# Understand the Basics of Centrifugal Pump Operation

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By starting from such fundamentals as head and pressure, the authors have developed practical tips for specification and operation that provide for cost-effectiveness and reliability.

Centrifugal pumps are the most common type of kinetic pump, and are used most often in applications with moderate-to-high flow and low head. As the workhorse of the chemical process industries (CPI), centrifugals are almost always more economical to own, operate and maintain than other types of pumps.

## Parameters needed in specifying

The process engineer is normally responsible for specifying the process requirements of the pump, including the conditions and physical properties of the liquid, and, most importantly, the flowrate, pressure, density and viscosity. The flowrate determines the capacity of the pump, and the head depends on the density and viscosity of the liquid.

In general, the required flowrate is determined by the material and energy balances. Design margins, typically between 0–25%, are added to the material-balance flowrate to account for unexpected variations in properties or conditions, or to ensure that the overall plant meets its performance criteria. Also, minimum flow protection is often added as continuous circulation. Occasionally, the required flowrate (including design margins) may fall in the low range of that for centrifugal pumps. In such cases, a minimum-size pump rated for continuous service is specified, and the extra pump capacity is typically consumed by circulation from the discharge to the source.

During specification, the maximum pressure a pump will develop during any aspect of operation, including startup, shutdown and upset conditions is determined. The shutoff pressure is the maximum pressure a pump will develop under zero-flow conditions, which reflects a fully blocked outlet. Variables to consider when determining the design pressure include:

• maximum pressure of the source (*e.g.*, relieving pressure of a vessel)

• maximum head developed by the pump (*i.e.*, shutoff head)

• maximum static head of the fluid in the pump's suction line

• maximum pump operating speed (for variable-speed drives)

• possibility of operator intervention during an upset.

The head *h* is the most commonly used measurement of the energy at any point of the system, or of the system as a whole. It is defined as:

$$h = \frac{v^2}{2g} + \frac{2.31P}{S_g} + z \qquad (1)$$

where $v$ = the velocity of the fluid (ft/s); $g$ = acceleration of gravity (32.2 ft/s²); $P$ = pressure (psia); $S_g$ = specific gravity; and $z$ = elevation above (+) or below (–) the pump (ft).

The energy that the pump imparts to the liquid, the total dynamic head, *TDH*, takes into account differences in pressure, liquid elevation and velocity between the

■ Figure 1. Understanding a simplified pump hydraulic-circuit schematic aids in selection.

source and destination. In addition, *TDH* accounts for line (friction) losses and the pressure drop through the instrumentation and other items in the flow path of the liquid:

$$TDH = \frac{144 \times [P_2 - P_1 + \Delta P_f + \Delta P_{other}]}{\rho}$$
$$+ \frac{[V_2^2 - V_1^2]}{2g} + [Z_2 - Z_1] \qquad (2)$$

where $P$ = pressure (psia); $\Delta P_f$ = frictional loss through piping (psi); $\Delta P_{other}$ = pressure loss through instrumentation and flow-restriction orifices (psi); $Z$ = elevation (ft); $V$ = velocity (ft/s); and $\rho$ = density (lb/ft$^3$). The subscripts 1 and 2 refer to source and destination, respectively. Figure 1 shows a typical setup that can be described by using Eq. 2.

There is an advantage to measuring the energy of a pump as head, rather than pressure. The head applies to any liquid that is pumped at the same rated capacity and speed, as long as the viscosity is low (generally, less than 10 cP). The head produced by a pump will remain constant (at a given flowrate and speed), even though the pressure differential and power requirements vary.

Eqs. 1 and 2 show that fluid properties have a significant impact on the head. In particular, as density and viscosity increase, so will the amount of work needed to drive the pump. This is why the process engineer must specify not only the normal values for density and viscosity, but also the maximum values that the pump is likely to encounter during extreme situations, such as startup, shutdown or process upsets. Also, the engineer must determine the maximum operating temperature, and whether the fluid may contain suspended solids or dissolved gases.

