Pumps

Continuing Education from the
American Society of Plumbing Engineers

May 2018

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CEU 259

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Pump applications in plumbing include specialty pumps for liquid supplies, pressure boosters for domestic water systems, fire suppression pump systems, water circulation pumps for temperature maintenance, and pumps for elevation increases in drainage systems, among others.

PUMP COMPONENTS

The basic parts of any pump consist of a passage and a moving surface. The passage is referred to as the pump casing. A prime mover, such as an electric motor but sometimes an engine, adds torque to the moving surface. Other parts include the impeller, seals, shaft bearings, and controls.

Casing

Casing materials are generally cast iron and cast bronze for domestic water supplies. Other materials include stainless steel and various polymers. For pumps used in potable water systems, the weighted average lead content in any component must be no more than 0.25 percent per the federal Reduction of Lead in Drinking Water Act.

Motors

Most pumps are driven by squirrel cage induction motors. Synchronous motors are also used for high horsepower (hp) pumps, particularly if power factor correction is important. Wound motors are typically used for variable-speed drives. Reduced-voltage starting and low in-rush current motors are used for high horsepower requirements where a reduction in voltage at starting would adversely affect other users. In the selection of low in-rush current motors, it is important to ensure that the starting torque developed by the motor at its full speed is in excess of the torque requirements of the pump; if not, an overheat condition will occur. Water-cooled motors are quiet and offer advantages in high horsepower applications where building air ventilation is required.

If a pumping system is designed to operate on a continuous basis, it is better to operate an engine at a lower speed and install a gear chain to increase the speed to meet the pump's requirements. If a standby pump is only required to operate during peak demand or during a power failure, then a higher-speed engine should be used.

The type and make of the engine, as well as the speed and horsepower rating, are extremely critical regarding maintenance. The selection of a slow-speed unit with higher capital costs and lower maintenance costs as compared to a high-speed unit with lower capital costs and higher maintenance costs can be made only after a detailed cost analysis of the specific application.

It is wise to choose a diesel rather than a gasoline or natural gas engine if an engine-driven pump is required to start immediately during a power failure. Although the capital cost of a diesel engine is much higher than a gas engine, it is easier to start and is more reliable. Furthermore, a diesel engine will take the full load almost immediately.

Impeller

An impeller is a rotating component of a centrifugal pump that transfers energy from the motor to the fluid being pumped by accelerating the fluid outward from the center of rotation. Impeller materials include cast iron, bronze, and various polymers. The vanes of an impeller are curved to produce a smooth flow of water with minimum turbulence. The characteristics of a centrifugal pump are largely determined by the angle of the tip of the vanes.

Figure 4-1 Impellers: (from left) Enclosed, Open, and Semi-Enclosed
Source: Courtesy of Xylem

Enclosed impellers (see Figure 4-1) generate head between the two shrouds of the rotating impeller. Semi-enclosed impellers generate head between the one wall of the rotating impeller and the facing stationary wall of the casing. Open impellers generate head between the two stationary walls of the casing.

Closed impellers require little maintenance. The wearing surfaces are relatively uncritical, and the original efficiency is maintained throughout the impeller's operating life. Semi-enclosed and open impellers require close tolerances between the rotating vanes and casing walls. As wear occurs, the clearances become greater, resulting in increased leakage losses within the pump and decreased efficiencies. Open impellers are generally selected only when the pumped water contains suspended solids.

The quantity and angle of the blades on the impeller and the shape of the blades vary. They may be two straight blades positioned radially, many curved blades angled forward, or, more commonly, many blades angled backward to the direction of rotation. While forward blades theoretically impart greater velocity, the conversion to pressure is unstable except within a narrow speed range.

Seals

Pump seals are required to prevent liquid from leaving the pump or air from entering the pump through the clearance around the driver shaft.

The two types of seals are packing (Figure 4-2) and mechanical (Figure 4-3). The performance of the seal depends on the characteristics of the water being pumped. In applications involving water with high abrasives, the packing seal is superior to the mechanical seal. Mechanical seals are superior where the water is free of abrasive material.

Packing is inexpensive, easy to install, readily available, and can be replaced without disassembling the pump. Its disadvantages are that it requires some liquid leakage, experiences shaft sleeve wear, requires periodic maintenance, has some horsepower loss, and the shaft sleeves need replacing.

Packing is a compression type of seal. When compressed by the packing gland, it expands outward and inward to come into contact with the packing box and shaft sleeve. Since the shaft rotates, the packing must not be compressed so tightly that all leakage is eliminated. A little leakage is necessary for lubrication to prevent packing burnout and shaft sleeve wear. The packing wears slightly and shrinks during service and thus requires periodic maintenance to tighten the packing gland to minimize excessive leakage.

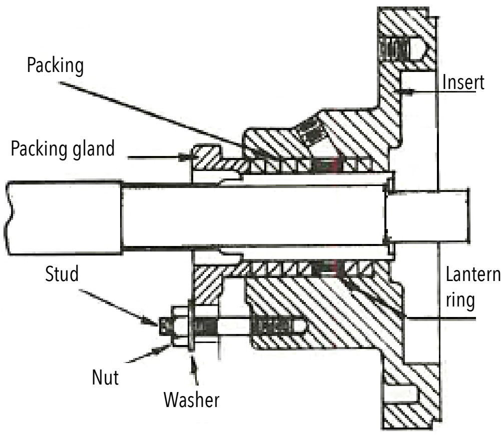

Figure 4-2 Packing Seal

Mechanical seals almost eliminate leakage, require no periodic maintenance, and eliminate shaft sleeve wear. They also function as a slider bearing since they utilize rotating and stationary members. These seals are more expensive than packing seals, are easily damaged, and require disassembly of the pump for replacement.

It is a common misconception that a mechanical seal allows absolutely no leakage of water. Some leakage must always flow through the faces of the seal for lubrication, or failure would result. Generally this leakage is so slight that it vaporizes, and only after a long period can some slight oxidation be noted outside the box near the shaft as evidence of the slight leakage.

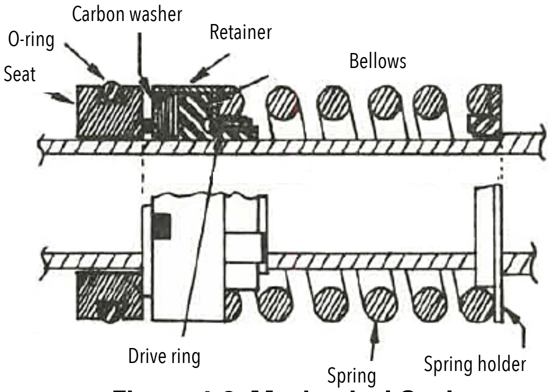

Figure 4-3 Mechanical Seal

Bearings

The three types of bearings are sleeve, roller, and ball. Ball bearings (see Figure 4-4) are used almost exclusively in pumps in most plumbing applications. The ball bearing experiences point contact between its races and, like the roller bearing, experiences rolling contact rather than sliding contact as in the sleeve bearing. The ball bearing can support high loads even at low speeds and is much quieter in operation than the roller bearing.

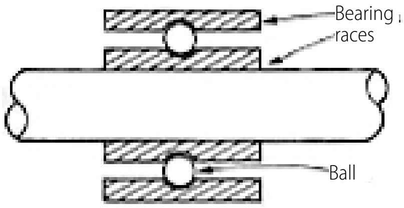

Figure 4-4 Ball Bearing

Pump Controls

Pump controls vary with the application. A small simplex sump pump may have a self-contained motor overload control, one external float switch, an electric plug, and no control panel. A larger pump may have a control panel with a motor controller, run indicator light, hand-off auto switch, run timer, audio/visual alarms for system faults, and building automation system interface. The control panel should be certified as complying with one or more safety standards, and the panel housing should be classified to match its installation environment.

