Basic Overview of Pumps and Variable Speed Pumping

Florida Board of Professional Engineers

Approved Course No. 0010329

4 PDH Hours

A test is provided to assess your comprehension of the course material – 24 questions have been chosen from each of the above sections. You will need to answer at least 17 out of 24 questions correctly (>70%) in order to pass the overall course. You can review the course material and re-take the test if needed.

You are required to review each section of the course in its entirety. Because this course information is part of your Professional Licensure requirements it is important that your knowledge of the course contents and your ability to pass the test is based on your individual efforts.

Course Description:

This course is course material is based entirely on US Department of Energy training materials: DOE-HDBK- 1018/1-93, Fundamentals Handbook, Mechanical Science, Volume 1 of 2 and Variable Speed Pumping — A Guide to Successful Applications. This course will provide a basic overview of the basic operating principles of pumps and pumping systems. In addition the course can be used as a guide to help determine whether variable speed pumping is a good choice for pumping systems.

How to reach Us …

If you have any questions regarding this course or any of the content contained herein you are encouraged to contact us at Easy-PDH.com. Our normal business hours are Monday through Friday, 10:00 AM to 4:00 PM; any inquiries will be answered within 2 days or less. Contact us by:

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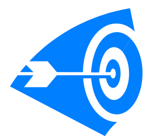
Refer to Course No. 0010329,

Basic Overview of Pumps and Variable Speed Pumping

How the Course Works…

What do you want To do?	LOOK For This!
 Search for Test Questions and the relevant review section	 Q1 Search the PDF for: Q1 for Question 1, Q2 for Question 2, Q3 for Question 3, Etc… (Look for the icon on the left to keep you ON Target!)

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24 QUESTIONS

Q1: A basic Centrifugal pump consists of:

(A) a stationary pump casing
(B) an impeller
(C) a rotating shaft
(D) All of the Above

Q2: Fluid that exits the diffuser section of a centrifugal pump:

(A) reduces in velocity as it exits
(B) converts from kinetic energy into flow pressure
(C) increases in velocity as it exits
(D) A and B

Q3: Which type of centrifugal pump impeller has circular plates attached to both sides of the blades:

(A) open type
(B) semi-open type
(C) enclosed type
(D) radial type

Q4: Axial flow pumps are sometimes called:

(A) propeller pumps
(B) propulsion pumps
(C) propagation pumps
(D) axis pumps

Q5: The area of a centrifugal pump where the rotating shaft that drives the impeller penetrates the pressure boundary of the pump is called:

(A) seal boundary
(B) pressure seal
(C) stuffing box
(D) stuffing seal

Q6: Conditions where a lantern ring may be used to seal the shaft of a centrifugal Pump include:

(A) if the pumped fluid is abrasive
(B) if the pumped fluid is too hot too hot to provide adequate cooling of the packing
(C) if the pump suction is under vacuum
(D) B and C

Q7: Cavitation in a centrifugal pump occurs when:

(A) the liquid being pumped to flashes to vapor
(B) the liquid being pumped to becomes too hot
(C) the liquid being pumped is sub-cooled
(D) the liquid being pumped is sublimates

Q8: To avoid pump cavitation, the NPSH available can be increased by:

(A) increasing the pressure at the suction of the pump
(B) decreasing the temperature of the liquid being pumped
(C) reduce head losses in the suction line of the pump
(D) All of the Above

Q9: What is the condition called where the pump casing is filled with gases or vapors to the point where the impeller is no longer able to contact enough fluid to function correctly:

(A) vapor contact
(B) vapor filling
(C) gas binding
(D) gas liberation

Q10: Positive displacement pumps differ from centrifugal pumps because Positive Displacement pumps:

(A) deliver a continuous flow for any given pump speed and discharge resistance
(B) deliver a continuous flow for only one specific pump speed and discharge resistance
(C) deliver an intermittent flow for any given pump speed and discharge resistanistance
(D) deliver an intermittent flow for only one specific pump speed and discharge resistance

Q11: A duplex Positive Displacement pump is designed such that:

(A) both pistons are in the same position (upstroke or downstroke)
(B) when one piston is on its upstroke the other piston is on its downstroke
(C) separate independent foundations are required for operation
(D) B and C

Q12: **In a Simple Gear Pump, two spur gears mesh together and revolve in opposite directions within a casing. The typical clearance between the gears is:**

(A) a few thousands of an inch
(B) a few hundredths of an inch
(C) a few tenths of an inch
(D) a few inches

Q13: **A variation of a simple gear pump is a Lobe Type Pump. A typical Lobe type pump has how many teeth per rotor:**

(A) 15 to 20
(B) 5 to 10
(C) 2 to 3
(D) NA, lobe pumps do not have teeth on the rotor

Q14: **A Diaphragm pump functions when a diaphragm is forced into reciprocating motion by all of the following EXCEPT:**

(A) movement of mechanical linkage
(B) a rotating shaft
(C) compressed air
(D) movement from an external pulsating fluid

Q15: **What factor(s) effect the flow rate in an ideal positive displacement pump**:

(A) flow resistance
(B) fluid viscosity
(C) the operating speed of the pump
(D) fluid temperature

Q16: **Pumping Systems account for what percentage of world energy used by electric Motors:**

(A) 1 to 5 percent
(B) between 5 and 10 percent
(C) between 10 and 15 percent
(D) nearly 20 percent

Q17: **Pressure needed to make a liquid flow at a required rate must overcome what types of losses:**
(A) static head
(B) viscosity changes
(C) frictional losses
(D) A and C

Q18: Changing a pump impeller diameter effectively changes the duty point in a given system at low cost but has what drawback(s):

(A) premature impeller
(B) this results in a permanent change in the pump curve
(C) the pump loses its control point
(D) potential pump cavitation

Q19: What effect does changing the pump speed have on pump cavitation:

(A) increasing the pump speed will increase the chances of cavitation
(B) increasing the pump speed will lessen the chances of cavitation
(C) decreasing the pump speed will increase the chances of cavitation
(D) NA, pump speed has not effect on cavitation

Q20: The practice of oversizing pumping system components is not recommended because this leads to:

(A) higher initial equipment costs
(B) higher life cycle costs
(C) higher operator oversight
(D) A and B

Q21: Many system designers allow for a contingency on the system head required. It is estimated that what percentage of pump systems are oversized:

(A) more than 75 percent
(B) between 50 and 60 percent
(C) between 30 and 50 percent
(D) less than 30 percent

Q22: Installation of a Variable Speed Drive as part of a pumping system has the following advantage(s):

(A) Energy Savings
(B) Improved Process Control
(C) Improved System Reliability
(D) All of the Above

Q23: Installation of Variable Speed Drives as part of a pumping system has a drawback where excessive vibration levels can be caused by through:

(A) Structural Resonance
(B) Structural fribulation
(C) Structural ionization
(D) Structural resolution

Q24: In order to control the flow of a pumping system, a constant-speed pump is typically pumping against a control valve which is normally designed to be what percentage closed for control purposes:

(A) 1 to 3 percent
(B) 3 to 5 percent
(C) 10 percent
(D) greater than 20 percent

END OF TEST QUESTIONS

DOE Fundamentals

MECHANICAL SCIENCE

Module 3

Pumps

CENTRIFUGAL PUMPS

Centrifugal pumps are the most common type of pumps found in DOE facilities. Centrifugal pumps enjoy widespread application partly due to their ability to operate over a wide range of flow rates and pump heads.

EO 1.1 **STATE** the purposes of the following centrifugal pump components:

a. Impeller
b. Volute
c. Diffuser
d. Packing
e. Lantern Ring
f. Wearing ring

EO 1.2 Given a drawing of a centrifugal pump, **IDENTIFY** the following major components:

a. Pump casing
b. Pump shaft
c. Impeller
d. Volute
e. Stuffing box
f. Stuffing box gland
g. Packing
h. Lantern Ring
i. Impeller wearing ring
j. Pump casing wearing ring

Q1

Introduction

Centrifugal pumps basically consist of a stationary pump casing and an impeller mounted on a rotating shaft. The pump casing provides a pressure boundary for the pump and contains channels to properly direct the suction and discharge flow. The pump casing has suction and discharge penetrations for the main flow path of the pump and normally has small drain and vent fittings to remove gases trapped in the pump casing or to drain the pump casing for maintenance.

Figure 1 is a simplified diagram of a typical centrifugal pump that shows the relative locations of the pump suction, impeller, volute, and discharge. The pump casing guides the liquid from the suction connection to the center, or eye, of the impeller. The vanes of the rotating *impeller* impart a radial and rotary motion to the liquid, forcing it to the outer periphery of the pump casing where it is collected in the outer part of the pump casing called the volute. The *volute* is a region that expands in cross-sectional area as it wraps around the pump casing. The purpose of the volute is to collect the liquid discharged from the periphery of the impeller at high velocity and gradually cause a reduction in fluid velocity by increasing the flow area. This converts the velocity head to static pressure. The fluid is then discharged from the pump through the discharge connection.

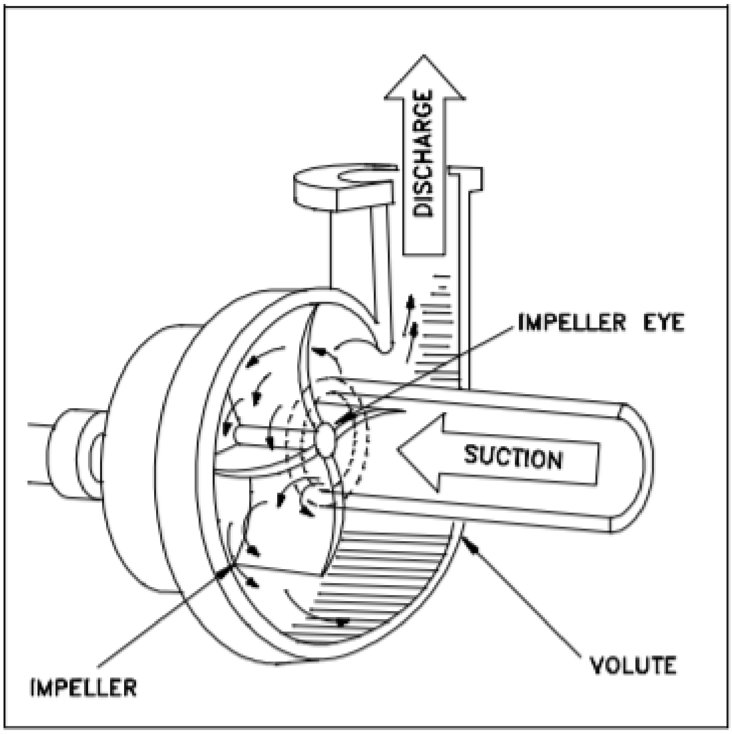


Figure 1 Centrifugal Pump

Centrifugal pumps can also be constructed in a manner that results in two distinct volutes, each receiving the liquid that is discharged from a 180° region of the impeller at any given time. Pumps of this type are called double volute pumps (they may also be referred to a split volute pumps). In some applications the double volute minimizes radial forces imparted to the shaft and bearings due to imbalances in the pressure around the impeller. A comparison of single and double volute centrifugal pumps is shown on Figure 2.

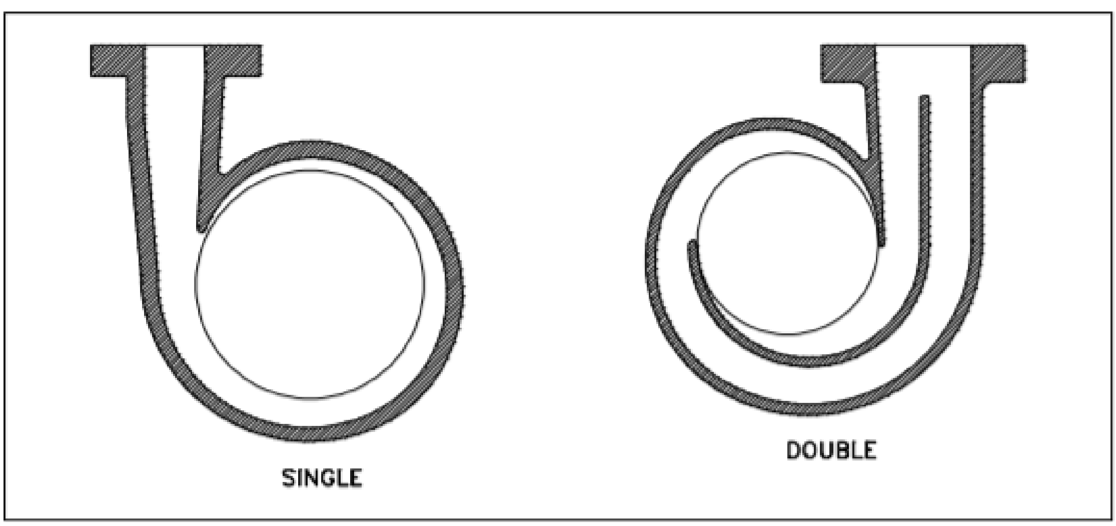


Figure 2 Single and Double Volutes

Diffuser

Q2

Some centrifugal pumps contain diffusers. A *diffuser* is a set of stationary vanes that surround the impeller. The purpose of the diffuser is to increase the efficiency of the centrifugal pump by allowing a more gradual expansion and less turbulent area for the liquid to reduce in velocity. The diffuser vanes are designed in a manner that the liquid exiting the impeller will encounter an ever-increasing flow area as it passes through the diffuser. This increase in flow area causes a reduction in flow velocity, converting kinetic energy into flow pressure.

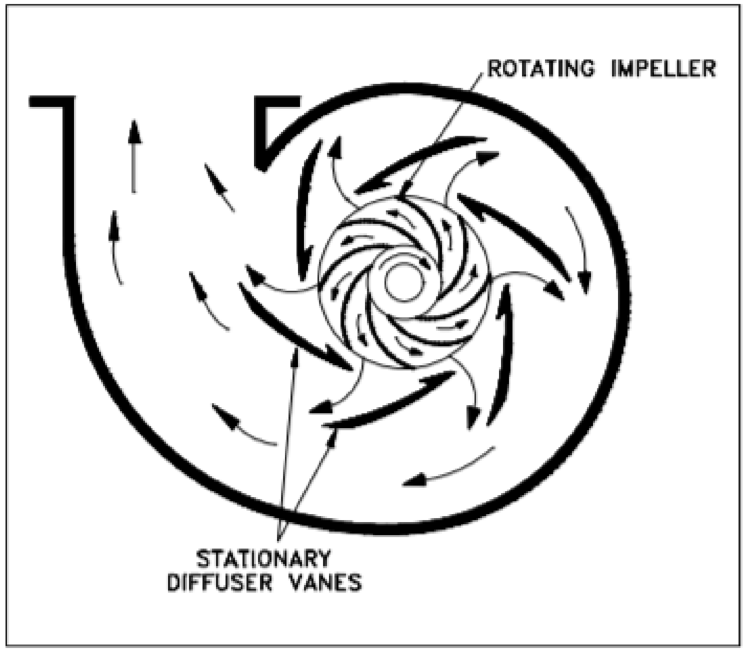


Figure 3 Centrifugal Pump Diffuser

Impeller Classification

Impellers of pumps are classified based on the number of points that the liquid can enter the impeller and also on the amount of webbing between the impeller blades.

Impellers can be either single-

suction or double-suction. A single-suction impeller allows liquid to enter the center of the blades from only one direction. A double-suction impeller allows liquid to enter the center of the impeller blades from both sides simultaneously. Figure 4 shows simplified diagrams of single and double-suction impellers.

