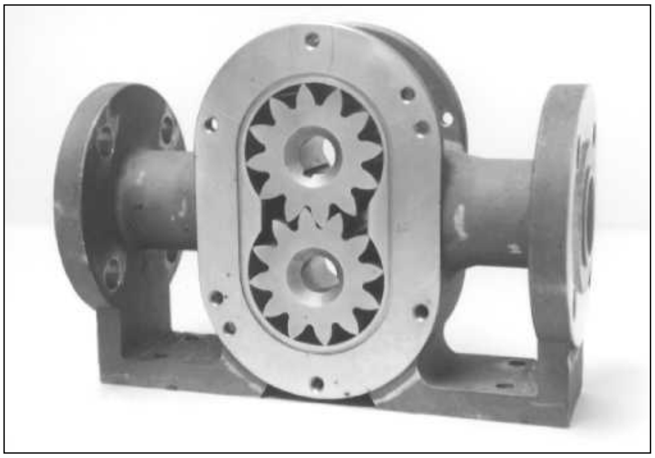


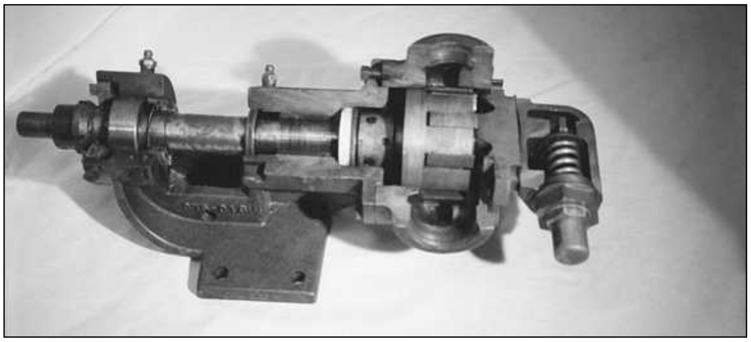
Figure 4.19 *External Gear Pump*

to a driver and is referred to as the power gear. External gear pumps consist of two mating gears that rotate inside a casing. The rotation of the driver gear turns the idler, or follower gear, trapping fluid and displacing it. Typically, in this type of operation, the driver gear is mounted on top. Most operators refer to external gear pumps as constant displacement pumps. The discharge of an external gear pump remains constant unless the shaft speed is changed.

The suction and discharge ports of an external gear pump are located on the opposite ends of the casing. When the pump is first started, air is forced out and into the discharge line. This process creates a low-level vacuum on the suction side. This vacuum causes fluid to enter the pump and be trapped between the gears. As the gears rotate, the fluid is swept around the housing and out of the discharge port.

Internal Gear Pumps

A Danish-American inventor, Jens Nielsen, invented the internal gear (IG) pump in 1915. Process technicians refer to the internal gear pump as the "gear-within-a-gear pump." Internal gear pumps operate with only two moving parts: a power gear driving an internal idler gear (Figures 4.20 and 4.21). When the power gear rotates, liquid enters the pump through the suction line. Since the pump is self-priming, the voids between the teeth of the power gear and the off-center idler gear fill with liquid. During rotation, liquid is separated by a crescent-shaped spacer. Liquid is pressed into the spaces above and below the crescent. As the gears rotate around the circular pump casing, the liquid is discharged out of the pump. The main components of an internal gear pump are a power gear or rotor; an idler gear; an idler pin; a driveshaft; a circular casing; the crescent, axial, and radial bearings; seals; and a relief valve. The idler gear rotates freely on a cylindrical idler pin. A main bearing and a second bearing