Motor control generally includes an electric power disconnect and the related control wiring, such as power-interrupting controls against motor overload, under-voltage, or over-current.

The largest pumps often include reduced-voltage starters. Duplex and triplex pump arrangements include these control features for each pump as well as an alternator device that alternates which pump first operates on rising demand. A microprocessor may be economically chosen for applications involving at least a dozen sensor inputs.

A booster pump has additional controls such as low flow, low suction pressure, high discharge pressure, a time clock for an occupancy schedule, and possibly a speed control such as a variable-frequency drive.

A circulation pump may include a temperature sensor that shuts down the pump if it senses high temperature in the return flow, which presumably indicates adequate hot water in each distribution branch. A time clock for an occupancy schedule shuts down the pump during off-hours.

The controls for a fire pump may include an automatic transfer between two power sources, engine control if applicable, and pressure maintenance through a secondary pump, which is called a jockey pump.

The controls for a drainage pump include one or more float switches and possibly a high water alarm.

PUMP TYPES

The field for application in plumbing systems can be narrowed down to two general pump classifications, centrifugal and rotary (positive displacement), as defined by the Hydraulic Institute.

Centrifugal Pumps

The most common type of pump used in plumbing and fire protection systems is the centrifugal pump. The centrifugal pump stands out because of its simple design and suitable head pressure. Furthermore, its rotational speed matches that of commonly available electric motors; drive belts or gears are rarely employed.

A simple analogy of a centrifugal pump is a bucket of water with a hole in the bottom. When the bucket is whirled overhead by means of a rope fastened to its handle, the water is thrown a considerable distance out of the hole. As the bucket is whirled faster, it empties more quickly, and the water is discharged further. In pump terminology, when the speed of rotation increases, more water is pumped (capacity) to a greater height (head).

Centrifugal pumps used in plumbing systems are classified, on the basis of the internal casing design, as volute or regenerative (turbine). On the basis of the main direction of the discharge of the liquid, impellers are classified as radial, axial, or mixed flow. Other means of classification are:

- Casing design: Vertical or horizontal split case
- Axis of shaft rotation: Vertical, horizontal, or inclined
- Direction of pump suction or discharge: Side, top, or bottom
- Number of impellers or stages: Single- or multistage
- Type of coupling of the motor to the pump: Close-coupled or flexible-coupled
- Position of the pump in relation to the liquid supply: Wet or dry pit mounted, submersible, or inline
- Pump service: Water, sewage, corrosive chemical, fire, etc.

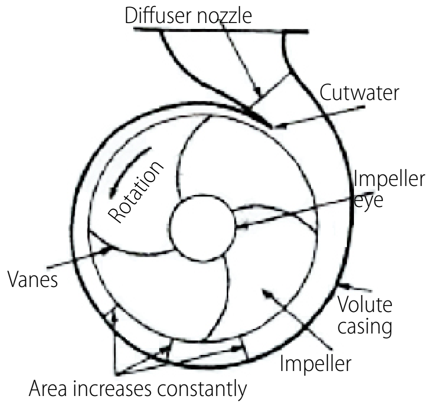

Figure 4-5 Volute Pump Casing

Volute Pumps

The most basic volute pump is the single-stage type, which consists of a rotating element (impeller) and a casing. The water enters the eye (center) of the impeller and is rotated by the vanes of the impeller. Centrifugal force impels the water from the eye to the periphery of the impeller at a greatly increased velocity. The casing enclosing the impeller has a volute- (spiral-) shaped passage of increasing area that collects the high-velocity flow leaving the impeller and converts a portion of the velocity head (kinetic energy) into static head (potential energy).

The volute pump has a spiral casing (see Figure 4-5) that is proportioned to produce an equal velocity of flow at all sections around the circumference at the best efficiency point (BEP) of the pump and also to gradually reduce the velocity of the water as it flows from the impeller to the discharge nozzle. It should be noted that the casing plays absolutely no part in the actual generation of head. The impeller delivers all of the energy imparted to the water, and the casing merely contains the pressure and converts the kinetic energy to potential energy. At the point of separation between the discharge nozzle and the volute is a small projection of the casing material called the volute tongue, or cutwater, which cuts the flow of water away from the impeller and helps direct the water into the discharge nozzle.

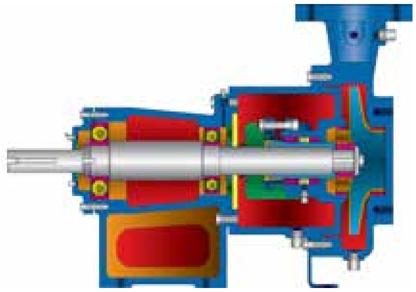
Figure 4-6 Single-Suction Volute Pump with End-Suction Design
Source: Patterson Pump Co.

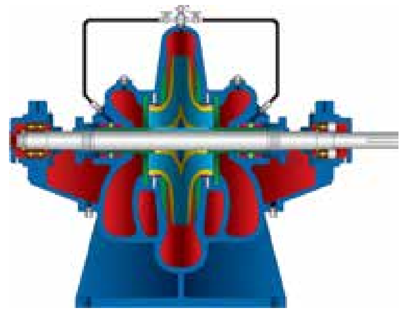
Figure 4-7 Double-Suction Volute Pump
Source: Patterson Pump Co.

Single-Suction and Double-Suction Pumps

Water enters the eye of the impeller from one side only in a single-suction pump (see Figure 4-6), and it is therefore subject to the axial hydraulic thrust of the unbalanced hydraulic pressure on the one side of the impeller. In a double-suction pump (see Figure 4-7), the water enters the impeller from both sides and thus tends to practically eliminate hydraulic imbalance. This is why double-suction pumps are specified for higher pressures and flows in preference to the single-suction configuration. It should always be ascertained that the bearings of a single-suction pump are capable of withstanding the imposed axial hydraulic thrust.

End-Suction and Inline Pumps

Pipes generally connect to pumps with standard flanges, but they may also connect by pipe threads or solder joints. The centerline of the inlet pipe may be aligned with the pump shaft. Figure 4-6 shows this type; it is referred to as an end-suction design. The outlet generally falls within the plane of the impeller. If the inlet and outlet connections align as if in a continuation of the pipe run, as shown in Figure 4-8, the pump is referred to as inline.


Figure 4-8 Inline Pump

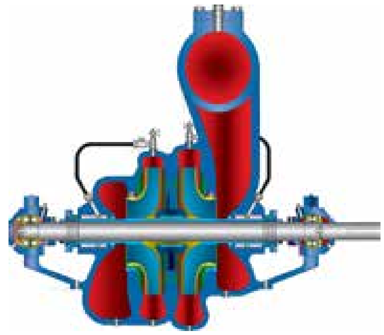
Figure 4-9 Horizontal Split-Case Pump
Source: Patterson Pump Co.

Vertical and Horizontal Split-Case Pumps

Single-suction pumps generally have vertical split casings, and double-suction pumps are generally of the horizontal split-case type (see Figure 4-9). Horizontal split casings allow dismantling of the pump for maintenance or repair without disturbing the piping connections. Many vertical split-case pumps are now available with a back pullout feature so the piping doesn't need to be disturbed when maintenance or repair is required.