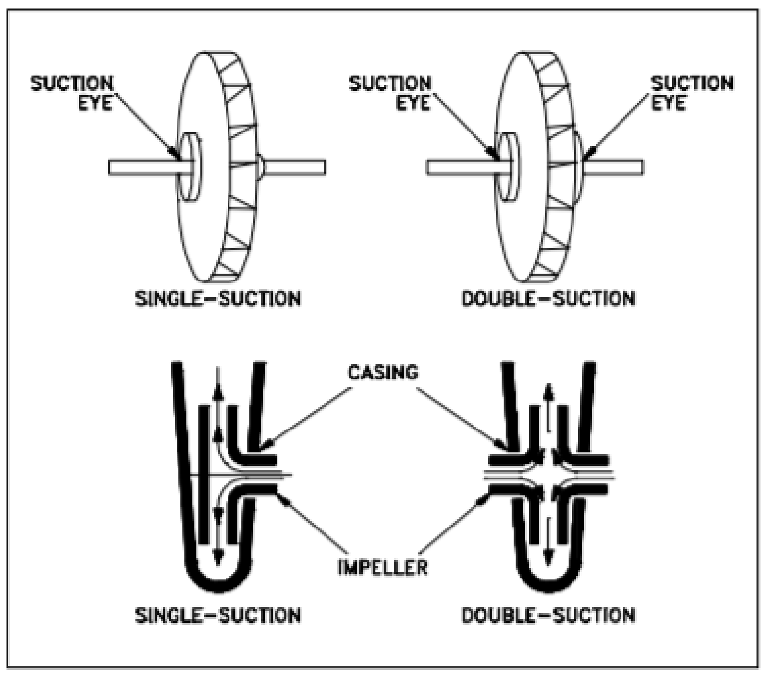


Figure 4 Single-Suction and Double-Suction Impellers

Q3

Impellers can be open, semi-open, or enclosed. The open impeller consists only of blades attached to a hub. The semi-open impeller is constructed with a circular plate (the web) attached to one side of the blades. The enclosed impeller has circular plates attached to both sides of the blades. Enclosed impellers are also referred to as shrouded impellers. Figure 5 illustrates examples of open, semi-open, and enclosed impellers.

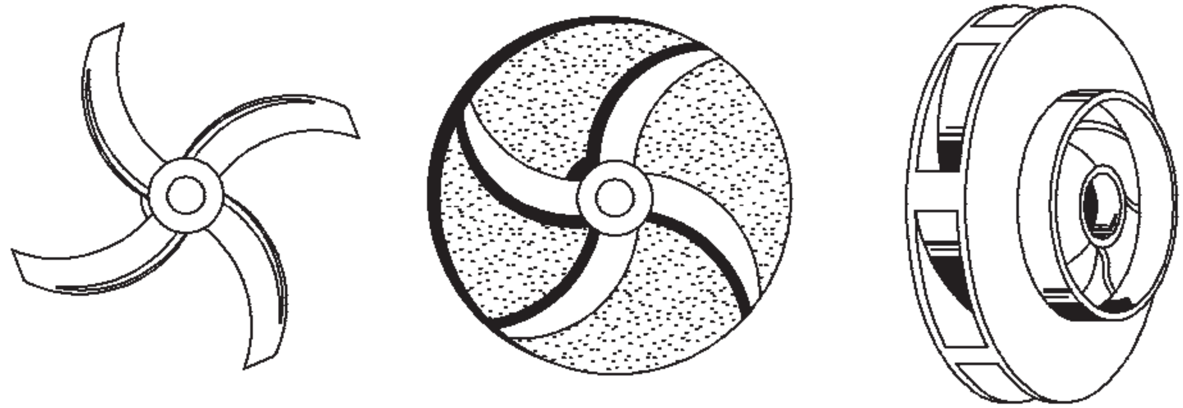


Figure 5 Open, Semi-Open, and Enclosed Impellers

The impeller sometimes contains balancing holes that connect the space around the hub to the suction side of the impeller. The balancing holes have a total cross-sectional area that is considerably greater than the cross-sectional area of the annular space between the wearing ring and the hub. The result is suction pressure on both sides of the impeller hub, which maintains a hydraulic balance of axial thrust.

Centrifugal Pump Classification by Flow

Centrifugal pumps can be classified based on the manner in which fluid flows through the pump. The manner in which fluid flows through the pump is determined by the design of the pump casing and the impeller. The three types of flow through a centrifugal pump are radial flow, axial flow, and mixed flow.

Radial Flow Pumps

In a radial flow pump, the liquid enters at the center of the impeller and is directed out along the impeller blades in a direction at right angles to the pump shaft. The impeller of a typical radial flow pump and the flow through a radial flow pump are shown in Figure 6.

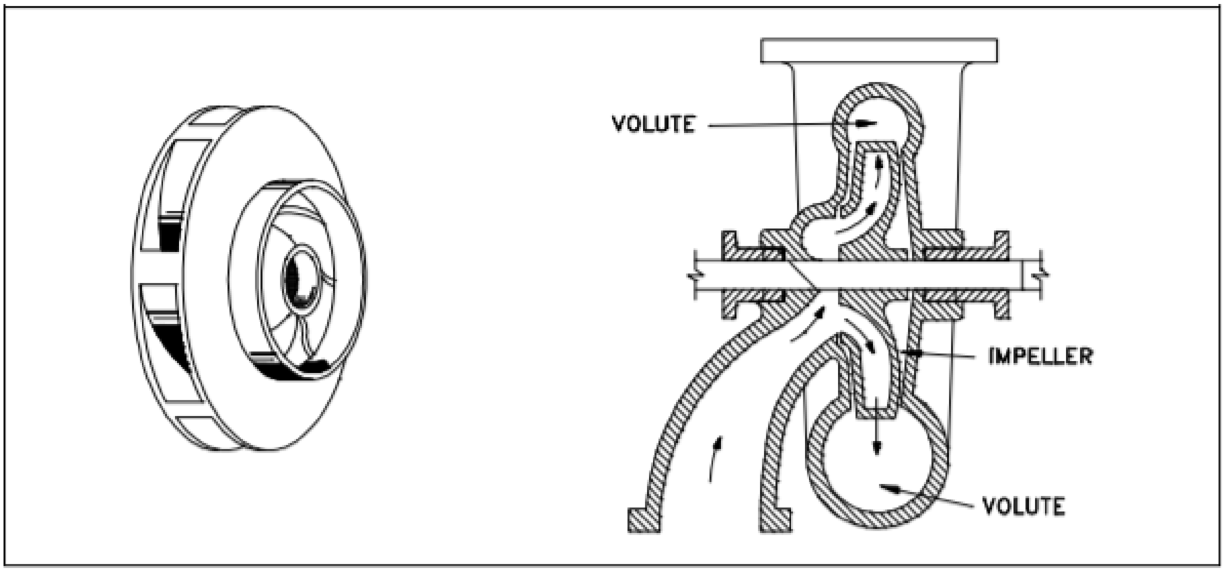


Figure 6 Radial Flow Centrifugal Pump

Axial Flow Pumps

Q4

In an axial flow pump, the impeller pushes the liquid in a direction parallel to the pump shaft. Axial flow pumps are sometimes called propeller pumps because they operate essentially the same as the propeller of a boat. The impeller of a typical axial flow pump and the flow through a radial flow pump are shown in Figure 7.

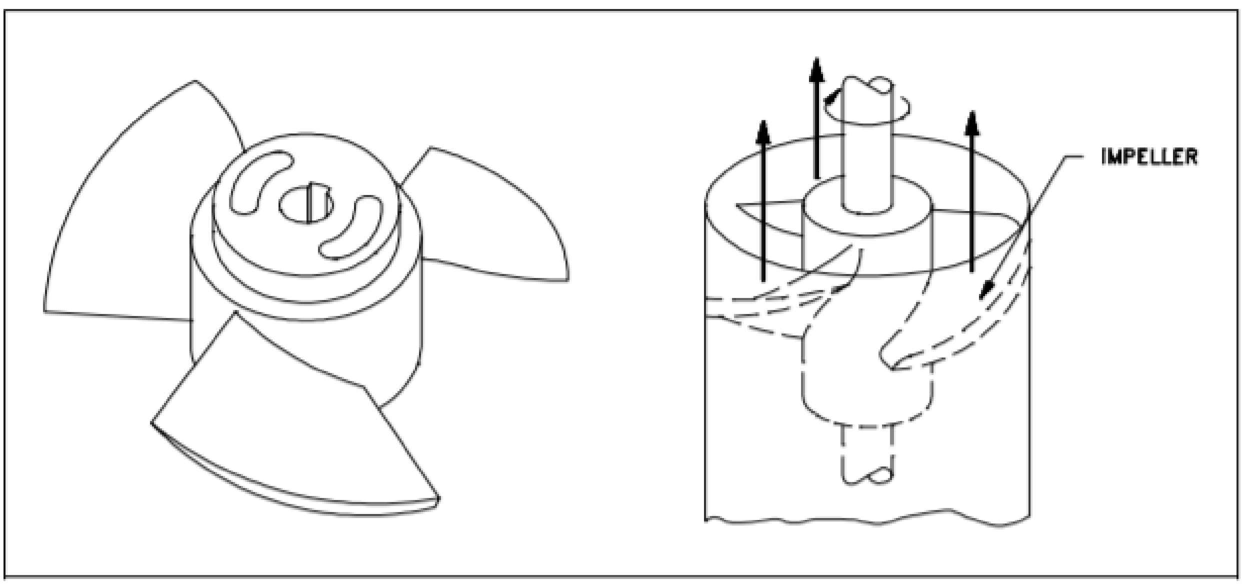


Figure 7 Axial Flow Centrifugal Pump

Mixed Flow Pumps

Mixed flow pumps borrow characteristics from both radial flow and axial flow pumps. As liquid flows through the impeller of a mixed flow pump, the impeller blades push the liquid out away from the pump shaft and to the pump suction at an angle greater than 90^{o}. The impeller of a typical mixed flow pump and the flow through a mixed flow pump are shown in Figure 8.

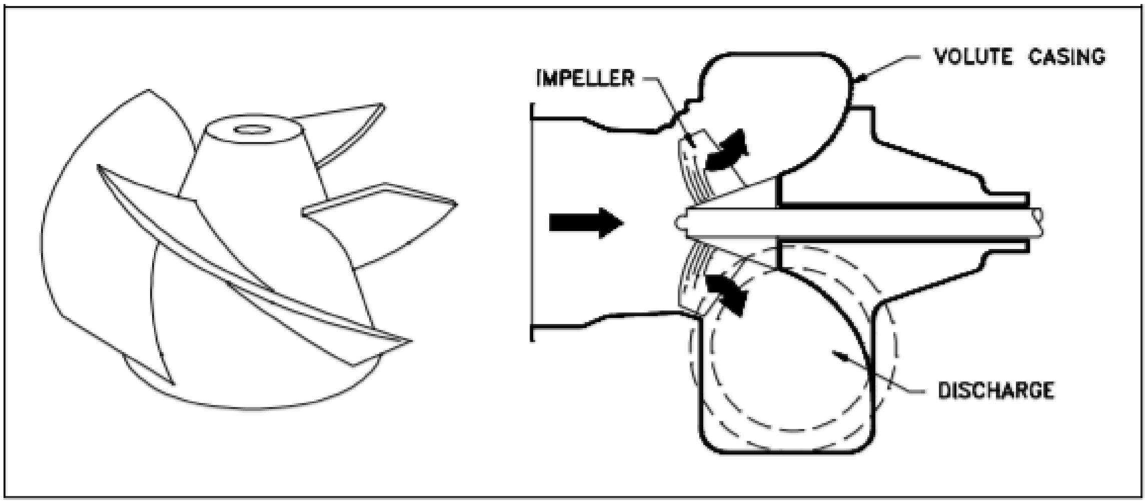


Figure 8 Mixed Flow Centrifugal Pump

Multi-Stage Centrifugal Pumps

A centrifugal pump with a single impeller that can develop a differential pressure of more than 150 psid between the suction and the discharge is difficult and costly to design and construct. A more economical approach to developing high pressures with a single centrifugal pump is to include multiple impellers on a common shaft within the same pump casing. Internal channels in the pump casing route the discharge of one impeller to the suction of another impeller. Figure 9 shows a diagram of the arrangement of the impellers of a four-stage pump. The water enters the pump from the top left and passes through each of the four impellers in series, going from left to right. The water goes from the volute surrounding the discharge of one impeller to the suction of the next impeller.

A *pump stage* is defined as that portion of a centrifugal pump consisting of one impeller and its associated components. Most centrifugal pumps are single-stage pumps, containing only one impeller. A pump containing seven impellers within a single casing would be referred to as a seven-stage pump or, or generally, as a multi-stage pump.

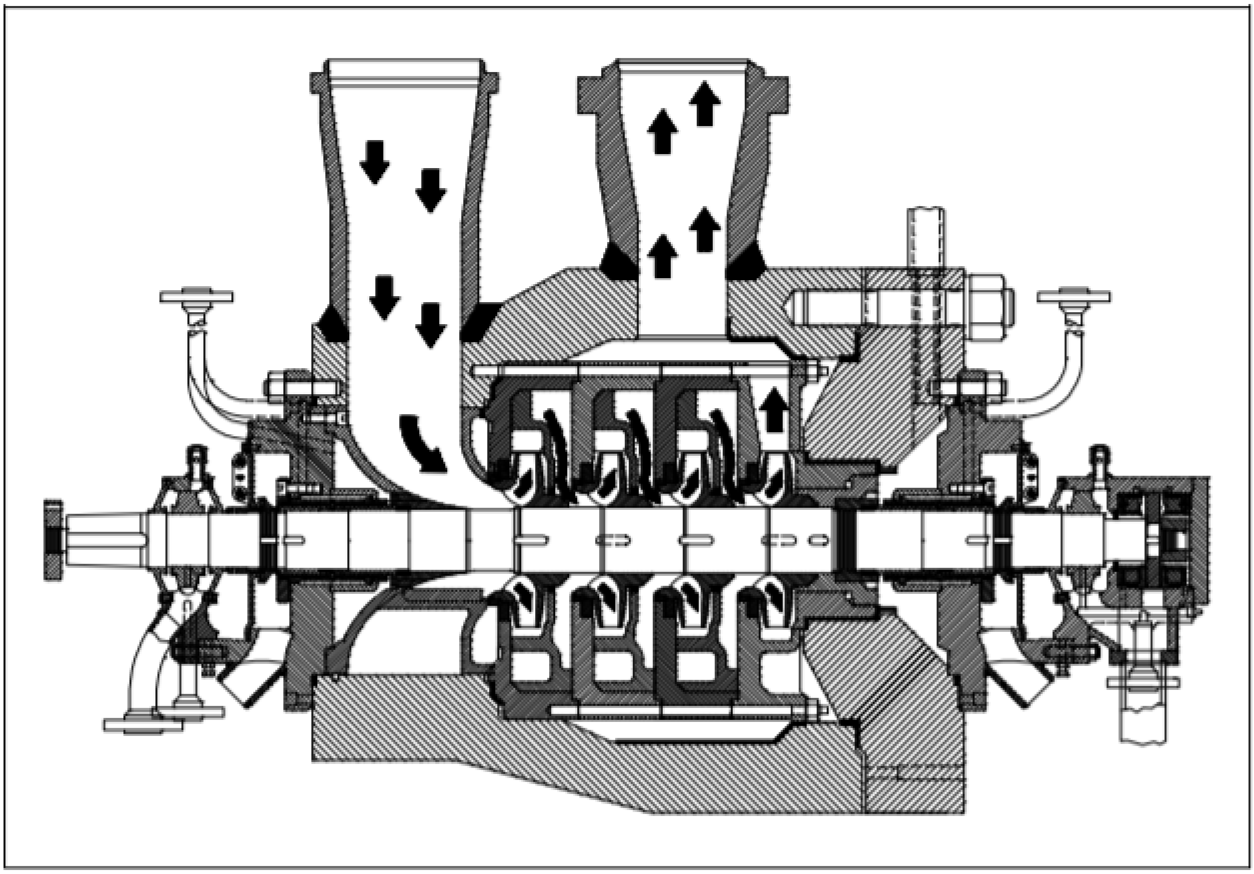


Figure 9 Multi-Stage Centrifugal Pump

Centrifugal Pump Components

Centrifugal pumps vary in design and construction from simple pumps with relatively few parts to extremely complicated pumps with hundreds of individual parts. Some of the most common components found in centrifugal pumps are wearing rings, stuffing boxes, packing, and lantern rings. These components are shown in Figure 10 and described on the following pages.