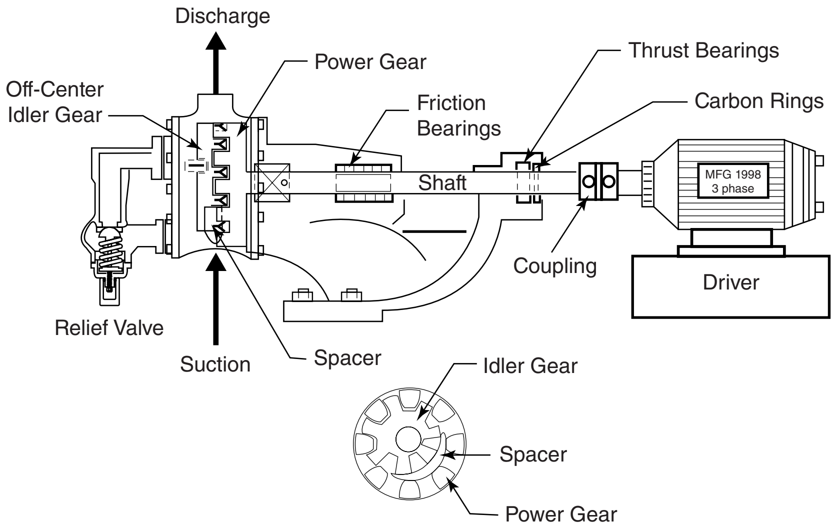
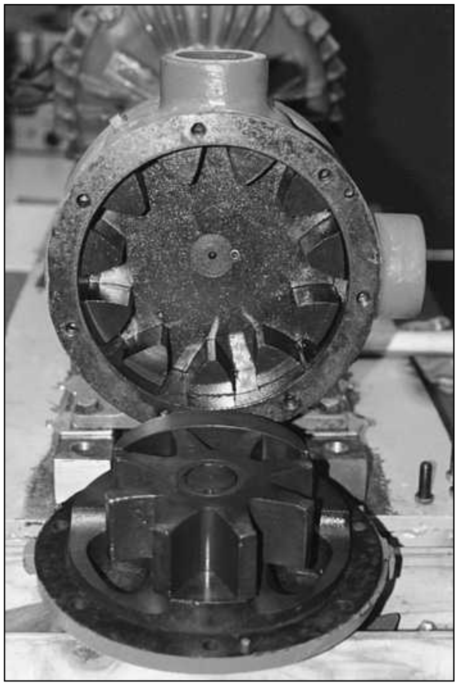