Further, the pump must be specified to avoid cavitation. Cavitation occurs when the suction pressure of the pumped fluid drops below its vapor pressure, leading to the formation of vapor bubbles. As the fluid becomes pressurized again in the pump, these bubbles implode, leading to pitting of the impeller and other pump components. In addition, since vapor has a lower density than liquid, cavitation leads to a reduction in the pump capacity and efficiency.

The net positive suction head (*NPSH*) is a measure of the proximity of a liquid to its bubble point (or vapor pressure). The available *NPSH* (*NPSHA*, ft) is given by:

$$NPSHA = \frac{[P_1 - P_{vp} - \Delta P_f] \times 144}{\rho} + [Z_1 - Z_{inlet}] \qquad (3)$$

where: $P_{vp}$ = vapor pressure of the pumped fluid (psia) and $Z_{inlet}$ = centerline elevation of the pump suction nozzle (ft). The other variables in Eq. 3 have the same meaning and units as in Eq. 2.
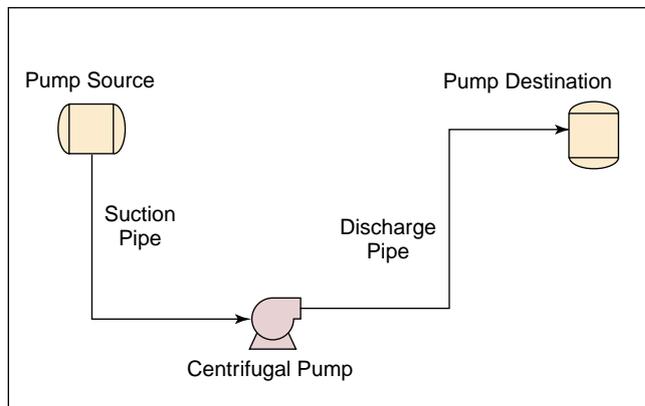
## Ensuring adequate available NPSH

Pump suppliers set the *NPSH* required (*NPSHR*) for a given pump. The *NPSHR* takes into account any potential head losses that might occur between the pump's suction nozzle and impeller, thus ensuring that the fluid does not drop below its vapor pressure. *NPSHA* must exceed the *NPSHR* set by the supplier.

There are a few options available to increase *NPSHA*, should it be at or below the *NPSHR*. Increasing the source pressure or reducing the fluid vapor pressure (by cooling) are rarely feasible. Therefore, there are two process variables remaining that can be adjusted — the static head and friction losses (see Eq. 3).

*Static head* can be raised by three methods:

1. Raise the elevation of the source point. This may prove impossible in some cases (*e.g.*, a tank that is set at grade).

2. Lower the elevation of the pump inlet. This is a less appealing option because pumps are typically located just above ground level, and lowering the inlet may require the suction nozzle to be below grade. This usually results in a much more expensive pump.

3. Raise the level of fluid in the suction vessel. The acceptability of this approach varies from company to company and should not be used without first consulting company procedures.

*Friction losses* can be reduced either by increasing the diameter of the pump suction-piping and/or reducing the equivalent length of the suction line. In a grassroots plant, friction losses should already be minimal, so raising static head is more viable. Reducing friction loss is usually more appealing for suction lines in existing plants where throughput has been increased above the original nameplate capacity.

There are also a few options to reduce the *NPSHR* of the pump, which include using a larger, slower-speed pump, a double-suction impeller, a larger impeller inlet (eye) area, an oversized pump and an inducer, which is a secondary impeller placed ahead of the primary impeller.

## Running in series or parallel

Centrifugal pumps operate within ranges of head and velocity. Operating outside of these ranges may require using a specialty pump. Other options for handling high-head or high-flow applications include using pumps in series or parallel. When running in series, the heads are added, and the total

capacity is equal to that of the pump with the smallest capacity. In parallel, the capacities of the pumps are added, and the head of all pumps will be equal at the point where the discharged liquids recombine. Parallel pumps are used for a variety of reasons, including cost (two smaller pumps may cost less than a larger one), an increase in the size of an existing plant, or to compensate for a process with varying capacity. Note that pumps operated in parallel must have similar head characteristics to avoid potential operating problems.