Wearing Rings

Centrifugal pumps contain rotating impellers within stationary pump casings. To allow the impeller to rotate freely within the pump casing, a small clearance is designed to be maintained between the impeller and the pump casing. To maximize the efficiency of a centrifugal pump, it is necessary to minimize the amount of liquid leaking through this clearance from the high pressure or discharge side of the pump back to the low pressure or suction side.

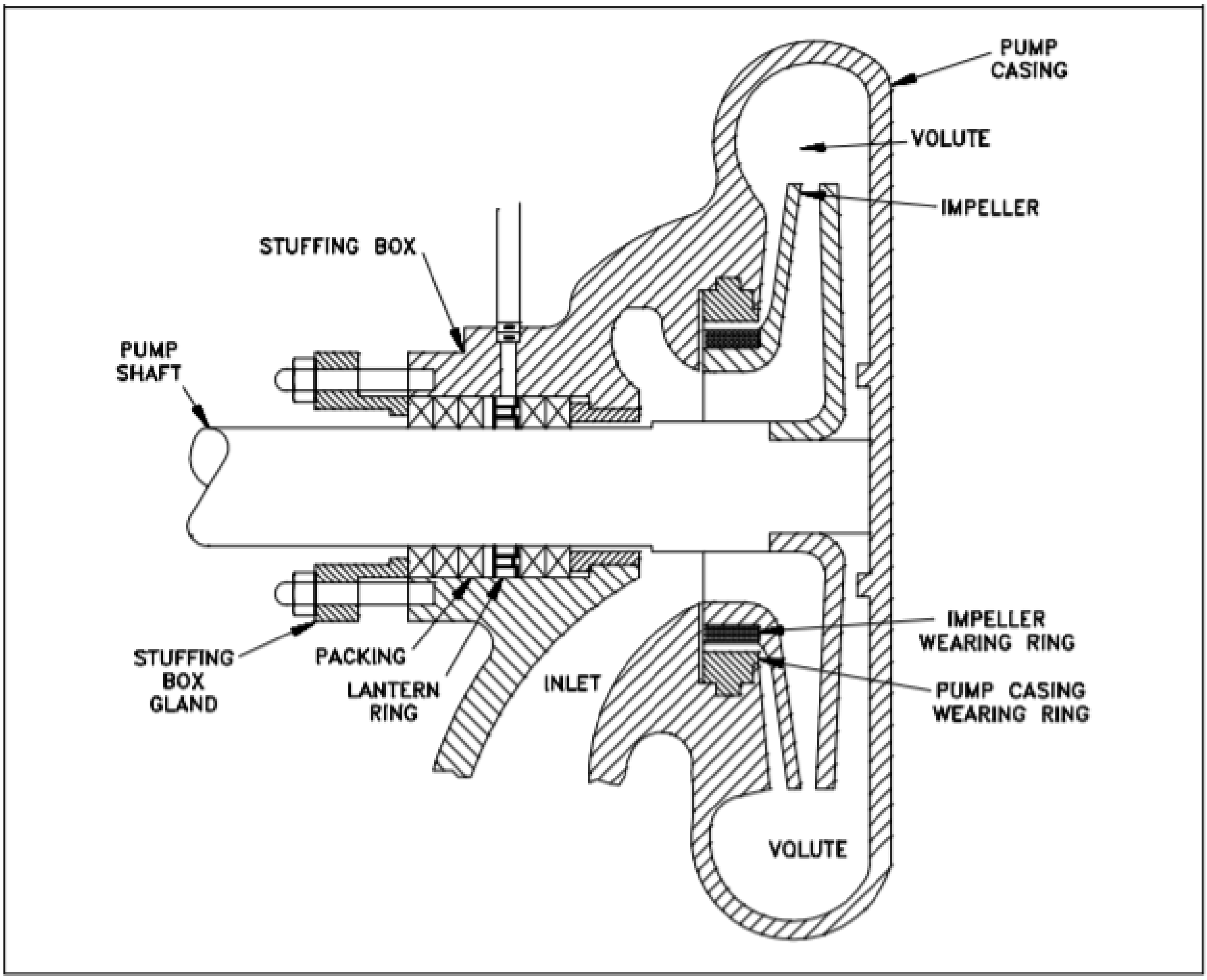


Figure 10 Centrifugal Pump Components

Some wear or erosion will occur at the point where the impeller and the pump casing nearly come into contact. This wear is due to the erosion caused by liquid leaking through this tight clearance and other causes. As wear occurs, the clearances become larger and the rate of leakage increases. Eventually, the leakage could become unacceptably large and maintenance would be required on the pump.

To minimize the cost of pump maintenance, many centrifugal pumps are designed with wearing rings. *Wearing rings* are replaceable rings that are attached to the impeller and/or the pump casing to allow a small running clearance between the impeller and the pump casing without causing wear of the actual impeller or pump casing material. These wearing rings are designed to be replaced periodically during the life of a pump and prevent the more costly replacement of the impeller or the casing.

Stuffing Box

Q5

In almost all centrifugal pumps, the rotating shaft that drives the impeller penetrates the pressure boundary of the pump casing. It is important that the pump is designed properly to control the amount of liquid that leaks along the shaft at the point that the shaft penetrates the pump casing. There are many different methods of sealing the shaft penetration of the pump casing. Factors considered when choosing a method include the pressure and temperature of the fluid being pumped, the size of the pump, and the chemical and physical characteristics of the fluid being pumped.

One of the simplest types of shaft seal is the stuffing box. The *stuffing box* is a cylindrical space in the pump casing surrounding the shaft. Rings of packing material are placed in this space. *Packing* is material in the form of rings or strands that is placed in the stuffing box to form a seal to control the rate of leakage along the shaft. The packing rings are held in place by a gland. The gland is, in turn, held in place by studs with adjusting nuts. As the adjusting nuts are tightened, they move the gland in and compress the packing. This axial compression causes the packing to expand radially, forming a tight seal between the rotating shaft and the inside wall of the stuffing box.

The high speed rotation of the shaft generates a significant amount of heat as it rubs against the packing rings. If no lubrication and cooling are provided to the packing, the temperature of the packing increases to the point where damage occurs to the packing, the pump shaft, and possibly nearby pump bearings. Stuffing boxes are normally designed to allow a small amount of controlled leakage along the shaft to provide lubrication and cooling to the packing. The leakage rate can be adjusted by tightening and loosening the packing gland.

Lantern Ring

It is not always possible to use a standard stuffing box to seal the shaft of a centrifugal pump. The pump suction may be under a vacuum so that outward leakage is impossible or the fluid may be too hot to provide adequate cooling of the packing. These conditions require a modification to the standard stuffing box. Q6

One method of adequately cooling the packing under these conditions is to include a lantern ring. A *lantern ring* is a perforated hollow ring located near the center of the packing box that receives relatively cool, clean liquid from either the discharge of the pump or from an external source and distributes the liquid uniformly around the shaft to provide lubrication and cooling. The fluid entering the lantern ring can cool the shaft and packing, lubricate the packing, or seal the joint between the shaft and packing against leakage of air into the pump in the event the pump suction pressure is less than that of the atmosphere.

Mechanical Seals

In some situations, packing material is not adequate for sealing the shaft. One common alternative method for sealing the shaft is with mechanical seals. Mechanical seals consist of two basic parts, a rotating element attached to the pump shaft and a stationary element attached to the pump casing. Each of these elements has a highly polished sealing surface. The polished faces of the rotating and stationary elements come into contact with each other to form a seal that prevents leakage along the shaft.

Summary

The important information in this chapter is summarized below.

Centrifugal Pumps Summary

- The impeller contains rotating vanes that impart a radial and rotary motion to the liquid.
- The volute collects the liquid discharged from the impeller at high velocity and gradually causes a reduction in fluid velocity by increasing the flow area, converting the velocity head to a static head.
- A diffuser increases the efficiency of a centrifugal pump by allowing a more gradual expansion and less turbulent area for the liquid to slow as the flow area expands.
- Packing material provides a seal in the area where the pump shaft penetrates the pump casing.
- Wearing rings are replaceable rings that are attached to the impeller and/or the pump casing to allow a small running clearance between the impeller and pump casing without causing wear of the actual impeller or pump casing material.
- The lantern ring is inserted between rings of packing in the stuffing box to receive relatively cool, clean liquid and distribute the liquid uniformly around the shaft to provide lubrication and cooling to the packing.

CENTRIFUGAL PUMP OPERATION

Improper operation of centrifugal pumps can result in damage to the pump and loss of function of the system that the pump is installed in. It is helpful to know what conditions can lead to pump damage to allow better understanding of pump operating procedures and how the procedures aid the operator in avoiding pump damage.

EO 1.3 **DEFINE** the following terms:

a. Net Positive Suction Head Available
b. Cavitation
c. Gas binding
d. Shutoff head
e. Pump runout

EO 1.4 **STATE** the relationship between net positive suction head available and net positive suction head required that is necessary to avoid cavitation.

EO 1.5 **LIST** three indications that a centrifugal pump may be cavitating.

EO 1.6 **LIST** five changes that can be made in a pump or its surrounding system that can reduce cavitation.

EO 1.7 **LIST** three effects of cavitation.

EO 1.8 **DESCRIBE** the shape of the characteristic curve for a centrifugal pump.

EO 1.9 **DESCRIBE** how centrifugal pumps are protected from the conditions of dead heading and pump runout.

Introduction

Many centrifugal pumps are designed in a manner that allows the pump to operate continuously for months or even years. These centrifugal pumps often rely on the liquid that they are pumping to provide cooling and lubrication to the pump bearings and other internal components of the pump. If flow through the pump is stopped while the pump is still operating, the pump will no longer be adequately cooled and the pump can quickly become damaged. Pump damage can also result from pumping a liquid whose temperature is close to saturated conditions.

Q7

Cavitation

The flow area at the eye of the pump impeller is usually smaller than either the flow area of the pump suction piping or the flow area through the impeller vanes. When the liquid being pumped enters the eye of a centrifugal pump, the decrease in flow area results in an increase in flow velocity accompanied by a decrease in pressure. The greater the pump flow rate, the greater the pressure drop between the pump suction and the eye of the impeller. If the pressure drop is large enough, or if the temperature is high enough, the pressure drop may be sufficient to cause the liquid to flash to vapor when the local pressure falls below the saturation pressure for the fluid being pumped. Any vapor bubbles formed by the pressure drop at the eye of the impeller are swept along the impeller vanes by the flow of the fluid. When the bubbles enter a region where local pressure is greater than saturation pressure farther out the impeller vane, the vapor bubbles abruptly collapse. This process of the formation and subsequent collapse of vapor bubbles in a pump is called *cavitation*.

Cavitation in a centrifugal pump has a significant effect on pump performance. Cavitation degrades the performance of a pump, resulting in a fluctuating flow rate and discharge pressure. Cavitation can also be destructive to pumps internal components. When a pump cavitates, vapor bubbles form in the low pressure region directly behind the rotating impeller vanes. These vapor bubbles then move toward the oncoming impeller vane, where they collapse and cause a physical shock to the leading edge of the impeller vane. This physical shock creates small pits on the leading edge of the impeller vane. Each individual pit is microscopic in size, but the cumulative effect of millions of these pits formed over a period of hours or days can literally destroy a pump impeller. Cavitation can also cause excessive pump vibration, which could damage pump bearings, wearing rings, and seals.

A small number of centrifugal pumps are designed to operate under conditions where cavitation is unavoidable. These pumps must be specially designed and maintained to withstand the small amount of cavitation that occurs during their operation. Most centrifugal pumps are not designed to withstand sustained cavitation.

Noise is one of the indications that a centrifugal pump is cavitating. A cavitating pump can sound like a can of marbles being shaken. Other indications that can be observed from a remote operating station are fluctuating discharge pressure, flow rate, and pump motor current. Methods to stop or prevent cavitation are presented in the following paragraphs.

Net Positive Suction Head

To avoid cavitation in centrifugal pumps, the pressure of the fluid at all points within the pump must remain above saturation pressure. The quantity used to determine if the pressure of the liquid being pumped is adequate to avoid cavitation is the net positive suction head (NPSH). The *net positive suction head available* ($NPSH_A$) is the difference between the pressure at the suction of the pump and the saturation pressure for the liquid being pumped. The *net positive suction head required* ($NPSH_R$) is the minimum net positive suction head necessary to avoid cavitation.

The condition that must exist to avoid cavitation is that the net positive suction head available must be greater than or equal to the net positive suction head required. This requirement can be stated mathematically as shown below.

$$NPSH_A \geq NPSH_R$$

A formula for $NPSH_A$ can be stated as the following equation.

$$NPSH_A = P_{suction} - P_{saturation}$$

When a centrifugal pump is taking suction from a tank or other reservoir, the pressure at the suction of the pump is the sum of the absolute pressure at the surface of the liquid in the tank plus the pressure due to the elevation difference between the surface of liquid in the tank and the pump suction less the head losses due to friction in the suction line from the tank to the pump.

$$NPSH_A = P_a + P_{st} - h_f - P_{sat}$$

Where:

$NPSH_A$ = net positive suction head available

P_a = absolute pressure on the surface of the liquid

P_{st} = pressure due to elevation between liquid surface and pump suction

h_f = head losses in the pump suction piping

P_{sat} = saturation pressure of the liquid being pumped

Preventing Cavitation

Q8

If a centrifugal pump is cavitating, several changes in the system design or operation may be necessary to increase the $NPSH_A$ above the $NPSH_R$ and stop the cavitation. One method for increasing the $NPSH_A$ is to increase the pressure at the suction of the pump. For example, if a pump is taking suction from an enclosed tank, either raising the level of the liquid in the tank or increasing the pressure in the space above the liquid increases suction pressure.

It is also possible to increase the $NPSH_A$ by decreasing the temperature of the liquid being pumped. Decreasing the temperature of the liquid decreases the saturation pressure, causing $NPSH_A$ to increase. Recall from the previous module on heat exchangers that large steam condensers usually subcool the condensate to less than the saturation temperature, called condensate depression, to prevent cavitation in the condensate pumps.

If the head losses in the pump suction piping can be reduced, the $NPSH_A$ will be increased. Various methods for reducing head losses include increasing the pipe diameter, reducing the number of elbows, valves, and fittings in the pipe, and decreasing the length of the pipe.

It may also be possible to stop cavitation by reducing the $NPSH_R$ for the pump. The $NPSH_R$ is not a constant for a given pump under all conditions, but depends on certain factors. Typically, the $NPSH_R$ of a pump increases significantly as flow rate through the pump increases. Therefore, reducing the flow rate through a pump by throttling a discharge valve decreases $NPSH_R$. $NPSH_R$ is also dependent upon pump speed. The faster the impeller of a pump rotates, the greater the $NPSH_R$. Therefore, if the speed of a variable speed centrifugal pump is reduced, the $NPSH_R$ of the pump decreases. However, since a pump's flow rate is most often dictated by the needs of the system on which it is connected, only limited adjustments can be made without starting additional parallel pumps, if available.

The net positive suction head required to prevent cavitation is determined through testing by the pump manufacturer and depends upon factors including type of impeller inlet, impeller design, pump flow rate, impeller rotational speed, and the type of liquid being pumped. The manufacturer typically supplies curves of $NPSH_R$ as a function of pump flow rate for a particular liquid (usually water) in the vendor manual for the pump.

Centrifugal Pump Characteristic Curves

For a given centrifugal pump operating at a constant speed, the flow rate through the pump is dependent upon the differential pressure or head developed by the pump. The lower the pump head, the higher the flow rate. A vendor manual for a specific pump usually contains a curve of pump flow rate versus pump head called a pump characteristic curve. After a pump is installed in a system, it is usually tested to ensure that the flow rate and head of the pump are within the required specifications. A typical centrifugal pump characteristic curve is shown in Figure 11.