Figure 4.20
Internal Gear Pump



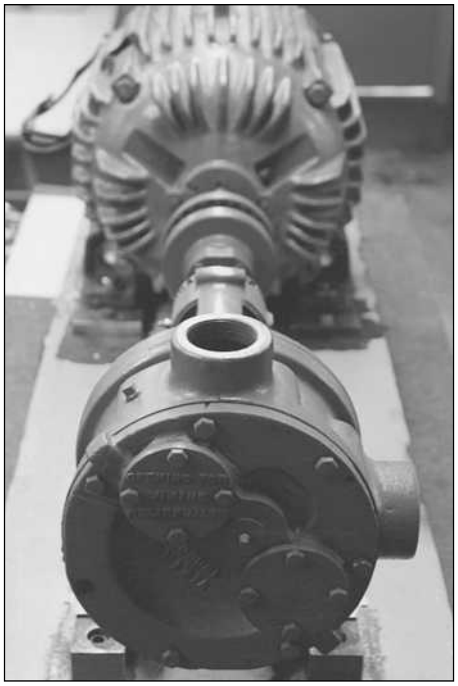


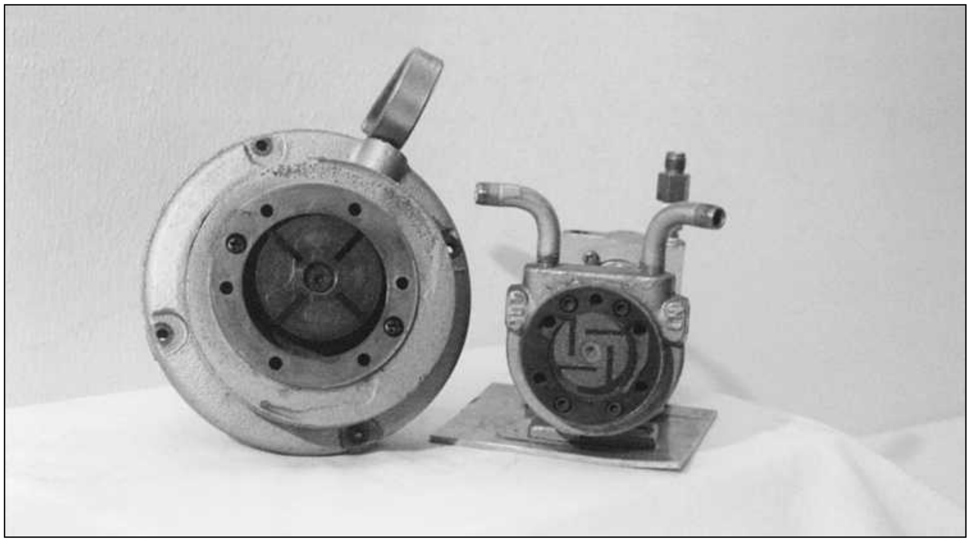
Figure 4.21
Internal Gear Pump

on the free end of the shaft support the driveshaft. Soft packing or mechanical seals can be used on the pump. Internal gear pumps require very little maintenance. Design parameters on internal gear pumps include flow rates from 1 to 750 GPM, speeds up to 1,750 RPM, temperatures up to 500°F (260°C), suction lift during operation up to 24 inches Hg vacuum, and differential pressures up to 250 psi. These pumps can be constructed of stainless steel for corrosive environments or of carbon steel or cast iron where applicable. The chemical processing industry uses internal gear pumps for chemicals such as acetone, acids, alcohol, alkalis, ammonium hydroxide, butadiene, polymers, resins, solvents, waxes, and xylenes. Internal gear pumps can also be magnetically coupled; magnetic coupling eliminates the need for shaft seals.

Sliding Vane Pumps

Sliding vane pumps (Figure 4.22) consist of spring-loaded or nonspring-loaded vanes attached to a rotor, or impeller, that rotates inside an oversized circular casing. As the offset impeller rotates by the inlet port, liquid is swept into the vane slots. A small crescent-shaped cavity is formed inside the pumping chamber that the vanes extend into. As the liquid nears the discharge port, it is compressed as the clearances narrow. The compressed liquid is released at the discharge port. The vanes on the pump are made of a softer material than the rotor and casing. A bevel on each vane closely matches the rounded edges of the chamber, and the softer vane material tends to wear evenly during the life of the vane. Sliding vane pumps typically are used with process liquids that have good lubricating qualities. Vane pumps are used in hydraulic systems, vacuum systems, and low-pressure oil systems. The typical vane pump has a capacity of 380 GPM and operates with a pressure differential of 50 psig.

Figure 4.22
Sliding Vane Pump



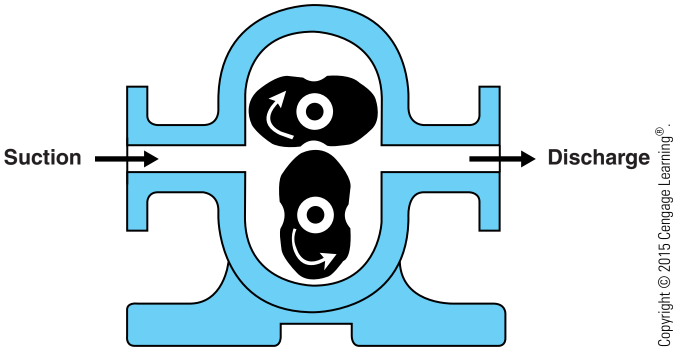


Figure 4.23
Lobe Pump

Flexible Vane Pumps

In a flexible pump system, the rotor is composed of a soft elastomer impeller, keyed to fit over the driveshaft that penetrates the pumping chamber. The pumping chamber is designed to provide good contact between the impeller and the inner chamber. Speeds are typically low since the rubbing velocity between the flexible vanes and chamber wall is significant. The impeller is centered in the pumping chamber. Flexible vane pumps are frequently used in vacuum service.

Lobe Pumps

Lobe pumps (Figure 4.23) have two rotating lobe-shaped screws that mesh during operation. As the lobes turn, voids are created that compress liquids around the outside of the pumping chamber. In a lobe pump, a set of external timing gears and bearings allows the lobes to turn in unison without making contact with each other. This feature allows the pump to transfer a wide variety of fluids. Because the lobes do not touch, the pump can run empty without damaging the system. A lobe pump has a driving and a driven shaft, two lobes, an external set of timing gears, and bearings. As fluid enters the pump, it is divided into two equal streams. The pumping action of the lobes moves the process fluid in two streams around the lobes in the close tolerances between the casing and the lobes. The streams combine at the discharge port. The direction of rotation of the driver will determine the locations of the inlet and outlet ports on the pump. Lobe pumps are designed to provide high flow rates at low pressures; they have excellent suction and pump a variety of fluids.

Reciprocating Pumps

Reciprocating pumps, especially in small volume sizes, are positive displacement pumps very commonly used in the petrochemical industry. Reciprocating pumps are engineered to transfer small volumes of liquid at relatively high pressures. Most reciprocating pumps are self-priming and are operated at relatively low speeds because of the back-and-forth motion and the effects of inertia on internal components. Reciprocating pumps can deliver consistently high volumetric efficiencies even when applied to a variety of fluid types. They deliver liquid when a piston, plunger, or diaphragm physically displaces it. The diaphragm, piston, or plunger pushes the fluid as it moves back and forth inside a cylinder or housing.