Vertical Volute Pumps

In a vertical volute pump, the shaft is vertical, and the impeller discharges radially and horizontally against the casing. The developed pressure forces the water up through the vertical discharge column. Both single-stage and multistage pumps are available and are of two general types: wet pit mounted and dry pit mounted (see Figure 4-10). The pumping chamber floor of the wet pit mounted type is located below the level of the pumped water, with the discharge generally at ground level. The suction inlet is usually located at the bottom, but side-suction types are also available. In dry pit mounted units, the pumping chamber's water level is located above the level of the water supply inlet. In each case, a suction screen is desirable unless solids are being pumped.

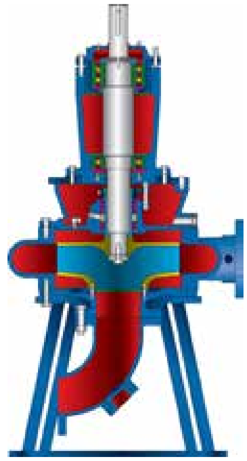

Figure 4-10 Dry Pit Mounted Vertical Pump
Source: Patterson Pump Co.

Vertical Turbine Pumps

Vertical turbine pump (see Figure 4-11) is a broad classification for bottom-suction centrifugal pumps with vertical shafts to which one or more impellers are fastened. The impellers are of the volute or mixed-flow type. Discharge occurs along the shaft axis and in some units is stabilized by diffuser vanes located at the bowl wall.

These pumps are further classified as water lubricated or oil lubricated. In water-lubricated units, the drive shaft is located directly in the flow path of the discharge water, which lubricates the shaft bearings, packing, and stabilizers. Oil-lubricated units are called for where the water is highly abrasive or corrosive. A tube enclosing the drive shaft is filled with oil to lubricate the bushings and sleeves. In the oil-lubricated units, these parts do not come in contact with the water, so the water is not contaminated with the oil. Both water-lubricated and oil-lubricated pumps should be equipped with a screen or strainer in the suction inlet. The total open area of the screen or strainer should be approximately four times the eye area of the impeller.

Each stage of a multistage vertical turbine pump has a separate bowl and impeller, and thus additional stages can be added without difficulty. Extremely high heads can be obtained merely by increasing the number of stages.

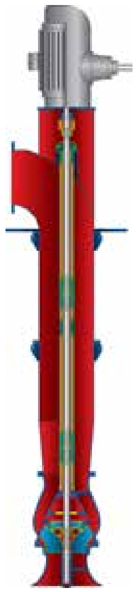

Figure 4-11 Vertical Turbine Pump
Source: Patterson Pump Co.

Close-Coupled and Flexible-Coupled Pumps

A close-coupled pump is one in which the pump housing is directly attached to the casing of the driving motor, and the motor shaft is also the pump shaft. A close-coupled pump has a low initial cost and low installation costs, does not require shaft alignment, and is relatively compact. One major disadvantage is that it generates more pipe and liquid-borne noise than a flexible-coupled pump. Also, motor replacement is difficult.

A flexible-coupled pump is one in which the pump shaft and motor shaft are joined by a flexible connector (shaft coupling). Both the pump and the motor are generally furnished complete to maintain shaft alignment. Large pumps will be mounted on a steel base.

Regenerative Turbine Pumps

One way to obtain greater pressure is by using a regenerative turbine pump. Unlike other centrifugal pumps, the outer edge of the impeller and its volute are intentionally employed with higher velocities by recirculating a portion of the flow from the volute to pass just inside the tip of the impeller. The close dimensions of these pumps limit their use to clean liquids. Applications of high-head pumps include water supplies in high-rise buildings, deep water wells, and fire pumps for certain automatic standpipe systems.

Multistage Pumps

To provide high pressure, two or more impellers and casings can be assembled on one shaft as a single unit, forming a multistage pump. Discharge from the first stage enters the suction of the second, and so on. The capacity is the rating in gallons per minute (gpm) of one stage; the pressure rating is the sum of the individual stages' pressure ratings, minus a small head loss.

Multistage centrifugal pumps may use single- or double-suction impellers. Single-suction impellers are hydraulically unbalanced and, when used in multistage pumps, have equal numbers of nozzles discharging in opposite directions. Since double-suction impellers are not subject to hydraulic unbalance, they are not so limited.

Rotary Pumps

The Hydraulic Institute identifies pumps used to pump viscous liquids as rotary pumps. These pumps are also described as positive-displacement pumps because the rotation of the shaft creates a positive pumping action. A basic difference between centrifugal and rotary pumps is the means of imposing pressure on the liquid. A centrifugal pump generates pressure due to the centrifugal force developed by the impeller rotating at a relatively high speed in the pump casing. A rotary pump generates pressure from a compressing (squeezing) action that can be created in either of two ways: by a rotor rotating in the pump casing to decrease the size of the pumping chamber or by the rotor screw threads meshing with an internal thread of a stator, or of a second screw, to cause axial displacement of the liquid.

Whereas a centrifugal pump can operate at shutoff conditions, a rotary pump, because of its positive-displacement characteristic, will continue to build up pressure if the discharge valve is closed. For this reason, a relief valve must always be provided to prevent possible damage to the pump. The relief valve may be either integral with the body or endplate or attachable. It may be adjustable through a predetermined range of pressures or have a fixed setting. It may be designed to bypass the fluid internally from the pump outlet to the pump inlet or externally through an auxiliary port.

Many positive-displacement pump manufacturers make only one or two types of positive-displacement pumps, and they become specialists in those types. They will have the selection criteria for each particular type and in many cases will also determine the viscosity at the pumping temperature if samples of the liquid being pumped are provided.

Positive-displacement rotary pumps are best used with liquids at high velocities and materials with low shear to product. The upper limit is 100,000 centipoise (cP), but this can be higher if fed with an auger feed unit.

Domestic Booster Pumps

A domestic booster pump system typically uses multiple parallel centrifugal pumps to increase pressure for a building's domestic water distribution. Particular design issues such as sizing, pump redundancy, pressure-reducing valves, other pump controls, adjustable-frequency drives, high-rise buildings, and break tanks are described in *Plumbing Engineering Design Handbook,* Volume 2, Chapter 5: "Cold Water Systems."

Fire Pumps

Fire pumps often are used to supplement supplies from public mains, gravity tanks, reservoirs, pressure tanks, or other sources. The centrifugal fire pump is standard due to its compactness, reliability, easy maintenance, hydraulic characteristics, and variety of available drivers (electric motors, steam turbines, and internal combustion engines).

Horizontal and vertical fire pumps are available with capacities up to 5,000 gpm. Pressure ratings range from 40 to 490 pounds per square inch (psi) for horizontal pumps and 75 to 387 psi or higher for vertical turbine pumps. The size of a horizontal centrifugal pump is generally the diameter of the discharge outlet. However, it is sometimes indicated by both the suction and discharge pipe flange diameters. The size of a vertical turbine pump is the diameter of the pump column.

These fire pumps take suction from the public water main, industrial system, or power penstock. As a prelude to installation, available fire flow in the area should be obtained by testing. The full overload capacity of the pump plus the probable flow drain from hydrants in the area by the fire department must be calculated. The pressure in the water mains should not be allowed to drop below 20 psi. The head rating of the pump should be sufficient to meet all pipe friction in the connection plus the pressure demand.

Vertical turbine fire pumps (see Figure 4-12) were originally designed to pump water from bored wells. As fire pumps, they are recommended in instances where horizontal pumps operate with suction lift. An outstanding feature of vertical pumps is their ability to operate without priming. (See NFPA 20: *Standard for the Installation of Stationary Fire Pumps for Fire Protection* for the required submergence.)