There are several terms associated with the pump characteristic curve that must be defined. *Shutoff head* is the maximum head that can be developed by a centrifugal pump operating at a set speed. *Pump runout* is the maximum flow that can be developed by a centrifugal pump without damaging the pump. Centrifugal pumps must be designed and operated to be protected from the conditions of pump runout or operating at shutoff head. Additional information may be found in the handbook on Thermodynamics, Heat Transfer, and Fluid Flow.

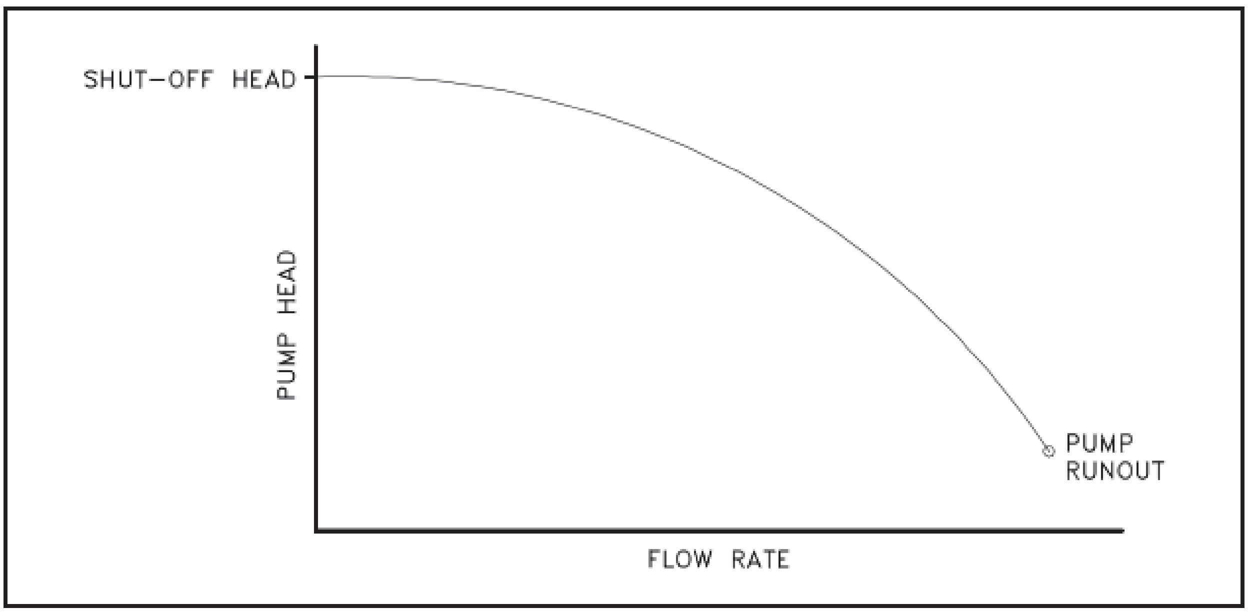


Figure 11 Centrifugal Pump Characteristic Curve

Centrifugal Pump Protection

A centrifugal pump is dead-headed when it is operated with no flow through it, for example, with a closed discharge valve or against a seated check valve. If the discharge valve is closed and there is no other flow path available to the pump, the impeller will churn the same volume of water as it rotates in the pump casing. This will increase the temperature of the liquid (due to friction) in the pump casing to the point that it will flash to vapor. The vapor can interrupt the cooling flow to the pump's packing and bearings, causing excessive wear and heat. If the pump is run in this condition for a significant amount of time, it will become damaged.

When a centrifugal pump is installed in a system such that it may be subjected to periodic shutoff head conditions, it is necessary to provide some means of pump protection. One method for protecting the pump from running dead-headed is to provide a recirculation line from the pump discharge line upstream of the discharge valve, back to the pump's supply source. The recirculation line should be sized to allow enough flow through the pump to prevent overheating and damage to the pump. Protection may also be accomplished by use of an automatic flow control device.

Centrifugal pumps must also be protected from runout. Runout can lead to cavitation and can also cause overheating of the pump's motor due to excessive currents. One method for ensuring that there is always adequate flow resistance at the pump discharge to prevent excessive flow through the pump is to place an orifice or a throttle valve immediately downstream of the pump discharge. Properly designed piping systems are very important to protect from runout.

Gas Binding

Q9

Gas binding of a centrifugal pump is a condition where the pump casing is filled with gases or vapors to the point where the impeller is no longer able to contact enough fluid to function correctly. The impeller spins in the gas bubble, but is unable to force liquid through the pump. This can lead to cooling problems for the pump's packing and bearings.

Centrifugal pumps are designed so that their pump casings are completely filled with liquid during pump operation. Most centrifugal pumps can still operate when a small amount of gas accumulates in the pump casing, but pumps in systems containing dissolved gases that are not designed to be self-venting should be periodically vented manually to ensure that gases do not build up in the pump casing.

Priming Centrifugal Pumps

Most centrifugal pumps are not self-priming. In other words, the pump casing must be filled with liquid before the pump is started, or the pump will not be able to function. If the pump casing becomes filled with vapors or gases, the pump impeller becomes gas-bound and incapable of pumping. To ensure that a centrifugal pump remains primed and does not become gas-bound, most centrifugal pumps are located below the level of the source from which the pump is to take its suction. The same effect can be gained by supplying liquid to the pump suction under pressure supplied by another pump placed in the suction line.

Summary

The important information in this chapter is summarized below.

Centrifugal Pump Operation Summary

- There are three indications that a centrifugal pump is cavitating.
    - Noise
    - Fluctuating discharge pressure and flow
    - Fluctuating pump motor current
- Steps that can be taken to stop pump cavitation include:
    - Increase the pressure at the suction of the pump.
    - Reduce the temperature of the liquid being pumped.
    - Reduce head losses in the pump suction piping.
    - Reduce the flow rate through the pump.
    - Reduce the speed of the pump impeller.
- Three effects of pump cavitation are:
    - Degraded pump performance
    - Excessive pump vibration
    - Damage to pump impeller, bearings, wearing rings, and seals
- To avoid pump cavitation, the net positive suction head available must be greater than the net positive suction head required.
- Net positive suction head available is the difference between the pump suction pressure and the saturation pressure for the liquid being pumped.
- Cavitation is the process of the formation and subsequent collapse of vapor bubbles in a pump.
- Gas binding of a centrifugal pump is a condition where the pump casing is filled with gases or vapors to the point where the impeller is no longer able to contact enough fluid to function correctly.
- Shutoff head is the maximum head that can be developed by a centrifugal pump operating at a set speed.

Centrifugal Pump Operation Summary (Cont.)

- Pump runout is the maximum flow that can be developed by a centrifugal pump without damaging the pump.
- The greater the head against which a centrifugal pump operates, the lower the flow rate through the pump. The relationship between pump flow rate and head is illustrated by the characteristic curve for the pump.
- Centrifugal pumps are protected from dead-heading by providing a recirculation from the pump discharge back to the supply source of the pump.
- Centrifugal pumps are protected from runout by placing an orifice or throttle valve immediately downstream of the pump discharge and through proper piping system design.

POSITIVE DISPLACEMENT PUMPS

Positive displacement pumps operate on a different principle than centrifugal pumps. Positive displacement pumps physically entrap a quantity of liquid at the suction of the pump and push that quantity out the discharge of the pump.

EO 2.1 **STATE** the difference between the flow characteristics of centrifugal and positive displacement pumps.

EO 2.2 Given a simplified drawing of a positive displacement pump, **CLASSIFY** the pump as one of the following:

a. Reciprocating piston pump
b. Gear-type rotary pump
c. Screw-type rotary pump
d. Lobe-type rotary pump
e. Moving vane pump
f. Diaphragm pump

EO 2.3 **EXPLAIN** the importance of viscosity as it relates to the operation of a reciprocating positive displacement pump.

EO 2.4 **DESCRIBE** the characteristic curve for a positive displacement pump.

EO 2.5 **DEFINE** the term slippage.

EO 2.6 **STATE** how positive displacement pumps are protected against overpressurization.

Introduction

Q10

A positive displacement pump is one in which a definite volume of liquid is delivered for each cycle of pump operation. This volume is constant regardless of the resistance to flow offered by the system the pump is in, provided the capacity of the power unit driving the pump or pump component strength limits are not exceeded. The positive displacement pump delivers liquid in separate volumes with no delivery in between, although a pump having several chambers may have an overlapping delivery among individual chambers, which minimizes this effect. The positive displacement pump differs from centrifugal pumps, which deliver a continuous flow for any given pump speed and discharge resistance.

Positive displacement pumps can be grouped into three basic categories based on their design and operation. The three groups are reciprocating pumps, rotary pumps, and diaphragm pumps.

Principle of Operation

All positive displacement pumps operate on the same basic principle. This principle can be most easily demonstrated by considering a reciprocating positive displacement pump consisting of a single reciprocating piston in a cylinder with a single suction port and a single discharge port as shown in Figure 12. Check valves in the suction and discharge ports allow flow in only one direction.

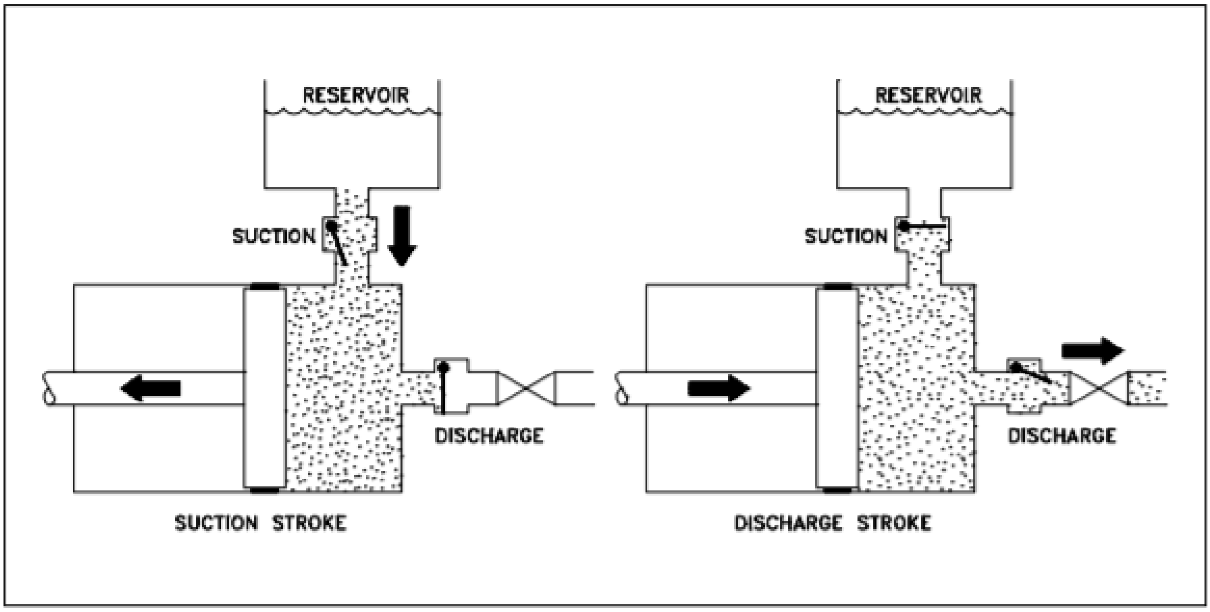


Figure 12 Reciprocating Positive Displacement Pump Operation

During the suction stroke, the piston moves to the left, causing the check valve in the suction line between the reservoir and the pump cylinder to open and admit water from the reservoir. During the discharge stroke, the piston moves to the right, seating the check valve in the suction line and opening the check valve in the discharge line. The volume of liquid moved by the pump in one cycle (one suction stroke and one discharge stroke) is equal to the change in the liquid volume of the cylinder as the piston moves from its farthest left position to its farthest right position.

Reciprocating Pumps

Reciprocating positive displacement pumps are generally categorized in four ways: direct-acting or indirect-acting; simplex or duplex; single-acting or double-acting; and power pumps.

Direct-Acting and Indirect-Acting Pumps

Some reciprocating pumps are powered by prime movers that also have reciprocating motion, such as a reciprocating pump powered by a reciprocating steam piston. The piston rod of the steam piston may be directly connected to the liquid piston of the pump or it may be indirectly connected with a beam or linkage. *Direct-acting* pumps have a plunger on the liquid (pump) end that is directly driven by the pump rod (also the piston rod or extension thereof) and carries the piston of the power end. *Indirect-acting* pumps are driven by means of a beam or linkage connected to and actuated by the power piston rod of a separate reciprocating engine.

Simplex and Duplex Pumps

Q11

A *simplex* pump, sometimes referred to as a single pump, is a pump having a single liquid (pump) cylinder. A *duplex* pump is the equivalent of two simplex pumps placed side by side on the same foundation.

The driving of the pistons of a duplex pump is arranged in such a manner that when one piston is on its upstroke the other piston is on its downstroke, and vice versa. This arrangement doubles the capacity of the duplex pump compared to a simplex pump of comparable design.

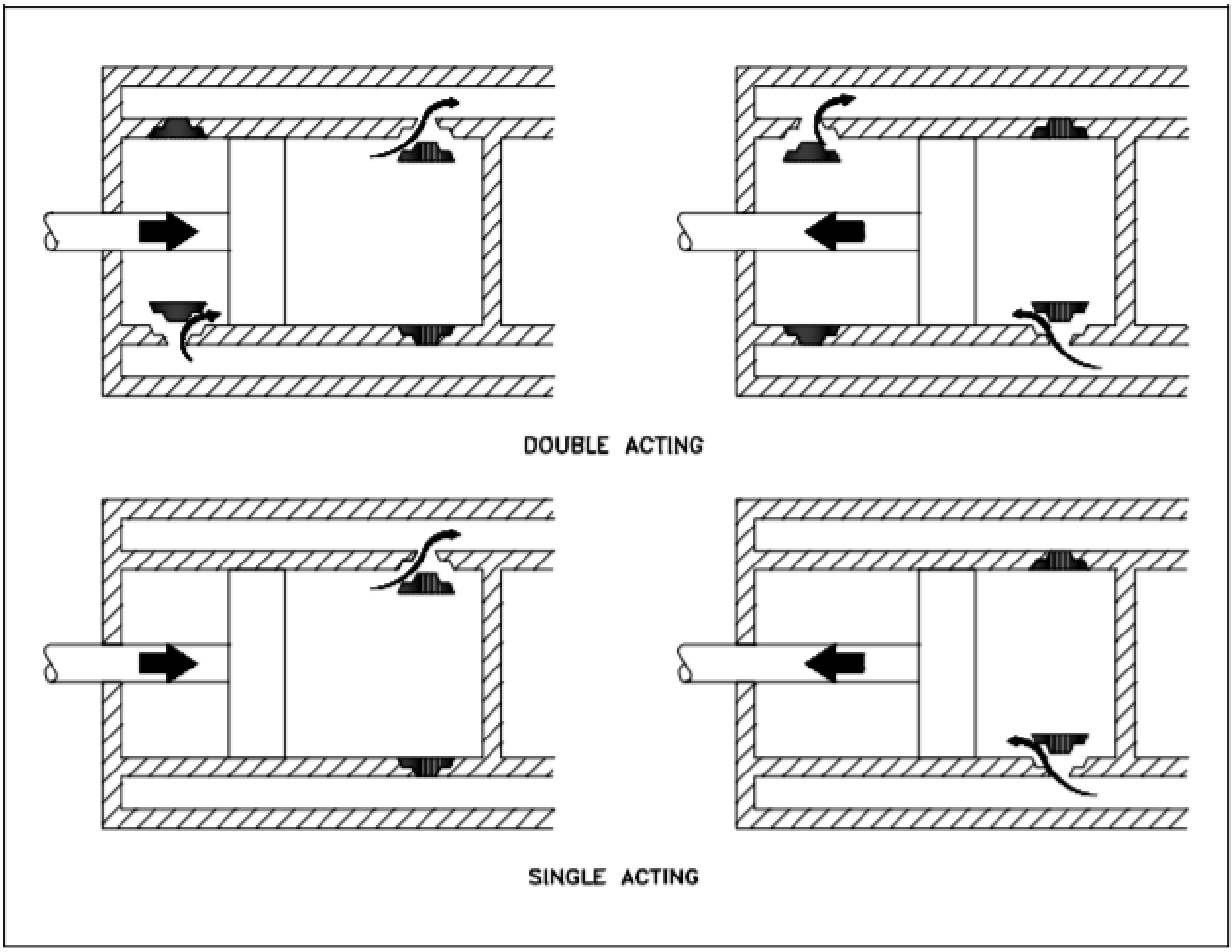


Figure 13 Single-Acting and Double-Acting Pumps

Single-Acting and Double-Acting Pumps

A *single-acting* pump is one that takes a suction, filling the pump cylinder on the stroke in only one direction, called the suction stroke, and then forces the liquid out of the cylinder on the return stroke, called the discharge stroke. A *double-acting* pump is one that, as it fills one end of the liquid cylinder, is discharging liquid from the other end of the cylinder. On the return stroke, the end of the cylinder just emptied is filled, and the end just filled is emptied. One possible arrangement for single-acting and double-acting pumps is shown in Figure 13.