Often, process engineers need to estimate the horsepower requirement of a pump during the early design stages of a project, before a selection is made. Brake horsepower (*BHP*) is related to the flowrate $Q$ (gpm), total dynamic head *TDH* (ft), specific gravity $S_g$, and efficiency $\eta$:

$$BHP = \frac{(TDH)(Q)(S_g)}{3,960\eta} \qquad (4)$$

The actual efficiency is set by the pump supplier when the final pump selection is made. It is normally based on shop tests of previously built pumps of the same model and size. A reasonable estimate can be determined by using a graph found in a handbook. In general, efficiency varies from a low of about 10% for a small centrifugal pump, to a high of 80% for a large cooling-water type pump.

Another item to consider is pump failure. Pumps in critical service that operate continuously should have a standby. Depending upon the criticality of the service, auto-start provisions may be necessary to start the standby upon sensing a low discharge pressure. The standby pump can reduce plant shutdowns and prevent economic losses.

### Tips for specification

Assuming that the rated head and flow are known, a preliminary selection can be made for pumps that fall within normal ranges of operation, as shown in Figure 2 *(1)*. This preliminary selection exercise gives a good assessment of the pump type that fits the required process conditions. The specific pump type will also influence what standard specifications might be required. Some industry and national specifications for centrifugal pumps include:

• ASME/ANSI B73.1, "Specification for Horizontal End Suction Centrifugal Pumps for Chemical Process," and ASME/ANSI B73.2M, "Specification for Vertical In-Line Centrifugal Pumps for Chemical Process" (www.asme.org).

• API-610, "Centrifugal Pumps for Petroleum, Heavy Duty Chemical and Gas Industry Services" (www.api.org).

• PIP RESP73H-97, "Application of ASME B73.1M–1991 Specification for Horizontal End Suction Centrifugal Pumps for Chemical Process," and PIP RESP73V-97, "Application of ASME B73.2M Specification for Vertical In-Line Centrifugal Pumps for Chemical Process" (www.pip.org).

API-610 sets standards that create a more robust and expensive pump. Individual company policies may have additional centrifugal pump specifications that must be met, as well.

Every pump has a specific curve that relates head, flow, power, *NPSHR* and efficiency for specific impeller diameters for that particular unit (Figure 3 *(2)*). This enables correct selection of the impeller diameter. During specification, the goal is to select a pump with a rated (or design) point as close as possible to the best efficiency point (BEP), as determined by the pump manufacturer.

### Selection rules-of-thumb

The general guidelines for proper selection are:
• Select the pump based on rated conditions.
• The BEP should be between the rated point and the normal operating point.
• The head/capacity characteristic-curve should continuously rise as flow is reduced to shutoff (or zero flow).
• The pump should be capable of a head increase at rated conditions by installing a larger impeller.
• The pump should not be operated below the manufacturer's minimum continuous flowrate.

As can be seen from the pump curve, the pump has a specific *NPSHR*, which varies, depending on the head and flow.

Once the specific pump model and size have been determined from the basic process information, the materials of construction must be chosen. Selection depends on fluid properties, such as corrosiveness or erosiveness, and the presence of dissolved gases. Knowing as much as possible about the chemical composition of the fluid helps to ensure proper material selection of the pump and its shaft seal.

### Drivers and seals

Referring to Figure 3, the required driver power for the pump is related to head and flow. The different types of drivers include electric motors, internal-combustion engines, steam and gas turbines, and hydraulic power-recovery turbines. Driver selection depends upon many factors including type of service, availability of steam or fuel (for turbines), and cost. The most common driver is the electric motor. Motors can vary in size depending upon power, speed, frame size, area classification, orientation and other considerations. Motor specifications should consist of both mechanical and electrical requirements, including the area hazard-classification set by the National Fire Protection Agency (NFPA). A motor should be sized to meet the maximum specified operating conditions and should be able to meet end-of-curve power requirements.