Vertical pumps may be used to pump from streams, ponds, wet pits, etc., as well as for booster service. Suction from wells is not recommended for fire service, although it is acceptable if the adequacy and reliability of the well are established and the entire installation conforms with NFPA 20. In many instances, the cost of a deep-well fire pump installation is prohibitive, especially if the pumping level at the maximum rate is more than 50 feet below ground level (200 feet is the limit).

If the yield from a reliable well is too small to supply a standard fire pump, low-capacity well pumps can be used to fill conventional ground-level tanks or reservoirs for the fire pump supply.

Figure 4-12 Vertical Turbine Fire Pump
Source: Patterson Pump Co.

Water Circulation Pumps

Maintaining an adequate water temperature in plumbing is achieved through circulation pumps. Applicable generally for hot water, but equally effective for chilled water to drinking fountains served by a remote chiller, the circulation pump maintains a limited temperature change. Heat transfer from hot water distribution piping to the surrounding space is quantified for each part of the distribution network. For a selected temperature drop from the hot water source to the remote ends of the distribution, an adequate flow in the circulation can be determined from Equation 4-1. Since the nature of circulation is as if it were a closed system, pump head is simply the friction losses associated with the circulation flow.

Equation 4-1

$$Q = \frac{q}{500 \times T}$$

where

Q = Flow, gpm (L/s)
q = Heat transfer rate, British thermal units per hour (Btuh) (W)
T = Temperature difference, °F (°C)

For International Standard (SI) units, replace 500 in Equation 4-1 with 4,187.

For example, if 1,000 Btuh transfers from a length of hot water piping and no more than 8°F is acceptable for a loss in the hot water temperature, the flow is determined to be 1,000/(500 × 8) = 0.25 gpm. In SI, if 293 W transfers from a length of hot water piping and no more than 4.4°C is acceptable for a loss in the hot water temperature, the flow is determined to be 293/(4,187 × 4.4) = 0.0159 L/s.

Drainage Pumps

Where the elevation of the municipal sewer is insufficient or if another elevation shortfall occurs, pumps are added to a drainage system. The issue may apply only to one fixture or one floor or the entire building. Elevation issues usually apply to subsoil drainage, so this water is also pumped. Lastly, if backflow is intolerable from floor drains in a high-value occupancy, pumps are provided for the floor drains.

The terminology varies to describe these pumps, but typical names include sewage pump, sump pump, sewage ejector, lift station pump, effluent pump, bilge pump, non-clog pump, drain water pump, solids-handling sewage pump, grinder pump, dewatering pump, and wastewater pump.

Drainage pumps generally have vertical shafts, cylindrical basins, and indoor or outdoor locations. Some pumps are designed to be submerged in the inlet basin and others in a dry pit adjacent to the basin, and in others the motor is mounted above with only the pump casing and impeller submerged. In any design, provision is required for air to enter or leave the basin as the water level varies.

The nature of solids and other contaminants in the water through these pumps necessitates several types of pump designs. For minimal contaminants, the design may be with an enclosed impeller, wear rings, and clearance dimensions that allow ¾-inch (19-mm) diameter spheres to pass through. Such a pump may be suitable for subsoil drainage or for graywater pumping.

For drainage flows from water closets and similar fixtures, manufacturers provide pumps of two designs. One design uses an open recessed impeller, no wear rings, and clearance dimensions that allow 2-inch (50-mm) diameter spheres to pass through. The other, referred to as a grinder pump, has a set of rotating cutting blades upstream of the impeller inlet to slice solid contaminants as they pass through a ring that has acute edges. Efficiency is compromised in both types for the sake of effective waste transport, in the latter more so than in the former, but with the benefit of a reduced pipe diameter in the discharge piping. Grinder pumps are available in centrifugal and positive-displacement types.

The installation of a pump in a sanitary drain system includes a sealed basin and some vent piping to the exterior or to a vent stack. In some cases, the pump can be above the water level, but only if a reliable provision is included in the design to prime the pump prior to each pumping event.

DETERMINING PUMP EFFICIENCY

Pumps add energy to the liquid being pumped, resulting in a higher pressure downstream to move the liquid. This added energy is called head, which refers back to the days of dams and water wheels. The descent of water was expressed as a level of energy per pound of water. The water descended adjacent to the dam through the water wheel, and the vertical distance between the water levels on either side of the dam was measured. In contrast to water wheels, all pumps add energy, but the amount is expressed in the same terminology.

In theory, if a sufficiently tall, open-top vertical pipe is mounted on a pipe both downstream and upstream of a pump, the liquid level in both can be observed. The level downstream will be higher than the level upstream. This difference in elevation between the two levels is called the total head for the pump. Another element of pump head is the difference in elevation between the upstream pipe and the pump; a distinction is made if the upstream elevation is above or below the elevation of the pump inlet. Suction head exists when the suction inlet is above the pump or under positive pressure. Suction lift exists when the suction inlet is below the pump. Discharge head is the pressure at the discharge of the pump (see Figure 4-13).

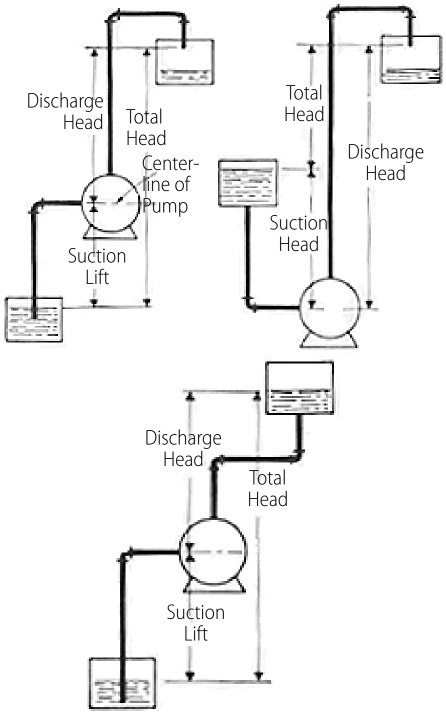

Figure 4-13 Head Terms

An ideal pump transfers all of the energy from the shaft to the liquid; therefore, the product of torque and rotational speed equals the product of mass flow and total head. However, hydraulic and mechanical losses result in performance degradation. Hydraulic losses result from friction within the liquid through the pump, impeller exit losses, eddies from sudden changes in diameter, leaks, turns in direction, or short-circuit paths from high-pressure sections to low-pressure sections. Mechanical losses include friction in bearings and seals. The amount of hydraulic and mechanical losses is from 15 to 80 percent in centrifugal pumps and lesser amounts for positive-displacement pumps.

Design features in centrifugal pumps that minimize hydraulic losses include a generous passage diameter to reduce friction, optimal impeller design, a gradual diameter change and direction change, the placement of barriers against short-circuits, and optimal matching of impeller diameter to pump casing. The design of a barrier against short-circuits includes multiple impeller vanes, seals at the impeller inlet, and minimal space between the impeller and the pump casing. The seals at the impeller inlet are commonly in the form of wear rings. Enclosed impellers achieve higher heads because of the isolation of the inlet pressure from the liquid passing through the impeller; thus, the original efficiencies are maintained over the pump's useful life.

Equation 4-2 illustrates the relationship between flow, total head, efficiency, and input power for pumps with cold water. For other liquids, the equation is appropriately adjusted.

Equation 4-2

$$P = \frac{Q \times h}{3{,}960 \times e} \qquad \text{For SI, } P = \frac{Q \times h \times 9.81}{e}$$

where

P = Power through the pump shaft, hp (W)
Q = Flow, gpm (L/s)
h = Total head, ft (meters)
e = Efficiency, dimensionless

Impellers with diameters significantly smaller than an ideal design generally compromise efficiency. The efficiency of centrifugal pumps varies greatly with head and flow. Hence, a pump with 85 percent efficiency at one flow may be only 50 percent at one-third of that flow.