The suction system requirements for a reciprocating pump are similar to those of other pumps except for one important factor—**acceleration head**. Acceleration head takes into account the back-and-forth inertia that a reciprocating pump creates. Acceleration head is defined as the fluctuations of suction pressure created by the intake stroke of a reciprocating pump. The suction line of a reciprocating pump should be as short as possible. Excessive valves, bends, and fittings should be eliminated. The line should be large enough to deliver fluid velocities of 3 feet per second. Booster pumps typically can be added to the suction line to increase suction pressure.

Diaphragm Pumps

A **diaphragm pump** (Figure 4.24) uses a flexible sheet (diaphragm) to displace fluid. This type of pump has a crankshaft or eccentric wheel attached to a connecting rod. The connecting rod is anchored firmly to the center of the diaphragm. The outer edge of the diaphragm is bolted or secured to the exterior casing. As the eccentric wheel (referred to simply as the *eccentric*) starts its rotation, the diaphragm connecting rod goes up and down. This reciprocating motion creates a pumping action that displaces fluid. The pumping chamber below the diaphragm is connected to suction and discharge lines. Spring-loaded valves open or close, depending on the pressure in the chamber.

Diaphragm pumps have several advantages compared with most other types of pumps. They completely seal off the area between the diaphragm

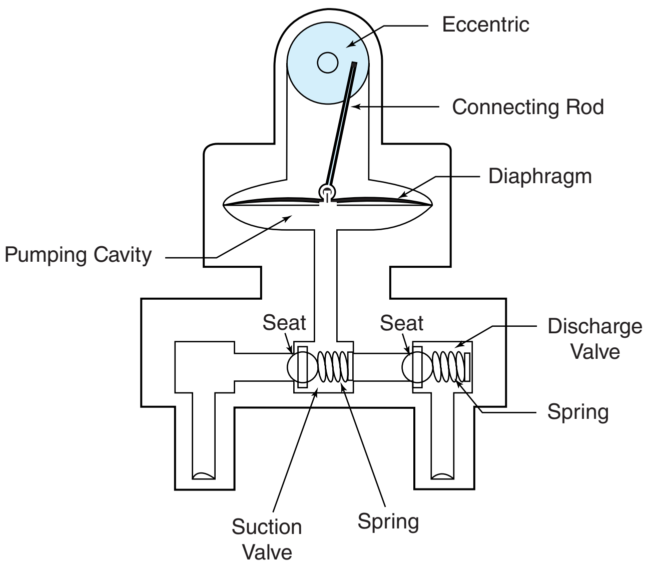


Figure 4.24 *Diaphragm Pump*

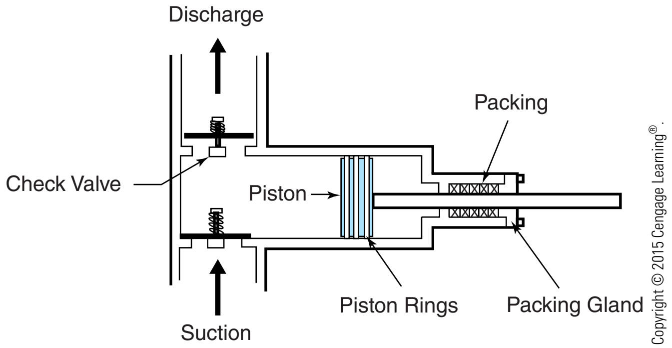


Figure 4.25
Simple Piston Design

and the pumping cavity; they can be used to pump a variety of chemicals; and they can be used with low or negative suction head.

Piston and Plunger Pumps

Reciprocating **piston pumps** (Figure 4.25) use a piston and a back-and-forth motion to displace fluid. During normal operation, the piston pump has a suction stroke and a discharge stroke. The suction stroke occurs when the piston pulls out of the cylinder. This motion creates a low- pressure vacuum in the cylinder, causing the discharge valve to close and the suction line to open, filling the cylinder. On the return stroke or discharge stroke, the suction valve slams shut, and the fluid is forced out the discharge valve. This type of pump continues to operate no matter how high the discharge head is.