Power Pumps

Power pumps convert rotary motion to low speed reciprocating motion by reduction gearing, a crankshaft, connecting rods and crossheads. Plungers or pistons are driven by the crosshead drives. Rod and piston construction, similar to duplex double-acting steam pumps, is used by the liquid ends of the low pressure, higher capacity units. The higher pressure units are normally single-acting plungers, and usually employ three (triplex) plungers. Three or more plungers substantially reduce flow pulsations relative to simplex and even duplex pumps.

Power pumps typically have high efficiency and are capable of developing very high pressures. They can be driven by either electric motors or turbines. They are relatively expensive pumps and can rarely be justified on the basis of efficiency over centrifugal pumps. However, they are frequently justified over steam reciprocating pumps where continuous duty service is needed due to the high steam requirements of direct-acting steam pumps.

In general, the effective flow rate of reciprocating pumps decreases as the viscosity of the fluid being pumped increases because the speed of the pump must be reduced. In contrast to centrifugal pumps, the differential pressure generated by reciprocating pumps is independent of fluid density. It is dependent entirely on the amount of force exerted on the piston. For more information on viscosity, density, and positive displacement pump theory, refer to the handbook on Thermodynamics, Heat Transfer, and Fluid Flow.

Rotary Pumps

Rotary pumps operate on the principle that a rotating vane, screw, or gear traps the liquid in the suction side of the pump casing and forces it to the discharge side of the casing. These pumps are essentially self-priming due to their capability of removing air from suction lines and producing a high suction lift. In pumps designed for systems requiring high suction lift and self-priming features, it is essential that all clearances between rotating parts, and between rotating and stationary parts, be kept to a minimum in order to reduce slippage. *Slippage* is leakage of fluid from the discharge of the pump back to its suction.

Due to the close clearances in rotary pumps, it is necessary to operate these pumps at relatively low speed in order to secure reliable operation and maintain pump capacity over an extended period of time. Otherwise, the erosive action due to the high velocities of the liquid passing through the narrow clearance spaces would soon cause excessive wear and increased clearances, resulting in slippage.

There are many types of positive displacement rotary pumps, and they are normally grouped into three basic categories that include gear pumps, screw pumps, and moving vane pumps.

Q12

Simple Gear Pump

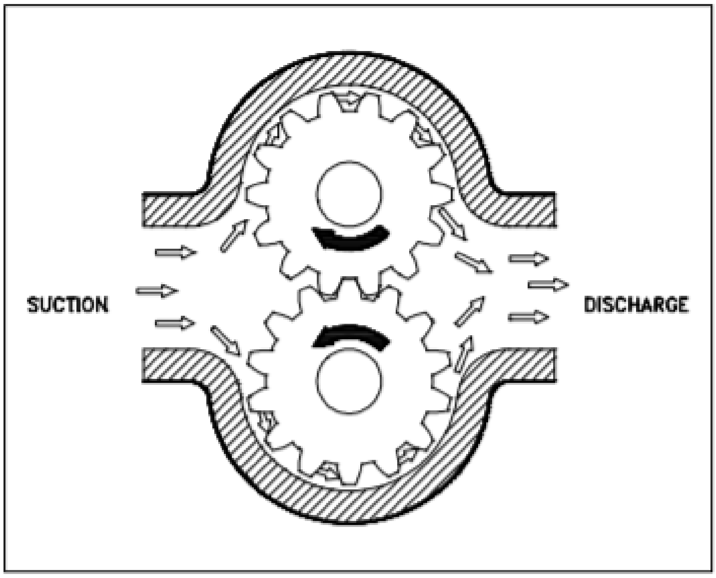


Figure 14 Simple Gear Pump

There are several variations of gear pumps. The simple gear pump shown in Figure 14 consists of two spur gears meshing together and revolving in opposite directions within a casing. Only a few thousandths of an inch clearance exists between the case and the gear faces and teeth extremities. Any liquid that fills the space bounded by two successive gear teeth and the case must follow along with the teeth as they revolve. When the gear teeth mesh with the teeth of the other gear, the space between the teeth is reduced, and the entrapped liquid is forced out the pump discharge pipe. As the gears revolve and the teeth disengage, the space again opens on the suction side of the pump, trapping new quantities of liquid and carrying it around the pump case to the discharge. As liquid is carried away from the suction side, a lower pressure is created, which draws liquid in through the suction line.

With the large number of teeth usually employed on the gears, the discharge is relatively smooth and continuous, with small quantities of liquid being delivered to the discharge line in rapid succession. If designed with fewer teeth, the space between the teeth is greater and the capacity increases for a given speed; however, the tendency toward a pulsating discharge increases. In all simple gear pumps, power is applied to the shaft of one of the gears, which transmits power to the driven gear through their meshing teeth.

There are no valves in the gear pump to cause friction losses as in the reciprocating pump. The high impeller velocities, with resultant friction losses, are not required as in the centrifugal pump. Therefore, the gear pump is well suited for handling viscous fluids such as fuel and lubricating oils.

Other Gear Pumps

There are two types of gears used in gear pumps in addition to the simple spur gear. One type is the helical gear. A helix is the curve produced when a straight line moves up or down the surface of a cylinder. The other type is the herringbone gear. A herringbone gear is composed of two helixes spiraling in different directions from the center of the gear. Spur, helical, and herringbone gears are shown in Figure 15.

The helical gear pump has advantages over the simple spur gear. In a spur gear, the entire length of the gear tooth engages at the same time. In a helical gear, the point of engagement moves along the length of the gear tooth as the gear rotates. This makes the helical gear operate with a steadier discharge pressure and fewer pulsations than a spur gear pump.

The herringbone gear pump is also a modification of the simple gear pump. Its principal difference in operation from the simple spur gear pump is that the pointed center section of the space between two teeth begins discharging before the divergent outer ends of the preceding space complete discharging. This overlapping tends to provide a steadier discharge pressure. The power transmission from the driving to the driven gear is also smoother and quieter.

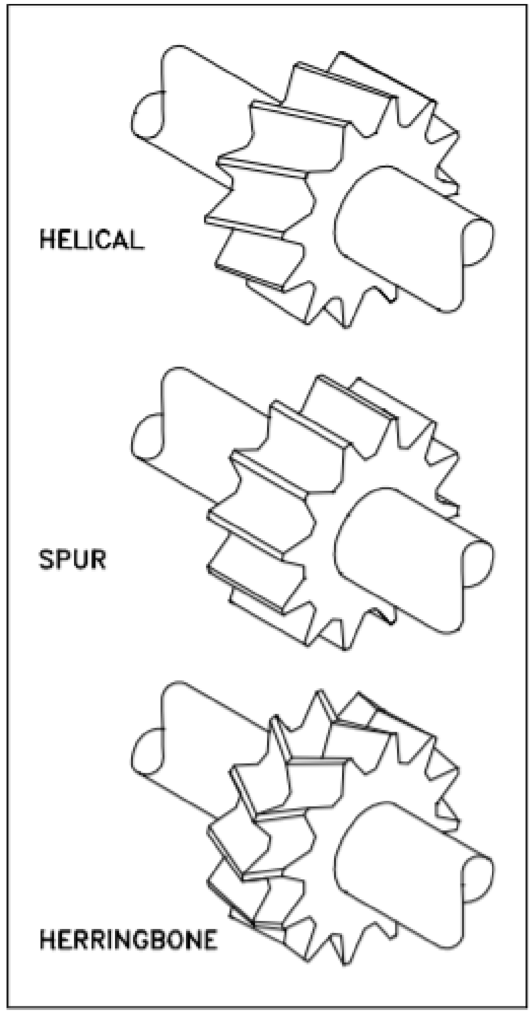


Figure 15 Types of Gears Used In Pumps

Lobe Type Pump

Q13

The lobe type pump shown in Figure 16 is another variation of the simple gear pump. It is considered as a simple gear pump having only two or three teeth per rotor; otherwise, its operation or the explanation of the function of its parts is no different. Some designs of lobe pumps are fitted with replaceable gibs, that is, thin plates carried in grooves at the extremity of each lobe where they make contact with the casing. The gib promotes tightness and absorbs radial wear.

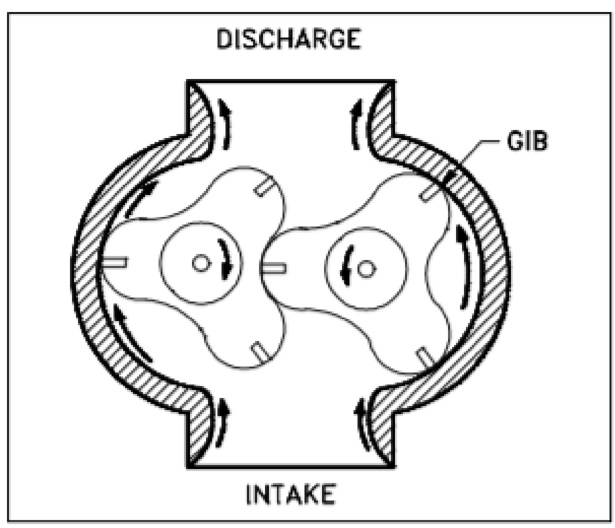


Figure 16 Lobe Type Pump

Screw-Type Positive Displacement Rotary Pump

There are many variations in the design of the screw type positive displacement, rotary pump. The primary differences consist of the number of intermeshing screws involved, the pitch of the screws, and the general direction of fluid flow. Two common designs are the two-screw, low-pitch, double-flow pump and the three-screw, high-pitch, double-flow pump.

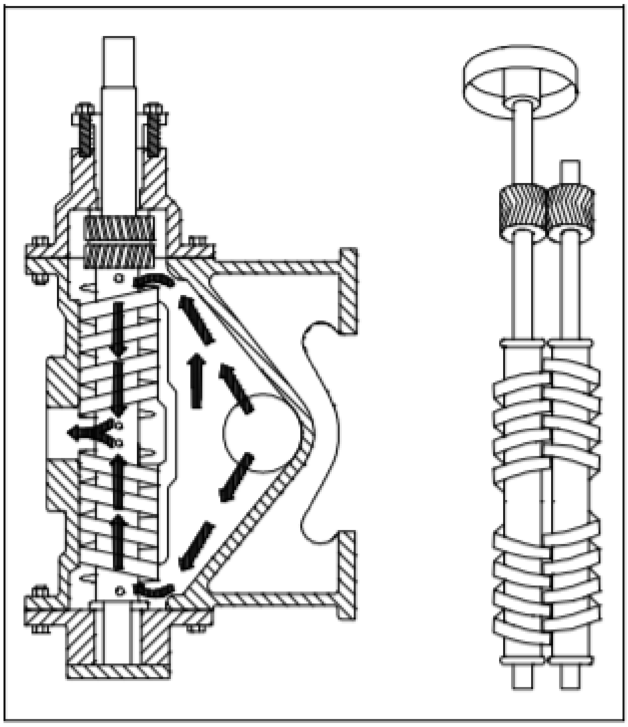


Figure 17 Two-Screw, Low-Pitch, Screw Pump

Two-Screw, Low-Pitch, Screw Pump

The two-screw, low-pitch, screw pump consists of two screws that mesh with close clearances, mounted on two parallel shafts. One screw has a right-handed thread, and the other screw has a left-handed thread. One shaft is the driving shaft and drives the other shaft through a set of herringbone timing gears. The gears serve to maintain clearances between the screws as they turn and to promote quiet operation. The screws rotate in closely fitting duplex cylinders that have overlapping bores. All clearances are small, but there is no actual contact between the two screws or between the screws and the cylinder walls.

The complete assembly and the usual flow path are shown in Figure 17. Liquid is trapped at the outer end of each pair of screws. As the first space between the screw threads rotates away from the opposite screw, a one-turn, spiral-shaped quantity of liquid is enclosed when the end of the screw again meshes with the opposite screw. As the screw continues to rotate, the entrapped spiral turns of liquid slide along the cylinder toward the center discharge space while the next slug is being entrapped. Each screw functions similarly, and each pair of screws discharges an equal quantity of liquid in opposed streams toward the center, thus eliminating hydraulic thrust. The removal of liquid from the suction end by the screws produces a reduction in pressure, which draws liquid through the suction line.

Three-Screw, High-Pitch, Screw Pump

The three-screw, high-pitch, screw pump, shown in Figure 18, has many of the same elements as the two-screw, low-pitch, screw pump, and their operations are similar. Three screws, oppositely threaded on each end, are employed. They rotate in a triple cylinder, the two outer bores of which overlap the center bore. The pitch of the screws is much higher than in the low pitch screw pump; therefore, the center screw, or power rotor, is used to drive the two outer idler rotors directly without external timing gears.

Pedestal bearings at the base support the weight of the rotors and maintain their axial position. The liquid being pumped enters the suction opening, flows through passages around the rotor housing, and through the screws from each end, in opposed streams, toward the center discharge. This eliminates unbalanced hydraulic thrust. The screw pump is used for pumping viscous fluids, usually lubricating, hydraulic, or fuel oil.

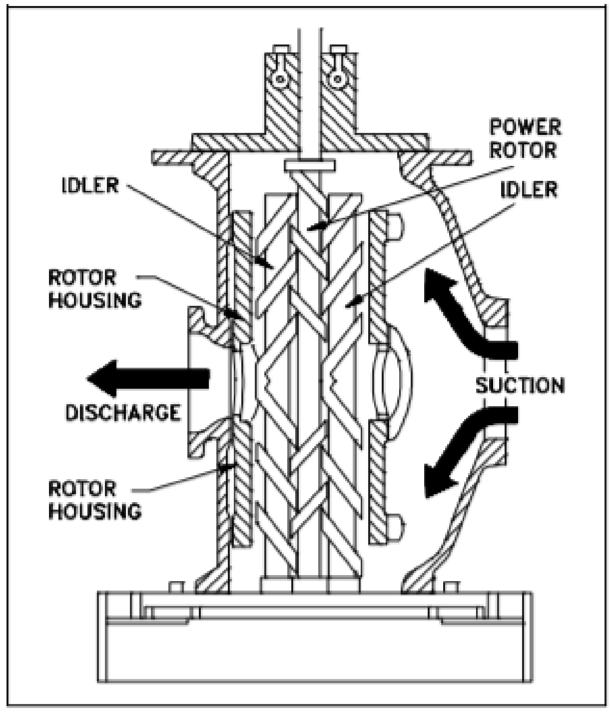


Figure 18 Three-Screw, High-Pitch, Screw Pump

Rotary Moving Vane Pump

The rotary moving vane pump shown in Figure 19 is another type of positive displacement pump used. The pump consists of a cylindrically bored housing with a suction inlet on one side and a discharge outlet on the other. A cylindrically shaped rotor with a diameter smaller than the cylinder is driven about an axis placed above the centerline of the cylinder. The clearance between rotor and cylinder is small at the top but increases at the bottom. The rotor carries vanes that move in and out as it rotates to maintain sealed spaces between the rotor and the cylinder wall. The vanes trap liquid or gas on the suction side and carry it to the discharge side, where contraction of the space expels it through the discharge line. The vanes may swing on pivots, or they may slide in slots in the rotor.