Motor Efficiency

The most important factors affecting motor efficiency are sizing the motor to the load, the type of motor specified, motor design speed, and the type of bearing specified. Oversizing the motor to the load results in poor efficiency. The type of motor specified is also significant in obtaining the highest efficiency. Higher-speed induction motors are inherently more efficient, as are ball bearings with rolling friction compared to sleeve bearings with sliding friction. The total power required to drive a three-phase motor is a function of both efficiency and the power factor. The formula is:

Equation 4-3

$$KVA = \frac{0.746 \text{ x hp}}{\text{Efficiency x Power factor}}$$

The value of KVA, which is the total power required to drive the motor, will increase as both motor efficiency and the power factor fall. For example, a typical 20-hp, high-efficiency motor would be two percentage points higher in efficiency than a standard motor. This same high-efficiency motor might have a higher power factor of six percentage points. In larger sizes, the high-efficiency and standard units approach each other in both efficiency and power factor.

Designing for the Best Efficiency Point

A centrifugal pump's first cost can be minimized by designing for the best efficiency points of the operating flow and head (see Figure 14-14). A lower total head also results in less bearing and shaft stresses, leading to a longer expected pump life.

Specific Speed

Specific speed correlates pump flow, head, and speed at optimum efficiency. It shows the relation of pump impellers to their geometric similarity. Specific speed is expressed as:

Equation 4-4

$$N_s = \frac{N\sqrt{Q}}{H^{3/4}}$$

where

Ns = Pump specific speed
N = Shaft speed, revolutions per minute (rpm)
Q = Flow at optimum efficiency, gpm (L/s)
H = Head, ft (m)

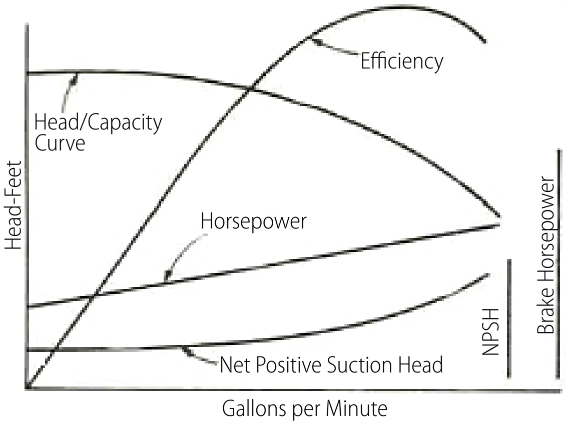

Figure 4-14 Pump Efficiency

The specific speed of a given impeller is defined as the revolutions per minute for a geometrically similar impeller if it were sized to discharge 1 gpm against 1 foot of head. Specific speed is an index of the impeller's shape and characteristics.

Once the values for head and capacity are established for a specific application, the pump's specific speed range can be determined to ascertain the selection of a pump with optimal efficiency.

Pump Affinity Laws

A definite relationship exists between the various pump characteristics. When the speed is changed, the following changes also occur:

- The capacity for a given point on the pump head/capacity curve varies proportional to the change in speed.
- The head varies proportional to the square of the change in speed.
- The brake horsepower varies proportional to the cube of the change in speed.

These relationships expressed mathematically are:

Equation 4-5

$$Q = Q_1(n/n_1);\ H = H_1(n/n_1)^2;\ BHP = BHP_1(n/n_1)^3$$

where

Q = Capacity at speed n, gpm
Q_1 = Original capacity at speed n_1, gpm
n = New speed, rpm
n_1 = Original speed, rpm
H = Head at speed n and capacity Q, ft
H_1 = Original head at speed n_1 and capacity Q_1, ft
BHP = Brake horsepower at speed n, head H, and capacity Q
BHP_1 = Brake horsepower at speed n_1, head H_1, and capacity Q_1

The total head is directly proportional to the square of the impeller's tip velocity, which is a product of the impeller's rotational speed and the impeller's radius. Thus, the total head is proportional to the square of the impeller's radius or of its diameter, and it is proportional to the square of the impeller's rotational speed, in rpm (radians per second). This is the second pump affinity law.

Additionally, since flow is directly proportional to area and velocity at any section through a pump, at a particular section the flow is proportional to the velocity of the impeller's tip. Hence, flow is proportional to the rotational speed of the impeller and to the diameter of the impeller. This is the first pump affinity law.

Since power is the product of flow and head, power is directly proportional to the cube of the velocity. This is the third pump affinity law.

The affinity laws allow easy identification of pump performance when the speed changes or the impeller diameter changes. For example, doubling the speed or impeller diameter doubles the flow, increases the head by four, and increases the required motor power by eight.

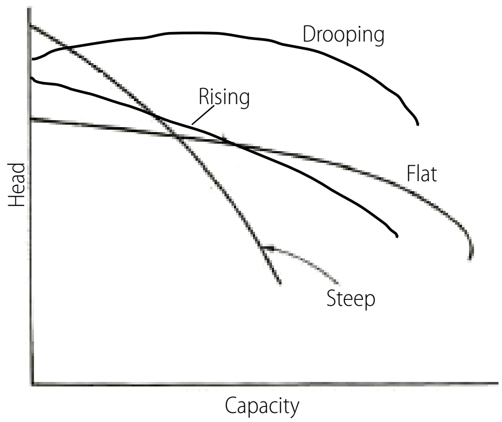

Figure 4-15 Pump Performance Curves

PERFORMANCE CURVES

A centrifugal pump operating at a constant speed will deliver a quantity of water from zero to a maximum value depending on the size of the pump, the pump's design and speed, and suction conditions. The total head developed by the pump, required horsepower, and efficiency will vary with the capacity. The interrelations of head, capacity, horsepower, and efficiency are called the pump characteristics, and when presented graphically the result is called the characteristic (or performance) curves of the pump. The head/capacity and horsepower curves are determined by tests, and the efficiency curve is calculated from these two curves. Pump curves are shown for water; therefore, adjustments must be made if a higher-viscosity fluid is used.

Pump head/capacity curves (see Figure 4-15) are commonly classified as follows and determined by the shape of the impeller.

- Rising characteristic curve: This is also called a rising head/capacity characteristic and is a curve where the head rises continuously as the capacity decreases.
- Drooping characteristic curve: This is also called a drooping head/capacity characteristic and is a curve where the head developed at shutoff is less than that developed at some other capacity. This is sometimes also called a looping curve. At one particular total dynamic head, two different flows could exist, so this is not a desirable pump curve to use.
- Steep characteristic curve: This is a rising head/capacity characteristic curve where a large increase in head is developed at shutoff in relation to the head developed at the design capacity. This is a good curve for use with multiple parallel pumps.
- Flat characteristic curve: This is a characteristic curve where the head from shutoff to the design capacity varies only slightly. The curve might also be drooping or rising. All drooping curves have a portion where the head is approximately constant over a range of capacities, and this range is called the flat portion of the curve. This curve is typically used for single-pump HVAC systems.

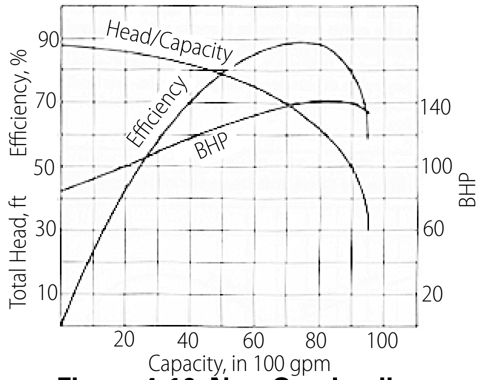

Figure 4-16 Non-Overloading Power/Capacity Curve

Power/capacity curves are also classified according to shape. Figure 4-16 illustrates a pump characteristic with a brake horsepower curve that flattens out and decreases as the capacity increases beyond the maximum efficiency point. This is called a non-overloading curve. When the BHP curve continues to increase with increased capacity (see Figure 4-17), the pump is said to be overloading. Pumps with non-overloading power curves are advantageous because the driver is not overloaded under any operating condition.