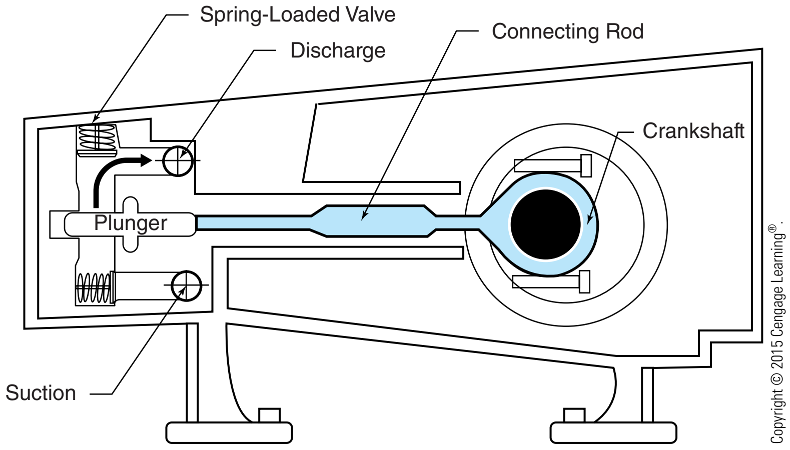
The typical piston pump has a piston, piston ring, connecting rod, suction and discharge valves, casing and cylinder, and relief valve. Piston pumps are sealed internally and externally. Internally, the piston rings form a seal on the piston that can be seen only by tearing down the pump. The external packing seal is located where the piston rod enters the casing.

Reciprocating plunger pumps (Figure 4.26) operate with a back-and-forth motion and a device called a plunger to displace controlled amounts of liquid. The primary difference between a plunger pump and a piston pump is in the shape of the piston or plunger element and the way they seal. A piston pump has rings mounted on the piston that form a seal. The plunger on a plunger pump does not have moving rings. The plunger moves in and out of an O-ring or packing medium to form its own stationary seal. A major advantage of this type of sealing system is that the pump seals easily and can be replaced without major breakdown of the equipment. The basic components of a plunger pump are a plunger, crankshaft, connecting rod, pumping chamber, suction inlet valve, and discharge outlet valve.

Double-Acting Design

The back-and-forth motion of a piston or plunger pump limits the smooth flow control characteristic of other pumps that do not have long suction intake and

Figure 4.26
Plunger Pump



discharge strokes. Piston and plunger pumps tend to have pulsing or spurting flow rates. Using a double-acting design can compensate for this feature. A double-acting piston (Figure 4.27) or plunger pump discharges and pulls in fluid on each side of the chamber, on a single stroke. Because the double-acting pump discharges on each stroke, a more uniform flow rate can be maintained. Some engineering designs include **pulsation dampeners** to offset the problem of pulsing or spurting flow rates. The dampener should absorb cyclical flow variations. The pulsation dampener is a small pressure vessel with a diaphragm and a cushion of air to offset surges.

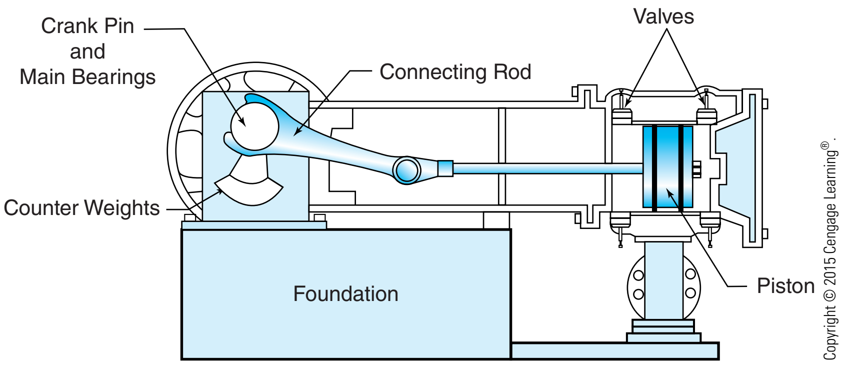
Duplex Design

Single-cylinder piston and plunger pumps have severe capacity limitations. Adding another cylinder compensates for this design flaw and doubles the flow capacity.