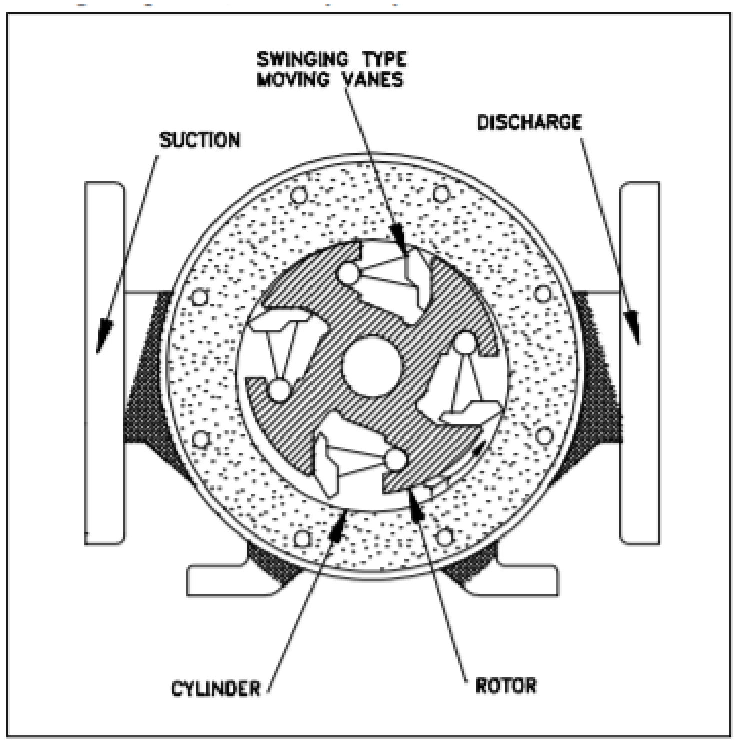


Figure 19 Rotary Moving Vane Pump

Diaphragm Pumps

Q14

Diaphragm pumps are also classified as positive displacement pumps because the diaphragm acts as a limited displacement piston. The pump will function when a diaphragm is forced into reciprocating motion by mechanical linkage, compressed air, or fluid from a pulsating, external source. The pump construction eliminates any contact between the liquid being pumped and the source of energy. This eliminates the possibility of leakage, which is important when handling toxic or very expensive liquids. Disadvantages include limited head and capacity range, and the necessity of check valves in the suction and discharge nozzles. An example of a diaphragm pump is shown in Figure 20.

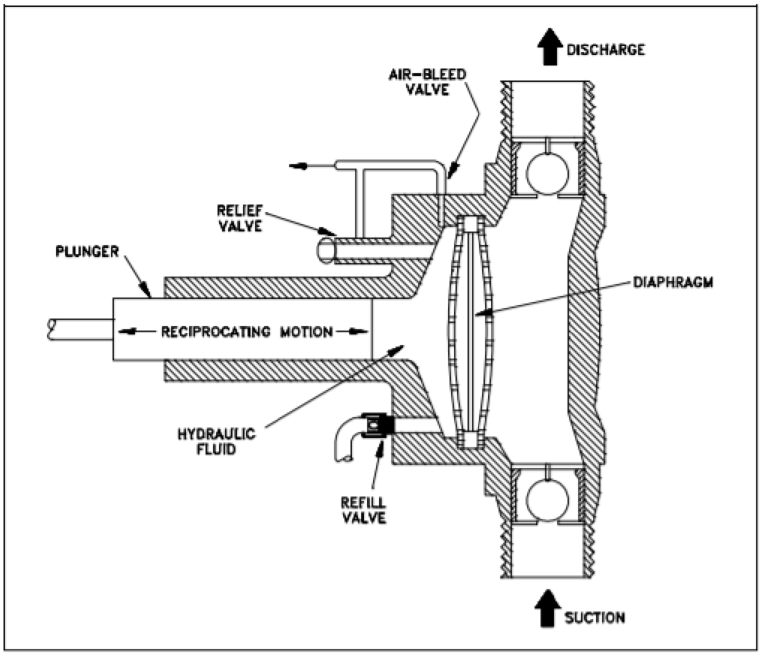


Figure 20 Diaphragm Pump

Positive Displacement Pump Characteristic Curves

Q15

Positive displacement pumps deliver a definite volume of liquid for each cycle of pump operation. Therefore, the only factor that effects flow rate in an ideal positive displacement pump is the speed at which it operates. The flow resistance of the system in which the pump is operating will not effect the flow rate through the pump. Figure 21 shows the characteristic curve for a positive displacement pump.

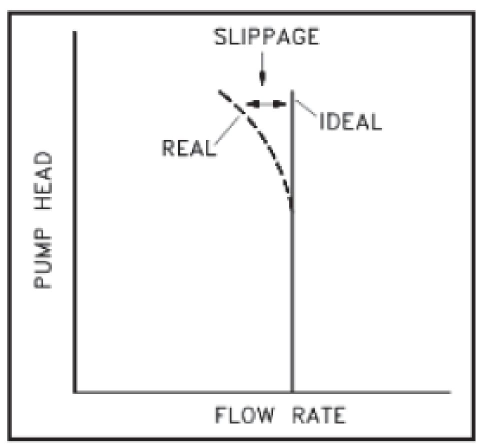


Figure 21 Positive Displacement Pump Characteristic Curve

The dashed line in Figure 21 shows actual positive displacement pump performance. This line reflects the fact that as the discharge pressure of the pump increases, some amount of liquid will leak from the discharge of the pump back to the pump suction, reducing the effective flow rate of the pump. The rate at which liquid leaks from the pump discharge to its suction is called *slippage.*

Positive Displacement Pump Protection

Positive displacement pumps are normally fitted with relief valves on the upstream side of their discharge valves to protect the pump and its discharge piping from overpressurization. Positive displacement pumps will discharge at the pressure required by the system they are supplying. The relief valve prevents system and pump damage if the pump discharge valve is shut during pump operation or if any other occurrence such as a clogged strainer blocks system flow.

Summary

The important information in this chapter is summarized below.

Positive Displacement Pumps Summary

- The flow delivered by a centrifugal pump during one revolution of the impeller depends upon the head against which the pump is operating. The positive displacement pump delivers a definite volume of fluid for each cycle of pump operation regardless of the head against which the pump is operating.
- Positive displacement pumps may be classified in the following ways:
    - Reciprocating piston pump
    - Gear-type rotary pump
    - Lobe-type rotary pump
    - Screw-type rotary pump
    - Moving vane pump
    - Diaphragm pump
- As the viscosity of a liquid increases, the maximum speed at which a reciprocating positive displacement pump can properly operate decreases. Therefore, as viscosity increases, the maximum flow rate through the pump decreases.
- The characteristic curve for a positive displacement pump operating at a certain speed is a vertical line on a graph of head versus flow.
- Slippage is the rate at which liquid leaks from the discharge of the pump back to the pump suction.
- Positive displacement pumps are protected from overpressurization by a relief valve on the upstream side of the pump discharge valve.

Variable Speed Pumping

A Guide to Successful Applications

Executive Summary

Variable Speed Drives
A Way To Lower Life Cycle Costs

Hydraulic Institute
Creating Pump Standards Since 1917

Europump

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Industrial Technologies Program
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Table of Contents

Acknowledgment

Variable Speed Pumping — A Guide to Successful Applications, Executive Summary is the result of a collaboration between the Hydraulic Institute, Europump, and the U.S. Department of Energy's (DOE) Industrial Technologies Program.

Introduction

Q16

Pumping systems account for nearly 20% of the world's energy used by electric motors and 25% to 50% of the total electrical energy usage in certain industrial facilities. Significant opportunities exist to reduce pumping system energy consumption through smart design, retrofitting, and operating practices. In particular, the many pumping applications with variable-duty requirements offer great potential for savings. The savings often go well beyond energy, and may include improved performance, improved reliability, and reduced life cycle costs.

Pumping applications with variable-duty requirements offer great potential for energy savings, improved performance, and reduced life cycle costs.

Most existing systems requiring flow control make use of bypass lines, throttling valves, or pump speed adjustments. The most efficient of these is pump speed control. When a pump's speed is reduced, less energy is imparted to the fluid and less energy needs to be throttled or bypassed. Speed can be controlled in a number of ways, with the most popular type of variable speed drive (VSD) being the variable frequency drive (VFD).

Pump speed adjustment is not appropriate for all pumping systems, however. This overview provides highlights from *Variable Speed Pumping — A Guide To Successful Applications*, which has been developed by Europump and the Hydraulic Institute as a primer and tool to assist plant owners and designers as well as pump, motor, and drive manufacturers and distributors. When the requirements of a pump and system are understood, the user can consult this guide to help determine whether variable speed pumping is the correct choice. The guide is applicable for both new and retrofit installations and contains flowcharts to assist in the selection process.

Pumping Systems

Q17

A proper discussion of pumping considers not just the pump, but the entire pumping "system" and how the system components interact. The recommended systems approach to evaluation and analysis includes both the supply and demand sides of the system.

Pumping System Hydraulic Characteristics

In a pumping system, the objective, in most cases, is either to transfer a liquid from a source to a required destination, e.g., filling a high-level reservoir, or to circulate liquid around a system, e.g., as a means of heat transfer. Pressure is needed to make the liquid flow at the required rate and this must overcome losses in the system. Losses are of two types: static and friction head.

The ratio of static to friction head over the operating range influences the benefits achievable from VSDs.

Static head, in its most simple form, is the difference in height of the supply and destination of the liquid being moved, or the pressure in a vessel into which the pump is discharging, if it is independent of flow rate. Friction head (sometimes called dynamic head loss), is the friction loss on the liquid being moved, in pipes, valves, and other equipment in the system. This loss is proportional to the square of the flow rate. A closed-loop circulating system, without a surface open to atmospheric pressure, would exhibit only friction losses.

Most systems have a combination of static and friction head. The ratio of static to friction head over the operating range influences the benefits achievable from VSDs. Static head is a characteristic of the specific installation. Reducing this head whenever possible generally reduces both the cost of the installation and the cost of pumping the liquid. Friction head losses must be minimized to reduce pumping cost, but after eliminating unnecessary pipe fittings and length, further reduction in friction head will require larger diameter pipes, which adds to installation cost.

Pump Types

Proper selection of pumps, motors, and controls to meet the process requirements is essential to ensure that a pumping system operates effectively, reliably, and efficiently. All pumps are divided into the two major categories of positive displacement (PD) and rotodynamic.

PD pumps can be classified into two main groups: rotary and reciprocating. Rotary pumps typically work at pressures up to 25 Bar (360 pounds per square inch [psi]). These pumps transfer liquid from suction to discharge through the action of rotating screws, lobes, gears, rollers, etc., which operate within a rigid casing. Reciprocating pumps typically work at pressures up to 500 Bar. These pumps discharge liquid by changing the internal volume. Reciprocating pumps can generally be classified as having a piston, plunger, or diaphragm, displacing a discrete volume of liquid between an inlet valve and a discharge valve. The rotary motion of the driver, such as an electric motor, is converted to the reciprocating motion by a crankshaft, camshaft, or swash-plate.

The performance of a pump can be expressed graphically as head against flow rate. The rotodynamic pump has a curve where the head falls gradually with increasing flow. However, for a PD pump, the flow is almost constant whatever the head. It is customary to draw the curve for PD pumps with the axes reversed, but for comparison, a common presentation is used here for the two pump types.

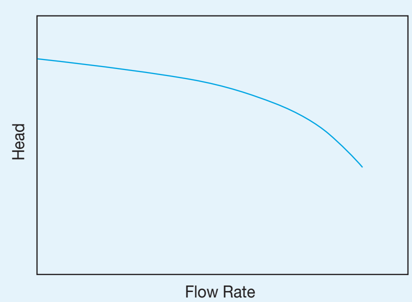


Figure ES-1.
Performance curve for a rotodynamic pump

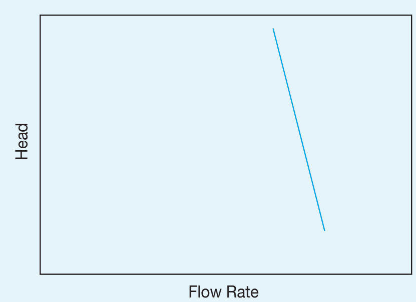


Figure ES-2.
Performance curve for a positive displacement pump

Interaction of Pumps and Systems

When a pump is installed in a system, the effect can be illustrated graphically by superimposing pump and system curves. The operating point will always be where the two curves intersect.

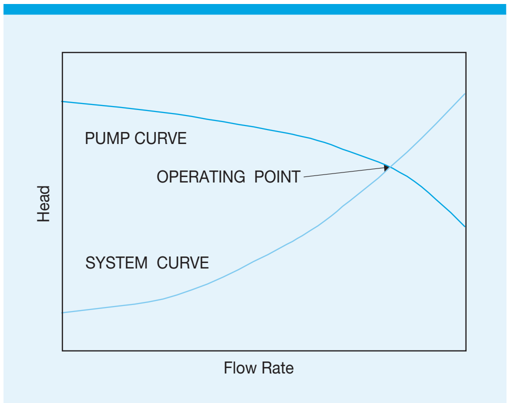


Figure ES-3. System curve and a performance curve for a rotodynamic pump

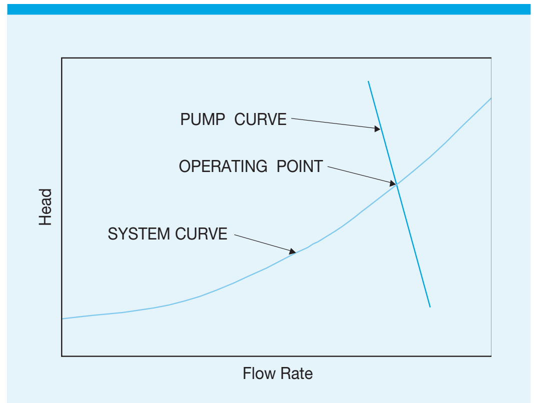


Figure ES-4. System curve and a performance curve for a positive displacement pump

Many pumping systems require a variable flow or pressure; variable speed reduces power during periods of reduced demand.

For a PD pump, if the system resistance increases, i.e., the system curve is moved upwards, the pump will increase its discharge pressure and maintain a fairly constant flow rate, dependent on viscosity and pump type. Unsafe pressure levels can occur without relief valves. For a rotodynamic pump, an increasing system resistance will reduce the flow, eventually to zero, but the maximum head is limited. Even so, this condition is only acceptable for a short period without causing problems. Adding comfort margins to the calculated system curve to ensure that a sufficiently large pump is selected will generally result in installing an oversized pump. The pump will operate at an excessive flow rate or will need to be throttled, leading to increased energy use and reduced pump life.

Many pumping systems require a variation of flow or pressure. Either the system curve or the pump curve must be changed to get a different operating point. Where a single pump has been installed for a range of duties, it will have been sized to meet the greatest output demand. It will therefore usually be oversized, and will be operating inefficiently for other duties. Consequently, there is an opportunity to achieve an energy cost savings by using control methods, such as variable speed, which reduce the power to drive the pump during the periods of reduced demand.

Q18

Effects of Speed Variation on Rotodynamic Pumps

Varying the rotational speed has a direct effect on the pump's performance.

A rotodynamic pump is a dynamic device with the head generated by a rotating impeller. Thus, there is a relationship between impeller peripheral velocity and generated head. Peripheral velocity is directly related to shaft rotational speed, for a fixed impeller diameter. Varying the rotational speed therefore has a direct effect on the pump's performance. The equations relating rotodynamic pump performance parameters of flow to speed, and head and power absorbed to speed, are known as the Affinity Laws.

Changing pump impeller diameter also effectively changes the duty point in a given system, and at low cost, but this can be used only for permanent adjustment to the pump curve and is not discussed further as a control method.