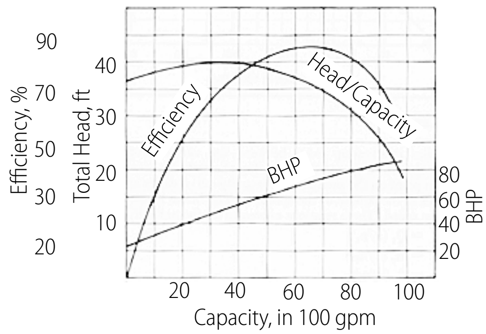

Figure 4-17 Overloading Power/Capacity Curve

While a curve is plotted for a given pump and with a given diameter impeller, a pump in operation under a constant head and speed has one particular flow. The point on the pump curve of this flow and head is referred to as the duty point or system balance point (see Figure 4-18). The pump will provide that flow if that head applies.

In plumbing, a particular flow may be required for a sump pump or a hot water circulation pump. In domestic water and fire suppression supply systems, the head varies with the quantity of open faucets, outlets, hose streams, or sprinkler heads. Further, the quantity of such open outlets varies with time. Thus, the duty point rides left and right along the curve with time.

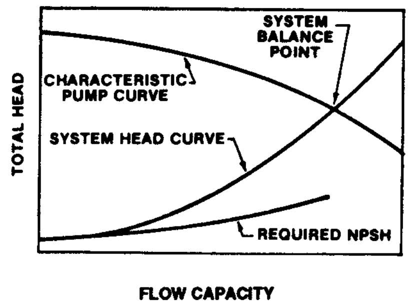

Figure 4-18 Typical Pump Curve Crossing a System Head Curve

Another curve that represents the building's distribution piping at peak demand can be plotted on a pump curve. This second curve, called the system head curve or building system curve, is shown in Figure 4-18. Equation 4-6 represents this familiar curve, where p_1 represents a pressure gauge reading at the pump inlet and p_2 and h_2 represent pressure and elevation head respectively at a particular system location such as at a remote fixture. The last term represents the entire friction head in the piping between the two points including control valves, if any, at the pump. The curve's shape is parabolic. This curve is applicable to any liquid that has a constant absolute viscosity over a wide flow range (a Newtonian fluid).

Equation 4-6

$$h_p = (p_2 - p_1)/d + h_2 + f(L/D)(v^2/2g)$$

At no flow, the friction term becomes zero since velocity is zero, and the point where this curve crosses the vertical axis is the sum of the remaining terms.

To select a pump, determine the peak flow and use Equation 4-6 to calculate the required pump head. The flow and head identify the duty point. Most catalogues from pump manufacturers offer a family of centrifugal pumps in one diagram. Separate graphs, one for each pump housing and shaft speed, show the pump performance for each of several impellers. Figure 4-19 illustrates such a graph for a pump measured at 1,750 rpm (183 radians per second). Pick a pump impeller that at least includes the duty point. An optimal pump is one whose pump curve crosses this point. However, with most pump selections, the pump curve crosses slightly above the point.

For example, if the duty point is 100 gpm at 30 feet of head (6.31 L/s at 9.14 m of head), the impeller number 694 in Figure 4-19 is a suitable choice because its pump curve (the solid line matched to 694) crosses above the duty point. Power requirements are marked in dashed lines in Figure 4-19. The pump's motor size, in horsepower or kilowatts, is identified by the dashed line above and to the right of the duty point. A more precise motor required can be estimated at 1.6 hp (1.2 kW), but engineers would typically pick the 2-hp (1.5-kW) motor size. Select the motor with a nominal 1,800-rpm (188 radians per second) rotational speed. The pump's efficiency can be estimated if efficiency curves are included on the chart. Comparing the efficiencies of several pumps can lead to an ideal choice. Alternatively, the flow and head of the duty point can determine the ideal power requirement. A pump's efficiency is found by dividing the ideal power, from Equation 4-2, by the graphically shown power. With this example, the efficiency is 0.758/1.6 = 47 percent.

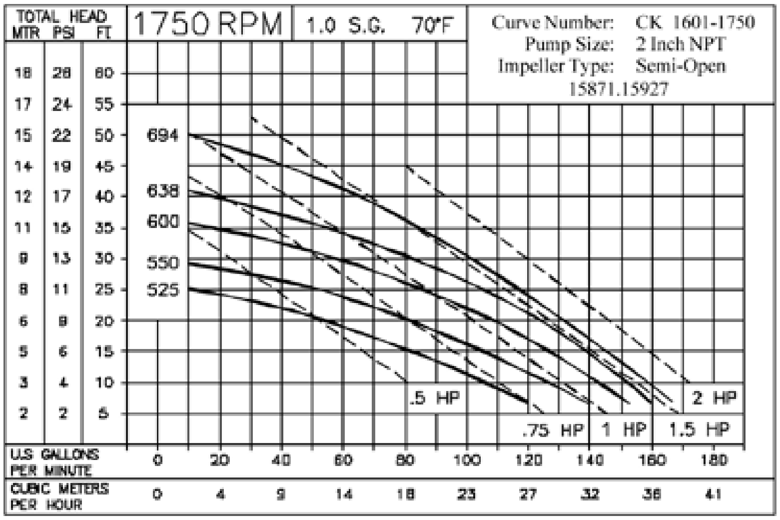

Figure 4-19 Typical Pump Curves and Power Requirements

CAVITATION

Cavitation occurs in a pump when insufficient net positive suction head (NPSH) is available. NPSH is the total suction head in feet absolute, determined at the suction nozzle, less the vapor pressure of the liquid. When the pressure of a liquid being pumped is reduced to a value equal to or less than its vapor pressure, small vapor bubbles (cavities) begin to form. Vapor pressure is the pressure at which equilibrium exists between the fluid and its surrounding pressure at its boiling temperature. Above this pressure and temperature, the fluid will boil. Below this pressure and temperature, the fluid will evaporate.

As the vapor bubbles move along the impeller vanes of a pump to an area of higher pressure, they collapse practically instantaneously. The collapse, or more accurately the implosion, is accompanied by a rumbling noise that sounds as though gravel were being pumped. The magnitude of the forces generated by the implosion of the bubbles causes minute pockets of fatigue failure on the surfaces of the impeller vanes. This action is progressive in nature and under severe conditions can cause serious pitting damage and eventual failure of the impeller.

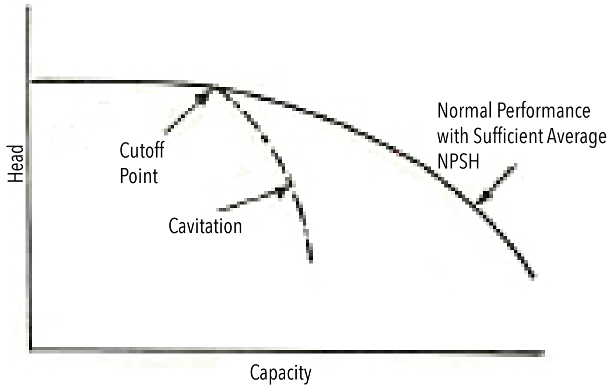

Figure 4-20 Cavitation's Effect on Pump Capacity

Whenever the noise is heard, cavitation most likely is occurring. In addition to impeller damage, cavitation generally results in reduced pump capacity (see Figure 4-20) due to the presence of vapor in the pump. The pump head may also be reduced and exhibit some instability. The power consumption may become erratic, and vibration and mechanical damage such as early bearing failure can also result.