Vacuum Pumps

Operating systems that require pressures below atmospheric pressure use vacuum pumps. The typical vacuum pump falls under a variety of reciprocating, rotary, and dynamic categories. Vacuum pumps are frequently used in distillation operations, refrigeration, and air conditioning. Vacuum pumps are connected to the system to be evacuated with hoses, piping,

Figure 4.27
Double-Acting Piston Pump



or manifold systems. The connection is typically made in a location where liquid is not present. A knockout system is used to trap liquids before they can enter the pump. Some vacuum pumps have an oil seal inside the casing of the pump. During the evacuation process, the process flow is drawn into the pump and discharged. Contaminants are trapped in the oil, which may require frequent changing. The primary cause for pump failure is contaminated oil. When the pump is first started, it makes a gurgling sound as gas or vapors are drawn into it. A distinct rapping sound can be heard once the pumpdown is complete. The suction side of a vacuum pump should be closed before the pump is turned off because vacuum oil will be drawn into the internal pumping chamber. This problem could cause the pump to fail on the next startup. Vacuum pumps may also be classified as compressors, since the primary medium being transferred is gas or vapors. A variety of compressors—such as sliding vane, piston, liquid ring, and lobe compressors—can be adapted to serve as vacuum-type devices.

Startup, Shutdown, and Troubleshooting

The basic components of both dynamic and positive displacement pump systems are a pump, piping, valves, instruments, and process equipment (Figure 4.28). The heart of the system is the pump. It is used to accelerate, or add energy to, the process fluid. In most operating systems, spare (redundant) pump arrangements are used to permit pump maintenance without shutting down the process. Each plant has a standard operating procedure that should be followed closely during startup and shutdown. Tables 4.1 and 4.2 illustrate typical startup and shutdown procedures. Table 4.3 illustrates troubleshooting charts for identifying and solving pump problems.

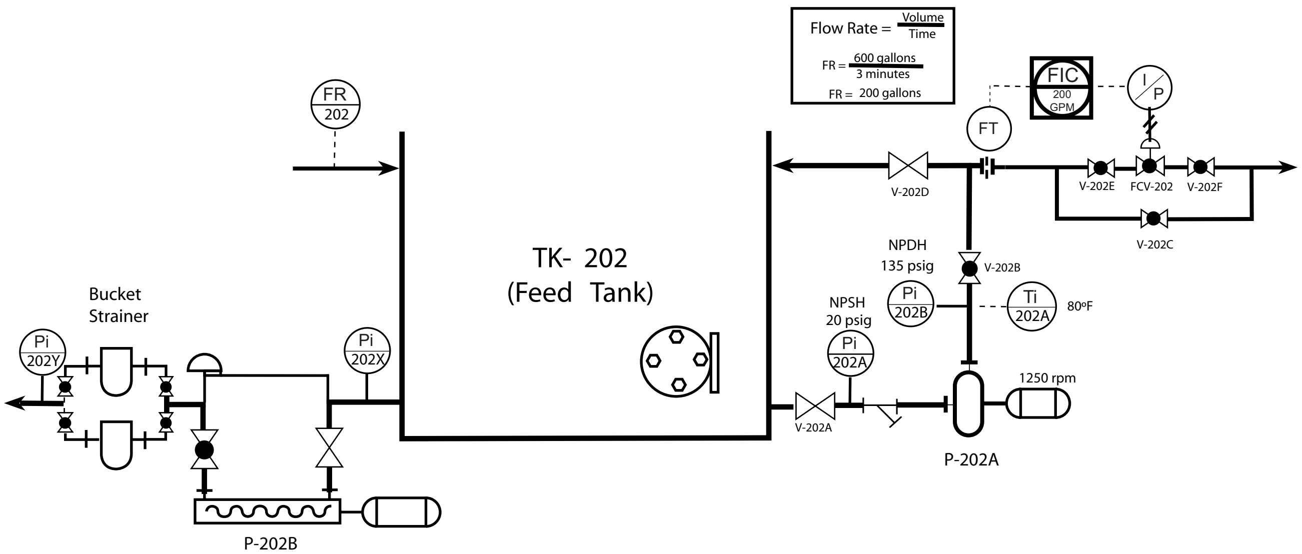


Figure 4.28 *Simple Pump System*

Table 4.1 *Start Up and Shut Down a Positive Displacement Pump*

Procedure	Comments
1. Review the standard operating procedure for the equipment.	Each unit will have its own operating procedure for equipment startup.
2. Check the pump driver oil level, cooling requirements, and other specifications.	Look for possible equipment damage.
3. Check pump lineup and tank levels.	Identify valves that need to be open and shut.
4. Open pump suction valves and fill pump.	Be sure all of the valves between the pump and the tank are open.
5. Open pump discharge valves.	PD pumps should never be started with the discharge line closed.
6. Recheck pump lineup and start pump.	
7. Monitor suction and discharge pressures and flow rates.	Be sure pump has adequate suction tank level.