For systems where friction loss predominates, reducing pump speed moves the intersection point on the system curve along a line of constant efficiency (see Figure ES-5). The operating point of the pump, relative to its best efficiency point, remains constant and the pump continues to operate in its ideal region. The Affinity Laws are obeyed, which means that there is a substantial reduction in power absorbed accompanying the reduction in flow and head, making variable speed the ideal control method.

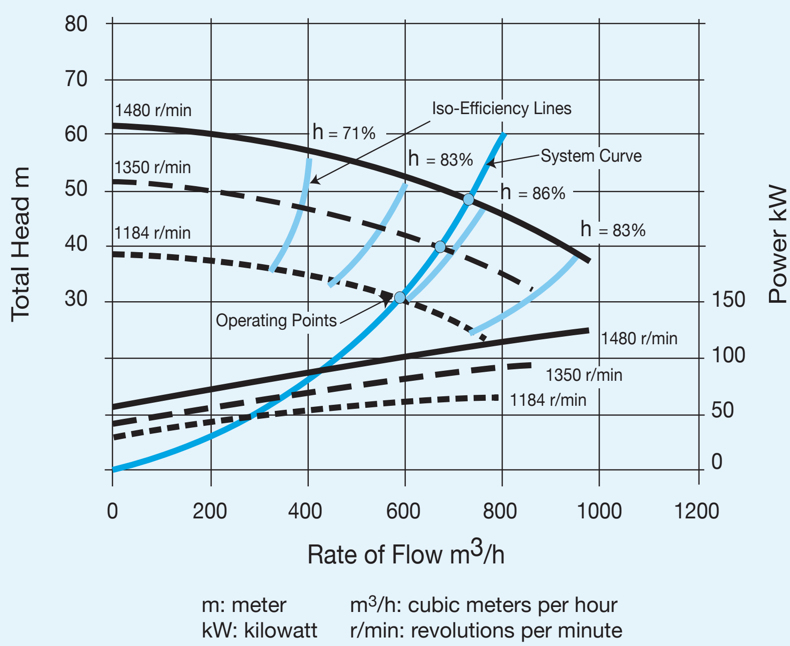
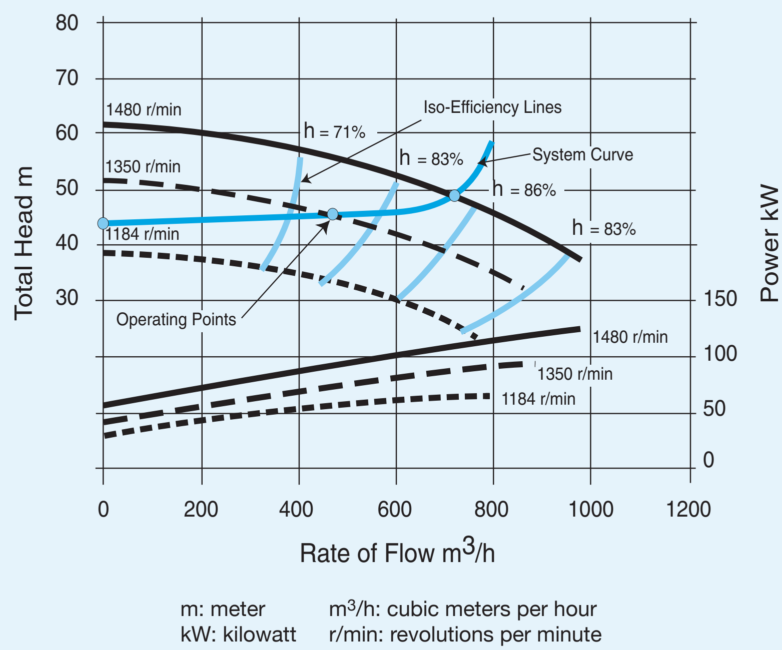


Figure ES-5. Example of the effect of pump speed change in a system with only friction loss

However, in systems with high static head, the system curve does not start from the origin but at some non-zero value on the y-axis corresponding to the static head. Hence, the system curve does not follow the curves of constant efficiency. Instead, it intersects them (see Figure ES-6). The reduction in flow is no longer proportional to speed; a small turn down in speed greatly reduces flow rate and pump efficiency. A common mistake is to also use the Affinity Laws to calculate energy savings in systems with static head. Although this may be done as an approximation, it can also lead to major errors.

Figure ES-6. Example of the effect of pump speed change in a system with high static head



It is relevant to note that flow control by speed regulation is always more efficient than by a control valve. In addition to energy savings, there could be other benefits to lower speed. The hydraulic forces on the impeller, created by the pressure profile inside the pump casing, reduce approximately with the square of speed. These forces are carried by the pump bearings, and so reducing speed increases bearing life. It can be shown that for a rotodynamic pump, bearing life is proportional to the seventh power of speed. In addition, vibration and noise are reduced and seal life is increased, provided that the duty point remains within the allowable operating range.

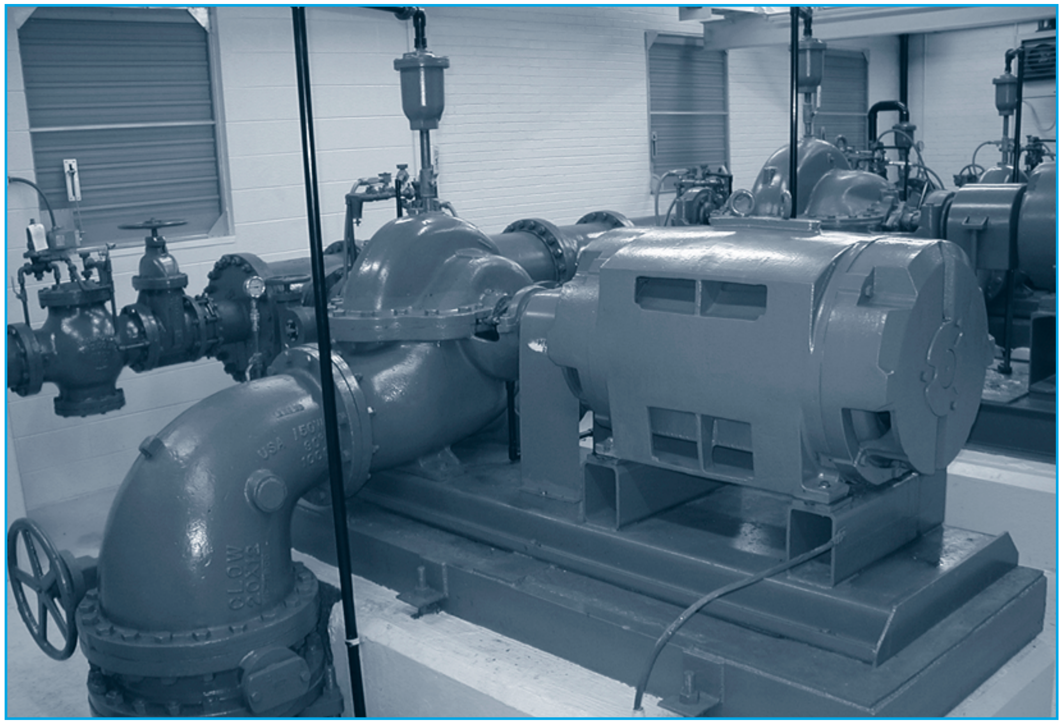


Photo: NREL/PIX 13296

Proper selection of pumps, motors, and controls to meet the process requirements is essential to ensure that a pumping system operates effectively, reliably, and efficiently.

Q19

Effect of Speed on Pump Suction Performance

Liquid entering the impeller eye turns and is split into separate streams by the leading edges of the impeller vanes, an action that locally drops the pressure below that in the inlet pipe to the pump. If the incoming liquid is at a pressure with insufficient margin above the vapor pressure, then vapor cavities, or bubbles, appear along the impeller vanes just behind the inlet edges. These collapse further along the impeller vane where the pressure has increased. This phenomenon is known as cavitation, and has undesirable effects on pump life.

Increasing pump speed will negatively affect pump suction performance, while reducing speed will have a positive effect.

Increasing pump speed will negatively affect pump suction performance and should be thoroughly investigated. Conversely, reducing speed will have a positive effect.

Effects of Speed Variation on Positive Displacement Pumps

To control flow in a PD pump, the speed needs to be changed or some of the flow has to be diverted. Throttling is not effective and is potentially dangerous. For many applications, some small flow rate changes need to be made while holding the pressure constant, and this is best achieved with a pressure-regulating valve. Such a valve will spill a small amount of liquid back to the source to maintain a constant system pressure. This will accommodate small amounts of wear in any restricting device; however, the use of such a valve to spill large volumes of liquid will be very inefficient, with the loss of energy manifesting as heat and noise.

A VSD is the preferred option for an application where the flow needs to vary on a regular basis. This is the most efficient method of flow control and it does not waste any of the shaft input energy.

A VSD provides the most efficient method of flow control for a PD pump and does not waste any of the shaft input energy.

For a PD pump, the flow is proportional to speed, but the pressure can be independent of speed. Consequently, power and energy savings do not fall so quickly when speed is reduced. Sometimes it is necessary to operate PD pumps over a wider speed range than rotodynamic pumps, typically up to 10:1. This large speed range and the characteristics of PD pumps have implications for both the pump and the drive train, including:

- Lower or higher operating speeds may require special consideration with respect to the method or type of lubrication and/or cooling.
- The motor may not be adequately cooled at the lowest speed. A separately driven fan may need to be considered.
- The flow rate may be so low that the valve opening is too small to be sustainable under the different forces, and the valve could flutter.
- The energy from the drive-train inertia becomes too small to smooth the torque ripple and the motor starts to hunt. Two possible solutions are a motor running at a higher speed with a bigger drive-train reduction ratio, or a compensating flywheel.
- At the system design stage, the constant torque characteristic and possible low-speed torque effects must be considered, because they impose demands on electronic VSDs.
- When liquids containing solids with a high settling rate are pumped, excessive solids accumulation can occur in the pump, causing wear. It is paramount, when reducing speed with such liquids, that the velocity be maintained high enough in the pump and in the pumping system to avoid settling out of the solids.
- A change in liquid temperature and viscosity could lead to cavitation.

Photo: Courtesy Don Casada, Diagnostic Solutions

Most existing pumping systems are oversized, many by more than 20%, thus providing substantial opportunity for systems optimization.

Motors

There are many types of pump prime movers available (such as diesel engines and steam turbines) but the majority of pumps are driven by an electric motor. Although this guide is principally about pumps and VSDs, it is important to appreciate that, on a typical industrial site, motor-driven equipment accounts for approximately two-thirds of electricity consumption. Improvements in motor efficiency, by using high-efficiency motors, can offer major energy savings and short payback. Many of the principles outlined in the guide apply to all motors on a site, not just those used as pump prime movers.

Variable Speed Drives

There are several types of VSDs, as shown in Figure ES-7. In applications that require flow or pressure control, particularly in systems with high friction loss, the most energy-efficient option for control is an electronic VSD, commonly referred to as a variable frequency drive (VFD). The most common form of VFD is the voltage-source, pulse-width modulated (PWM) frequency converter (often incorrectly referred to as an inverter). In its simplest form, the converter develops a voltage directly proportional to the frequency, which produces a constant magnetic flux in the motor. This electronic control can match the motor speed to the load requirement. This eliminates a number of costly and energy inefficient ancillaries, such as throttle valves or bypass systems.

Q20

Selection Process — New Systems

It is essential to commence the sizing exercise with the hydraulic system, and to work systematically to select the pump, motor, and drive. When the pump maximum duty is known, the peak power and speed for the drive will become clear. It is common to oversize system components (pumps, motors, and drives); however, this practice is not recommended because it leads to higher initial equipment costs and higher life cycle costs.

When selecting a rotodynamic pump in combination with a VSD for a system with some static head, a pump should be chosen such that the maximum flow rate is slightly to the right-hand side of the best efficiency point (BEP). The exception is for a constant flow regulated system, in which case the recommendation is to select a pump that operates to the left of BEP at maximum pressure. This approach optimizes pump operating efficiency.

All operating conditions must be considered when designing the system. Some operating profiles may be satisfied best by installing multiple pumps, which could be fixed or variable speed. On/off control can be used to vary flow rate for systems in which an intermittent flow is acceptable. This can be an energy-efficient solution, but these systems often require a liquid storage facility.

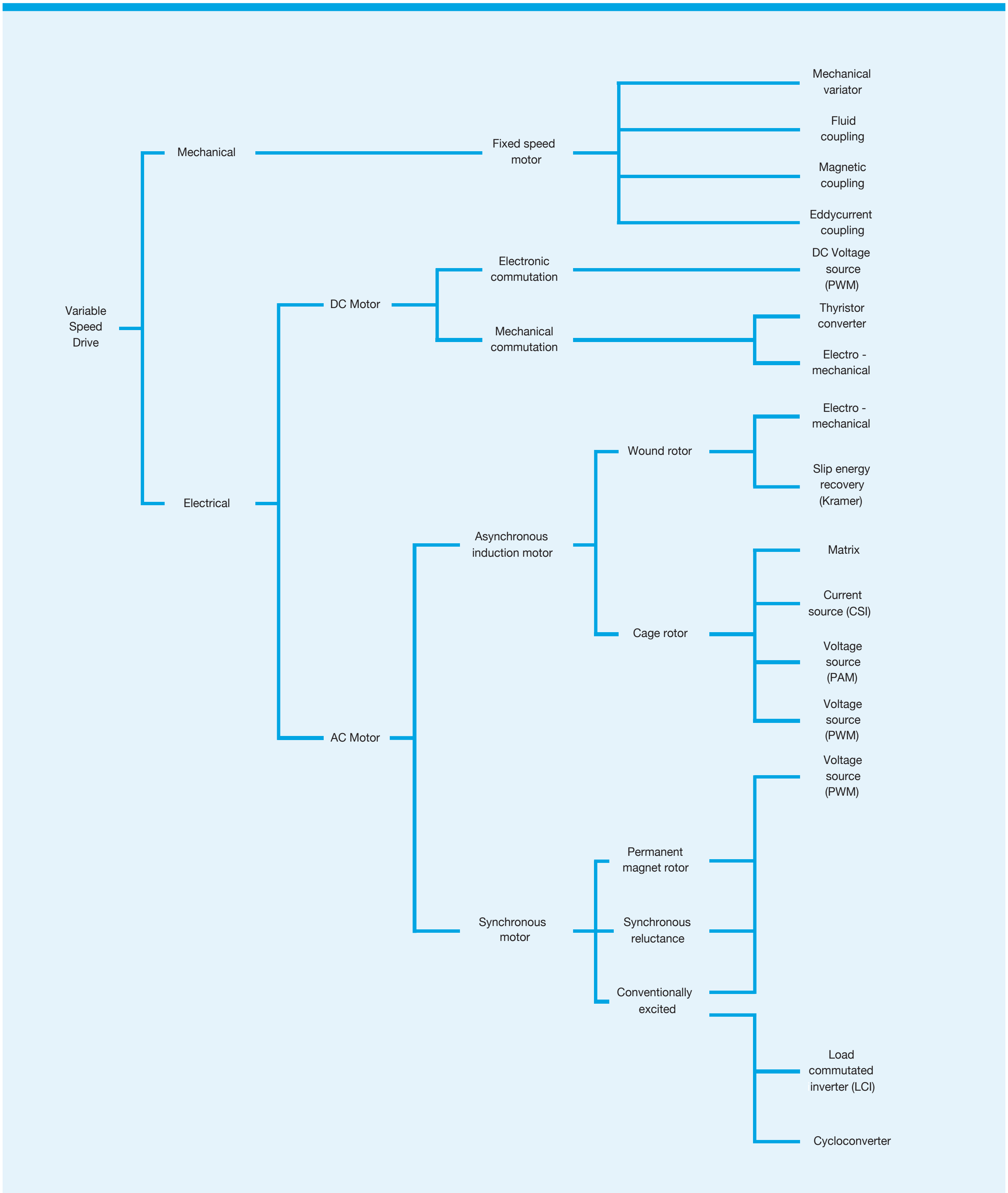


Figure ES-7.
Types of Variable Speed Drives

Q21

Selection Process — Retrofitting to Existing Equipment

There are approximately 20 times more pumps in service than are supplied new every year. It is therefore apparent that a major opportunity exists for modifying installed systems to make them more energy efficient. Most system designers allow a contingency on the system head required. It is estimated that 75% of pump systems are oversized, many by more than 20%. It follows that retrofitting with VSDs could match pump systems to actual system requirements more accurately and save considerable amounts of energy.