The sure way to avoid the undesirable effects of cavitation is to make certain that the net positive suction head available ($NPSH_A$) is greater than the net positive suction head required ($NPSH_R$) by the pump. Pump curves generally show the $NPSH_R$ for various capacities.

In general, cavitation indicates insufficient available NPSH. Excessive suction pipe friction, combined with low static suction head and high temperatures, contributes to this condition. If the system cannot be changed, it may be necessary to change conditions so a different pump with lower NPSH requirements can be used. Larger pumps might require the use of a booster pump to add pressure head to the available NPSH.

A pump requires a minimum pressure at its inlet to avoid cavitation. Destructive effects occur when a low absolute pressure at the entry to the impeller causes the water to vaporize and then collapse further into the impeller. The resulting shock wave erodes the impeller, housing, and seals and overloads the bearings and the shaft. The pockets of water vapor also block water flow, which reduces the pump's capacity. Cavitation can be avoided by verifying Equation 4-7:

Equation 4-7

$$h_r \leq h_a - h_v + h_s - h_f$$

where

h_r = $NPSH_R$ (obtained from the pump manufacturer), ft (m)

h_a = Local ambient atmospheric pressure converted to feet (m) of water

h_v = Vapor pressure of the water at the applicable temperature, ft (m)

h_s = Suction head (negative value for suction lift), ft (m)
h_f = Friction head of the piping between the pump and where h_s is measured, ft (m)

Increasing h_s resolves most issues regarding cavitation, generally by mounting the pump impeller as low as possible. Note that h_r varies with flow and impeller diameter: h_a = 33.96 feet (10.3 m) for an ambient of 14.7 psi (101 kPa), and h_v = 0.592 feet (0.180 m) for water at 60°F (15.5°C). Suction head, h_s, may be the inlet pressure converted to head, but it also may be the vertical distance from the impeller's centerline to the surface of the water at the inlet. The ambient head, h_a, also may need adjusting for sewage pumps, with the basin connected to an excessively long vent pipe. Reciprocating positive-displacement pumps have an additional acceleration head associated with keeping the liquid filled behind the receding piston.

SERIES AND PARALLEL OPERATION

Very frequently it is not feasible to employ a single pump to satisfy the requirements of a system. Thus, pumps are operated in series to obtain greater heads when it is inefficient or not advantageous to add additional stages to a single pump. Pumps are operated in parallel to obtain greater capacities and flexibility of operation.

It is generally desirable to use two or more pumps in parallel when the system demand varies greatly. One pump can be sequenced to shut down when demand drops, and the remaining pump or pumps can operate closer to peak efficiency. An additional advantage of a multi-pump system is that repairs or maintenance can be performed on one pump without shutting down the entire system.

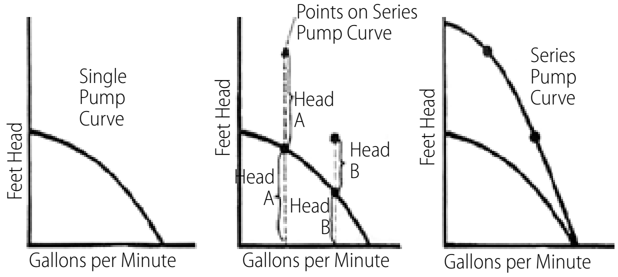

Figure 4-21 Series Pump Curve Construction

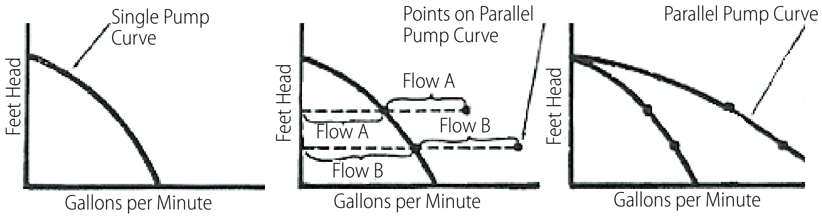

Figure 4-22 Parallel Pump Curve Construction

Determining the combined head/capacity curve for any multiple pump system is relatively simple. For series operation of two or more pumps, the combined performance curve is obtained by adding the heads vertically at the same capacity (see Figure 4-21). For parallel operation of two or more pumps, the combined performance curve is obtained by adding the capacities horizontally at the same head (see Figure 4-22).

For proper operation, all of the pumps in a multiple pump system should have a continuously rising characteristic. For series operation, the pump capacities must be equal, but the pump heads may have different values. For parallel operation, pump capacities may be different, but all of the heads should be the same. The second pump will provide no gpm to the system until it is at the same total dynamic head (pressure) as the first pump.

REDUNDANCY

Redundancy can be considered for any pump application. The aggregate capacity of a set of pumps may exceed the peak demand by any amount; however, the summation for centrifugal pumps involves adding the flow at each head to create a composite performance curve. Discretion is further made to the amount of redundancy, whether for each duplex pump at 100 percent of demand or each triplex pump at 40 percent, 50 percent, or 67 percent. For efficiency's sake, a mix may be considered for a triplex (e.g., 40 percent for two pumps and 20 percent for the third).

PUMP MAINTENANCE

The selection of a pump includes factors such as the need to monitor, repair, or replace the pump. Pumps in accessible locations can readily be monitored. Sensors on remote pumps, such as seal leak probes and bearing vibration sensors, assist in pump monitoring to prevent catastrophic pump failure.

Pump maintenance can be facilitated when disassembly requires minimal disturbance of piping or wiring. Disassembly may be with the casing split horizontally along a horizontal shaft or with the casing split perpendicularly to the shaft. The latter allows impeller replacement without disturbing the pipe connection to the pump body.

Complete pump replacement can be facilitated with adequate access, a lifting mechanism, shutoff valves, nearby motor disconnects, minimal mounting fasteners, direct mounting of the motor on the pump housing (close-coupled pump), and pipe joints with bolted fasteners. A simpler arrangement, commonly used for submersible drainage pumps, allows removal of the pump from the basin by merely lifting a chain to extract it. The lift or return is facilitated by special guide rails, a discharge connection joint held tight by the weight of the pump, and a flexible power cable.

INSTALLATION

Pumping effectiveness and efficiency require uniform velocity distribution across the pipe diameter or basin dimensions at the pump inlet. An elbow, an increaser with a sudden diameter change, a check valve, or any other flow disturbance at the pump inlet creates an irregular velocity profile that reduces the flow and possibly the discharge head. To prevent air entrapment, eccentric reducers with the straight side up are used on inlet piping rather than concentric reducers.

In addition to shutoff valves, pump installations may include drain ports, pressure gauges, automatic or manual air release vents, and vibration isolation couplings. Pressure gauges upstream and downstream of the pump allow easy indication of the rated pump performance. Check valves are provided for each pump of duplex and similar multiple-pump arrangements, fire pumps, and circulation pumps.

A fire pump includes provisions for periodic flow testing. Fire pumps also may include a pressure relief valve if low flows create high heads that exceed pipe material ratings.

Submergence is a consideration for pumps joined near or in a reservoir or basin. A shallow distance from the pump inlet to the surface of the water may create a vortex formation that introduces air into the pump unless the reservoir exit is protected by a wide plate directly above. In addition to lost flow capacity, a vortex may cause flow imbalance and other damage to the pump. To prevent these problems, the basin can be made deeper to mount the pump lower, and the elevation of the water surface can be unchanged to keep the same total head.