Table 4.2 *Start Up and Shut Down a Centrifugal Pump*

Procedure	Comments
1. Review the standard operating procedure for this piece of equipment.	Each unit will have its own operating procedure for equipment startup.
2. Check lineups in auxiliary sealing, cooling, and flush systems.	
3. Check the pump and driver and the oil levels.	Look for possible equipment damage.
4. Check pump lineup and tank levels.	Identify valves that will need to be open and shut. Estimate NPSH and discharge head. Look at tank levels.
5. Open pump suction line and pump vent valve to liquid-fill (prime) the pump.	Be sure all of the valves between the pump and the tank are open.
6. Crack open pump discharge valve. **NOTE:** If pump is multistage, be sure that the minimum flow system is lined up.	In some cases, the pump may be started to press up or take the slack out of the line.
7. Recheck pump's lineup and start pump. When pump operation is stable, open the discharge line valve wide.	Adjust discharge valve if the discharge line is slack. Starting into a slack line allows the pump to outrun the suction, damaging the pump.
8. Monitor suction and discharge pressures and flow rates.	Check lubrication, bearings, and seals for proper operation.

Table 4.3 *Troubleshoot Typical Pump Problems*

Problem	Possible Cause	Solution
Pump is cavitating	• High suction temperature • Viscosity • Low suction pressure • Restriction in line • Too much horsepower • Pump speed too high • Too high NPSH • Small suction	• Lower temperature • Agitate suction tank • Increase level or pressure • Shut down and clear • Decrease horsepower • Lower RPM • Lower NPSH requirements • Increase diameter suction line
Pump vapor locked	• Pump not vented before startup • Variable-speed pumps	• Shut down and bleed off • Use a turbine or variable-speed motor drive
Specific gravity of product changes	• Different product composition	• Leave alone; will not affect pump capacity
Excessive vibration	• Starved suction • Bearings worn • Caused by the formation of vapor pockets • Pump misaligned • Rotor out of balance; usually intermittent • Shaft bent • Loose foundation bolts • Driver vibrating • Instrument malfunctions	• Pinch down discharge valve on pump • Shut down and replace • Vent pump to reestablish full capacity • Shut down and have realigned • Remove rotating element, check impeller; if passages clogged, remove foreign material; if impeller is damaged, a new one will need to be installed • Shut down and repair • Secure pump to foundation • Disconnect coupling and check driver • Locate and correct
Fails to deliver liquid	• Pump not primed • Wrong rotation • Suction line not filled with liquid • Air/vapor in suction line • NPSH insufficient • Low level in suction tank • Total head required greater than available	• Prime it • Reverse • Fill suction line • Bleed off • Increase NPSH • Increase level • Increase pump size

Pump Symbols

Each type of pump can be represented by a symbol. Pumps symbols are illustrated in Figure 4.29.

Summary

Pumps can be classified as dynamic or positive displacement. The two most common types of pumps are centrifugal and positive displacement. Centrifugal pumps are dynamic pumps that use centrifugal force and the design of the volute to add energy or velocity to the liquid. Positive-displacement (PD) pumps displace a specific volume of fluid (gas or liquid)