When sizing the hydraulic system, consider all operating conditions and work systematically to select the pump, motor, and drive.

When considering adding a VSD to an existing motor, care should be taken to match the electrical characteristics of the motor and frequency converter; otherwise, the risk of premature failure is introduced into the system. Early frequency converters produced outputs with a very high harmonic content in the waveform, which caused substantial additional heating of motor windings, and therefore motors were derated for inverter use. A modern inverter output causes relatively small levels of harmonic current distortion in the motor windings, and therefore little derating is normally required. High-efficiency motors are less affected by harmonics than standard efficiency types.

Q22

Benefits of VSDs

VSDs offer several benefits, some of which are relatively easy to quantify, and others of which are less tangible, but there are some potential drawbacks, which must be avoided.

Energy Savings

With rotodynamic pump installations, savings of between 30% and 50% have been achieved in many installations by installing VSDs. Where PD pumps are used, energy consumption tends to be directly proportional to the volume pumped and savings are readily quantified.

Improved Process Control

By matching pump output flow or pressure directly to the process requirements, small variations can be corrected more rapidly by a VSD than by other control forms, which improves process performance. There is less likelihood of flow or pressure surges when the control device provides rates of change, which are virtually infinitely variable.

Improved System Reliability

Any reduction in speed achieved by using a VSD has major benefits in reducing pump wear, particularly in bearings and seals. Furthermore, by using reliability indices, the additional time periods between maintenance or breakdowns can be accurately computed.

Q23

Potential Drawbacks of VSDs

VSDs also have some potential drawbacks, which can be avoided with appropriate design and application.

Structural Resonance

Resonance conditions can cause excessive vibration levels, which in turn are potentially harmful to equipment and environment. Pumps, their support structure, and piping are subject to a variety of potential structural vibration problems (resonance conditions). Fixed-speed applications often miss these potential resonance situations because the common excitation harmonics due to running speed, vane passing frequency, plunger frequency, etc., do not coincide with the structural natural frequencies. For VSD applications, the excitation frequencies become variable and the likelihood of encountering a resonance condition within the continuous operating speed range is greatly increased. Pump vibration problems typically occur with bearing housings and the support structure (baseplate for horizontal applications, motor and stool for vertical applications).

A number of analyses may be performed to predict and avoid potential resonance situations.

Pressure pulsations are the common excitation mechanism. These pressure pulsations may be further amplified by acoustic resonance within the pump or the adjacent piping. There are a number of analyses that can be performed to predict and avoid potential resonance situations, including:

- Simple hydraulic resonance calculations
- Passing frequency analysis
- Structural resonance, for example, utilizing Finite Element Analysis
- Modal testing of the actual machine.

Modal testing can supplement the regular vibration test. Very often, a pump intended for variable speed operation will only be tested at one single speed.

Rotor Dynamics

The risk of the rotating element encountering a lateral critical speed increases with the application of a VSD. Lateral critical speeds occur when running speed excitation coincides with one of the rotor's lateral natural frequencies. The resulting rotor vibration may be acceptable or excessive, depending on the modal damping associated with the corresponding mode. Additionally, drive-induced torque harmonics may cause resonance conditions with torsional rotor dynamic modes. However, such conditions are usually correctible or preventable.

Variable speed vertical pumps are more likely than horizontal machines to exhibit operational zones of excessive vibration. This is because such pumps' lower natural frequencies are more likely to coincide with running speed. Small, vertical close-coupled and multistage pumps normally do not present this type of problem.

Additional Considerations for VFDs

The introduction of VFDs requires additional design and application considerations. VFDs can be fitted to most existing motors in Europe and other areas, which use a 400 Volt (V) network. However, this is generally not the case in the United States, and other areas where network voltages exceed 440 V. Hence, reinforced insulation "inverter duty" motors are often needed.

The high rate of switching in the PWM waveform can occasionally lead to problems. For example:

- The rate of the wavefront rise can cause electromagnetic disturbances, requiring adequate electrical screening (screened output cables). Filters in the inverter output can eliminate this problem.
- Older motor insulation systems may deteriorate more rapidly due to the rapid rate of voltage change. Again, filters will eliminate this problem.
- Long cable runs can cause "transmission line" effects, and cause raised voltages at the motor terminals.

Voltages can be induced in the shafts of larger motors, potentially leading to circulating currents, which can destroy bearings. The following corrective measures are required:

- Insulated non-drive-end bearings are recommended on all motors over 100 kilowatt (kW) output rating.
- Common mode filters may additionally be required for higher powers and voltages.

The converter will have losses, and ventilation requirements for the electronics can be an important issue. The life expectancy of the converter is generally directly related to the temperature of the internal components, especially capacitors.

The converter may require installation in a less onerous environment than the motor control gear it replaces. Specifically:

- Electronics are less able to cope with corrosive and damp locations than conventional starters.
- Operating a VFD in a potentially explosive atmosphere is not usually possible.

Estimating Pumping Energy Costs

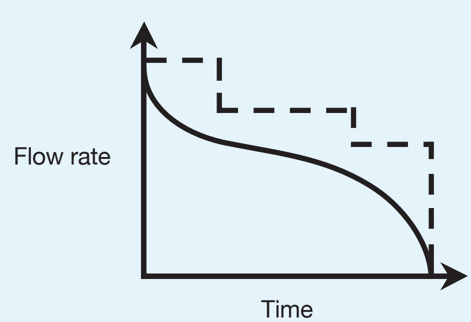
Use a duration diagram to help estimate pumping energy costs.

To compare different system and pumping equipment proposals and make an intelligent choice, some basic facts will need to be established.

- Will the process require varying flow rate, and, if so, must it be continuously variable or can flow rate be varied in steps?
- Can on-off batch pumping be used?
- What is the peak flow rate and how is the flow rate distributed over time?

The answers to these questions will determine if, and how, to regulate the flow. It will also give some guidance regarding the pumping system design. A helpful way of showing the flow demand is to use a duration diagram. A duration diagram in its simplest form (see Figure ES-8) shows how many hours during a year that a given flow rate is needed — the dashed line. The solid curve in the same diagram is interpreted differently. Each point on the solid curve tells how many hours during a year the flow rate exceeds the value on the y-axis.

Figure ES-8. Example of a duration diagram



This diagram is instrumental in understanding the pumping needs. The system must be able to deliver the peak flow, but, from an economic point of view, it is also important to know at what flow rates the system is going to operate most of the time. To find the total cost of operating the pump, the running cost at each operating condition must be calculated and summated.

Q24

Capital Cost Savings

When designing and installing a new pumping system, the capital cost of a VSD can often be offset by eliminating control valves, bypass lines, and conventional starters, as explained below.

Elimination of Control Valves

Offset the capital cost of a VSD by eliminating control valves, by-pass lines, and conventional starters.

Control valves are used to adjust rotodynamic pump output to suit varying system requirements. Usually a constant-speed pump is pumping against a control valve, which is partially closed for most of the time. Even at maximum flow conditions, a control valve is normally designed to be 10% shut, for control purposes. Hence, a considerable frictional resistance is applied. Energy is therefore wasted overcoming the added frictional loss through the valve. Using a VSD to control flow can eliminate the control valve.

Elimination of Bypass Lines

All fixed-speed centrifugal pumps have a minimum flow requirement. If the pump is operated at flow rates below the minimum for extended periods, various mechanical problems can occur. If the flow requirements in a system can drop below this minimum flow capacity, it is necessary to install a constant or switched bypass to protect the pump. The use of a VSD greatly reduces the volume to be bypassed.

Financial Justification

An LCC analysis is a very appropriate way to compare technical alternatives in pump system design to make a financial justification.

The initial cost of pumping equipment is often a very small part of the total life cycle cost (LCC). An LCC analysis is therefore a very appropriate way to compare different technical alternatives in the design of a pumping system and make a financial justification. The components of an LCC analysis typically include initial costs, installation and commissioning costs, energy costs, operation costs, maintenance and repair costs, downtime costs, environmental costs, and decommissioning and disposal costs (see Figure ES-9). The LCC equation can be stated as:

$$LCC = C_{ic} + C_{in} + C_e + C_o + C_m + C_s + C_{env} + C_d$$

C = cost element
ic = initial cost, purchase price (pump, system, pipes, auxiliaries)
in = installation and commissioning
e = energy costs
o = operating cost (labor cost of normal system supervision)
m = maintenance cost (parts, man-hours)
s = downtime, loss of production
env = environmental costs
d = decommissioning

A very well documented guide, *Pump Life Cycle Costs: LCC Analysis for Pumping Systems*[1], has been published jointly by Hydraulic Institute and Europump. This guide explains how the operating costs of a pumping system are influenced by system design and shows in detail how to use a life cycle cost analysis to make comparative cost assessments. Many case studies have been included in the guide to highlight the value of possible savings in real applications.

[1]*Pump Life Cycle Costs: LCC Analysis for Pumping Systems,* 2001, is available through both the Hydraulic Institute (www.pumps.org) and Europump (www.europump.org).

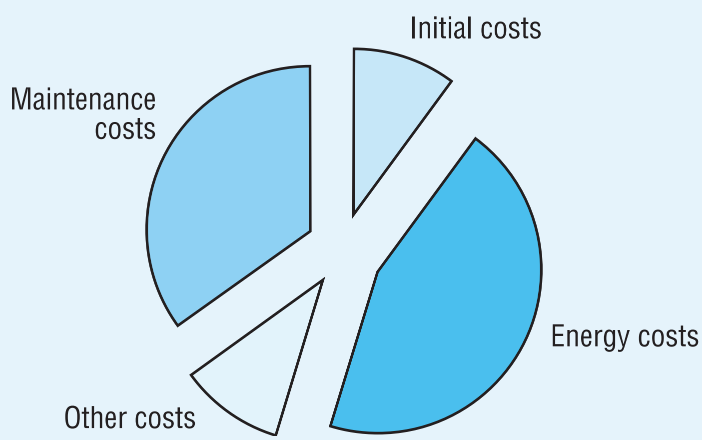


Figure ES-9. Typical LCC components for a medium-sized industrial pumping system

Example: Variable Speed Drives Fitted on a Primary Feed Pump and Product Transfer Pump in a Refinery

Summary

At a San Francisco refinery, installing a VFD on a product transfer pump saved €/$120,000 (euros/U.S. dollars) per year, and on a primary feed pump, saved €/$220,000. Vibration was reduced and mechanical seal and bearing failures have been eliminated. There was no investment cost to the refinery, but savings were shared with the contractor, who provided the capital investment.

Other Potential Applications

Suitable applications include any in which the pump is sized for an intermittent maximum flow rate but runs mostly at a reduced (but variable) rate.

Investment Cost

The energy services contractor agreed to install the VFDs and upgrade the equipment at no charge to the refinery, but took a share of the savings. The total investment was €/$1.2 million.

Savings Achieved

Over the course of a year, the VFDs saved €/$340,000 and the total project saved €/$750 000 per year.

Payback Period

Overall payback was about 1.6 years, but this was not applicable to the refinery, which gained immediately with its share of the savings.

Installation and Operation Details

Conversion of the refinery's vacuum gas oil plant to a Diesel Hydro Treater (DHT) left the pumps grossly oversized. Several were often operating at 40% of best efficiency point, causing low hydraulic efficiency, excessive vibration, and seal or bearing failure about once a year.

The full range of upgrades consisted of:

- Installing VFDs on the 1,650-kW (2,250-horsepower [hp]) primary feed pump and on the 500-kW (700-hp) product transfer pump
- Replacing the internal elements on the 1,650-kW (2,250-hp) secondary feed pump and on a 400-hp Power Recover Turbine (PRT)
- Changing operating procedures for the main 3,700-kW (5,000-hp) and 3,000-kW (4,000-hp) back-up pumps.

At a San Francisco refinery, installing a VFD on product transfer and primary feed pumps saved energy and money, reduced vibration, and eliminated mechanical seal and bearing failures.

Installing the VFDs on the primary feed pump and product transfer pump saved energy by reducing losses through flow control valves. The energy saved from using VFDs was 500,000 kWh per month. Resizing the PRT and secondary feed pump, along with a more energy-efficient operating procedure for the back-up pumps, saved another 500,000 kWh per month. Cost savings shared by the refinery and contractor were €/$340,000 from the variable speed pumps and €/$750,000 overall. The demand charge previously levied on the DHT process was eliminated. Since the upgrade, there have been no seal or bearing failures and process control has improved. It should be noted that a VFD was not considered appropriate for all the oversized pumps. If the flow rate does not vary, then resizing the pump (e.g., replacing the impeller and diffuser element), reduced impeller diameters, or even a new pump will usually give greater lifetime cost savings and better payback than a VSD.

Notes

Notes

Variable Speed Pumping Full Report

Further details and specific guidance are available in the complete *Variable Speed Pumping — A Guide to Successful Applications*. This comprehensive document provides information on the design, specification, and operation of efficient, cost-effective variable speed pumping systems. It covers both the basic principles of pump, motor, and drive technology as well as more advanced, specific, and detailed concepts, and provides step-by-step guidance on using a systems approach to incorporating variable speed drives in pumping system applications.

The guide contains over 150 pages, and is compiled, written, edited, and critiqued by pump, motor, and drive experts from academia and industries worldwide.

The guide is available at a cost of €/$95 from both the Hydraulic Institute (www.pumps.org, phone: 973-267-9700) and Europump (www.europump.org, phone: +32 2 706 82 30).

For More Information

About the **Hydraulic Institute**
The Hydraulic Institute (HI), established in 1917, is the largest association of pump producers and leading suppliers in North America. HI serves member companies and pump users by providing product standards and forums for the exchange of industry information. HI has been developing pump standards for over 80 years. For information on membership, organization structure, member and user services, and energy and life cycle cost issues, visit *www.pumps.org.*

About **Europump**
Europump, established in 1960, acts as spokesperson for 15 national pump manufacturing associations in Europe and represents more than 400 manufacturers. Europump serves and promotes the European pump industry. For information on Europump, visit *www.europump.org.*

About the Office of Energy Efficiency and Renewable Energy

A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. By investing in technology breakthroughs today, our nation can look forward to a more resilient economy and secure future.

Far-reaching technology changes will be essential to America's energy future. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies that will:

- Conserve energy in the residential, commercial, industrial, government, and transportation sectors
- Increase and diversify energy supply, with a focus on renewable domestic sources
- Upgrade our national energy infrastructure
- Facilitate the emergence of hydrogen technologies as vital new "energy carriers."

The Opportunities

Biomass Program
Using domestic, plant-derived resources to meet our fuel, power, and chemical needs

Building Technologies Program
Homes, schools, and businesses that use less energy, cost less to operate, and ultimately, generate as much power as they use

Distributed Energy Program
Expanding clean on-site energy choices for greater efficiency, reliability, and security

Federal Energy Management Program
Leading by example, saving energy and taxpayer dollars in federal facilities

FreedomCAR & Vehicle Technologies Program
Less dependence on foreign oil, and eventual transition to an emissions-free, petroleum-free vehicle

Geothermal Technologies Program
Tapping the Earth's energy to meet our heat and power needs

Hydrogen, Fuel Cells & Infrastructure Technologies Program
Paving the way toward a hydrogen economy and net-zero carbon energy future

Industrial Technologies Program
Boosting the productivity and competitiveness of U.S. industry through improvements in energy and environmental performance

Solar Energy Technology Program
Utilizing the sun's natural energy to generate electricity and provide water and space heating

Weatherization & Intergovernmental Program
Accelerating the use of today's best energy-efficient and renewable technologies in homes, communities, and businesses

Wind & Hydropower Technologies Program
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DOE/GO-102004-1913
May 2004