ENVIRONMENTAL CONCERNS

In addition to any concerns about how a pump may affect the environment, the environment may affect the design requirement for a pump. An example of the former is a provision in an oil-filled submersible pump to detect an oil leak, such as a probe in the space between the shaft seals that signals a breach of the lower seal. Another example is vibration isolation for a pump located near sensitive equipment.

The external environment can affect a pump in many ways. For instance, a sewage ejector may be subjected to methane gas, causing a potential explosion hazard. Loss of power is a common concern, as are abrasive or corrosive conditions. The former can be prevented with the inclusion of a parallel pump powered by a separate battery, and correct material selection can help prevent the latter. Other examples include the temperature of the water through the pump, the temperature of the air around the pump, and the nature of any contaminants in the water. Sand and metal shavings are a concern with grinder pumps as they can erode the blades.

GLOSSARY

Available net positive suction head The inherent energy in a liquid at the suction connection of a pump.

Axial flow When most of the pressure is developed by the propelling or lifting action of the impeller's vanes on the liquid. The flow enters axially and discharges nearly axially.

Bernoulli's theorem When the sum of three types of energy (heads) at any point in a system is the same as in any other point in the system, assuming no friction losses or the performance of extra work.

Brake horsepower (BHP) The total power required by a pump to do a specified amount of work.

Capacity coefficient The ratio of the radial velocity of a liquid at the impeller to the velocity of the impeller's tip.

Churn The maximum static head of a pump—typically the head when all flow is blocked.

Design working head The head that must be available in the system at a specified location to satisfy design requirements.

Diffuser A point just before the tongue of a pump casing where all of the liquid has been discharged from the impeller. It is the final outlet of the pump.

Flat head curve When the head rises slightly as the flow is reduced. As with steepness, the magnitude of flatness is a relative term.

Friction head The rubbing of water particles against each other and against the walls of a pipe, which causes pressure loss in the flow line.

Head The energy of a fluid at any particular point of a flow stream per the weight of the fluid, generally measured in feet (meters).

Head coefficient Pump head divided by the square of the velocity of the impeller tip.

Horsepower The power delivered while doing work at the rate of 500 foot-pounds per second or 33,000 foot-pounds per minute.

Independent head Head that does not change with flow.

Mechanical efficiency The ratio of power output to power input.

Mixed flow When pressure is developed partly by centrifugal force and partly by the lift of the vanes on the liquid. The flow enters axially and discharges in an axial and radial direction.

Multistage pumps When two or more impellers and casings are assembled on one shaft as a single unit. The discharge from the first stage enters the suction of the second and so on. The capacity is the rating of one stage, and the pressure rating is the sum of the pressure ratings of the individual stages, minus a small head loss.

Net positive suction head Static head, velocity head, and equivalent atmospheric head at a pump inlet minus the absolute vapor pressure of the liquid being pumped.

Packing A soft semi-plastic material cut in rings and snugly fit around a shaft or shaft sleeve.

Potential head An energy position measured by the work possible in a decreasing vertical distance.

Pumps in parallel An arrangement in which the head for each pump equals the system head and the sum of the individual pump capacities equals the system flow rate at the system head.

Pumps in series An arrangement in which the total head/capacity characteristic curve for two pumps in series can be obtained by adding the total heads of the individual pumps for various capacities.

Pump performance curve A chart of the head hp, efficiency, and NPSH required for proper pump operation.

Radial flow When pressure is developed principally by centrifugal force action. Liquid normally enters the impeller at the hub and flows radially to the periphery.

Required net positive suction head The energy in a liquid that a pump must have to operate satisfactorily.

Shutoff brake horsepower One-half of the full load brake horsepower.

Slip A loss in delivery due to the escape of liquid inside a pump from discharge to suction.

Specific speed An index relating pump speed, flow, and head used to select an optimal pump impeller.

Standpipe A theoretical vertical pipe placed at any point in a piping system so the static head can be identified by observing the elevation of the free surface of the liquid in the vertical pipe. The connection of the standpipe to the piping system for a static head reading is perpendicular to the general flow stream.

Static head The elevation of water in a standpipe relative to the centerline of a piping system. Any pressure gauge reading can be converted to static head if the density of the liquid is known.

Static pressure head The energy per pound due to pressure; the height a liquid can be raised by a given pressure.

Static suction head The vertical distance from the free surface of a liquid to the pump datum when the supply source is above the pump.

Static suction lift The vertical distance from the free surface of a liquid to the pump datum when the supply source is below the pump.

Steep head curve When the head rises steeply and continuously as the flow is reduced.

Suction head The static head near the inlet of a pump above the pump's centerline.

Suction lift The vertical dimension between the pump's centerline and the surface of a liquid that is below the pump.

System head curve A plot of system head versus system flow. System head varies with flow since friction and velocity head are both a function of flow.

Total discharge head The sum of static head and velocity head at a pump discharge.

Utility horsepower Brake horsepower divided by drive efficiency.

Total head The total head at the pump discharge minus suction head or plus suction lift.

Variable-speed pressure booster pump A pump used to reduce power consumption to maintain a constant building supply pressure by varying pump speeds through coupling or mechanical devices.

Velocity head The velocity portion of head with its units converted to an equivalent static head.

Water horsepower The power required by a pump motor for pumping only.

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CE Questions — "Pumps" (CEU 259)
Test written by Jeremy Ferriter, CPD

1. The basic parts of any pump consist of a ________ and a ________.
   a. casing; motor
   b. impeller; seal
   c. passage; moving surface
   d. bearing; pump control

2. The ________ is the most common type of pump used in plumbing and fire protection systems.
   a. rotary pump
   b. positive-displacement pump
   c. vertical turbine pump
   d. centrifugal pump

3. Fire pumps may require pressure maintenance through a secondary pump, which is called a ________.
   a. jockey pump
   b. volute pump
   c. vertical turbine pump
   d. multistage pump

4. Requirements for the installation of a vertical turbine fire pump can be found within ________.
   a. NFPA 1
   b. NFPA 13
   c. NFPA 20
   d. NFPA 24

5. ________ are used to maintain adequate water temperature in plumbing systems.
   a. drainage pumps
   b. domestic booster pumps
   c. sump pumps
   d. circulation pumps

6. Pumps add energy, also known as ________, to the liquid being pumped
   a. force
   b. speed
   c. thrust
   d. head

7. To maximize motor efficiency, it is important to ________.
   a. size the motor to the load
   b. oversize the impeller
   c. install multiple pumps in series
   d. none of the above

8. When the speed of a pump is changed, ________.
   a. the capacity for a given point on the pump head/capacity curve increases
   b. the capacity for a given point on the pump head/capacity curve decreases
   c. the capacity for a given point on the pump head/capacity curve varies proportional to the change in speed
   d. the capacity for a given point on the pump head/capacity curve remains constant

9. A ________ is a curve where the head rises continuously as the capacity decreases.
   a. rising characteristic curve
   b. drooping characteristic curve
   c. steep characteristic curve
   d. flat characteristic curve

10. ________ occurs in a pump when insufficient net positive suction head (NPSH) is available.
   a. axial flow
   b. cavitation
   c. churn
   d. radial flow

11. Pumps are operated ________ to obtain greater heads when it is inefficient or not advantageous to add additional stages to a single pump.
   a. at variable speeds
   b. at fixed speeds
   c. in parallel
   d. in series

12. ________ upstream and downstream of the pump allow easy indication of the rated pump performance.
   a. check valves
   b. pressure gauges
   c. testing ports
   d. air release vents