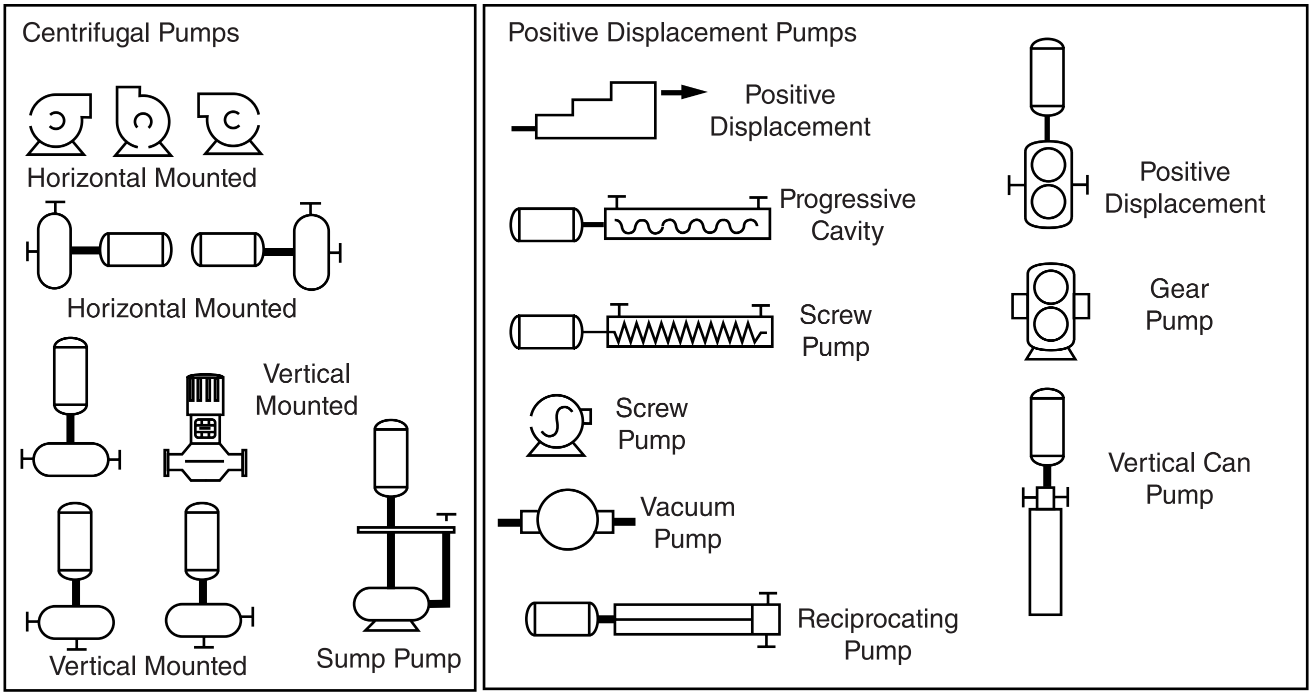


Figure 4.29 *Pump Symbols*

on each stroke or rotation. PD pumps can be classified as rotary or reciprocating. Rotary pumps displace fluids with screws, gears, vanes, or lobes. Reciprocating pumps move fluids by drawing them into a chamber on the intake stroke and positively displacing them with a piston, plunger, or diaphragm on the discharge stroke.

Internal slip is the percentage of fluid that leaks or slips past the internal clearances of a pump over a given time. Centrifugal pumps can operate with 100% slip over short periods of time (discharge valve closed). Positive displacement pumps are not designed to tolerate slip (discharge valve closed).

In a centrifugal pump, liquids must be pushed (not sucked or pulled) into the impellers. Suction head is a term used to describe the pressure required to force liquid into a pump. A centrifugal pump must be primed or liquid full before the pump can be engaged. Net positive suction head (NPSH) usually is calculated in feet of liquid.

Cavitation is defined as the formation and collapse of gas pockets around the impeller of a centrifugal pump. Cavitation occurs when suction pressure drops below required NPSH. At this point, the liquid vaporizes and forms gas pockets inside the pump casing. As these pockets form and collapse, the pump can be severely damaged.

During pump operation, a PD pump should never be blocked in on the discharge side until the pump is turned off. Equipment and personnel can be severely damaged if the discharge **pressure relief valve** fails to function.

Review Questions

1. Define NPSH, and describe how it affects industrial pump operation.
2. Briefly review the history of positive displacement pumps and centrifugal pumps.
3. Describe the primary scientific principles associated with centrifugal pump operation and identify key components.
4. Describe the operation of positive displacement pumps.
5. List the various types of rotary pumps.
6. Describe the basic components and operation of a screw pump.
7. Explain how external and internal gear pumps operate.
8. Describe the basic components and operation of sliding and flexible vane pumps.
9. Describe the basic components of a lobe pump.
10. List the various types of reciprocating pumps.
11. Explain the operation of diaphragm pumps.
12. Describe the operation and design of piston pumps.
13. Describe a plunger pump.
14. List the typical startup and shutdown procedures for a positive-displacement pump.
15. List the typical startup and shutdown procedures for a centrifugal pump.
16. What specific problems are associated with the operation of centrifugal and reciprocating pumps?
17. Draw a simple axial pump.
18. Draw a simple pump system using a tank, pump, and connecting piping.
19. Draw the symbol for a progressive cavity pump and a screw pump.
20. Explain how variations in NPSH affect the operation of a centrifugal pump.