Figure 3 shows that there are a number of different impeller diameters available for each pump. Selection of geometry and type are governed by the operating conditions, and properties and composition of the liquid. Select an impeller that allows for future changes in the diameter. Pumps are rarely operated at their exact rated point. Therefore, the flow or head may need to be changed to increase the pump efficiency, or to accommodate changes in process requirements.
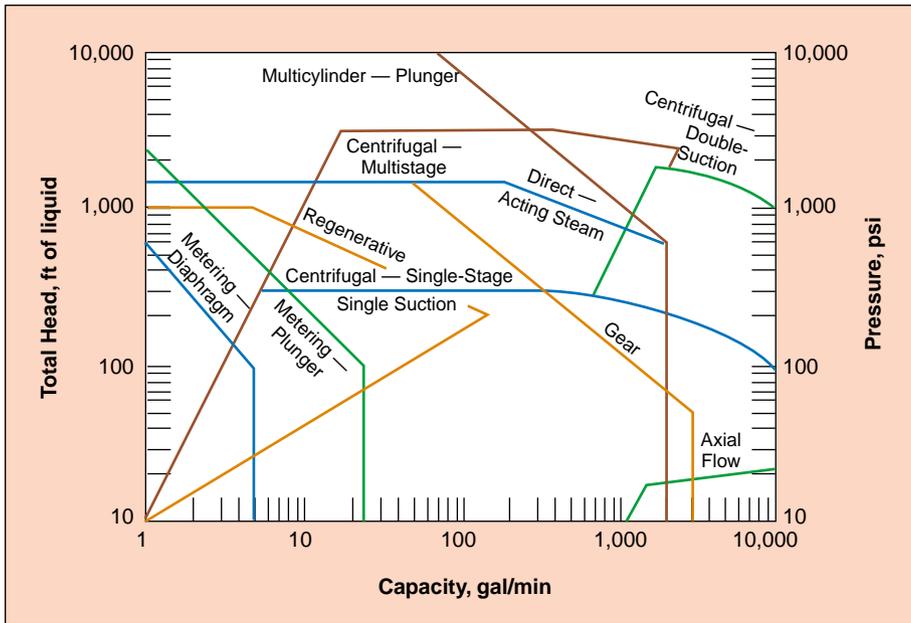
■ Figure 2. Selection guide for various types of pumps *(1)*.
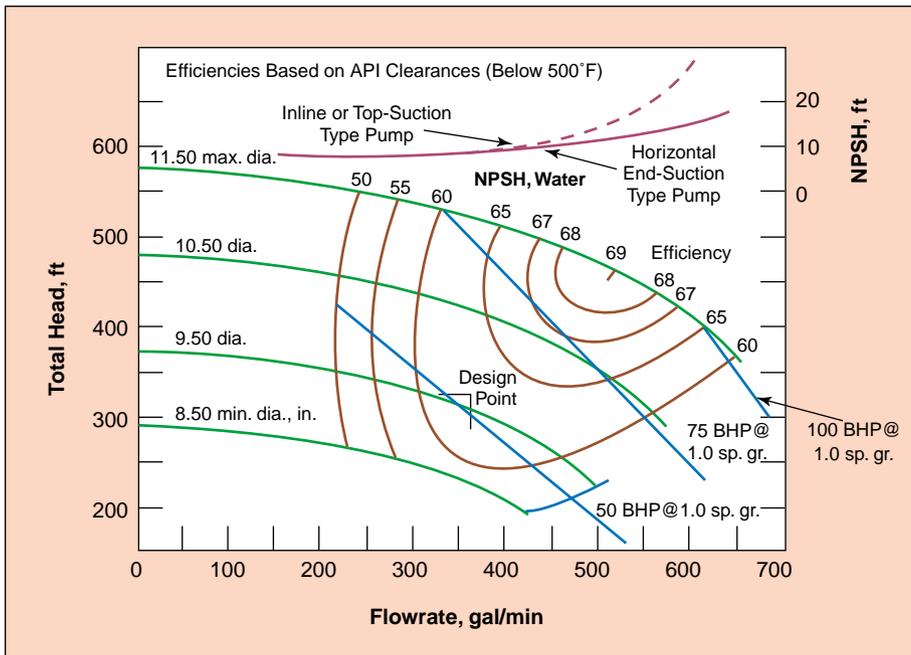


■ Figure 3. Typical operating curves for a centrifugal pump, here for a depropanizer reflux pump *(2)*. (Courtesy of Gas Processors Suppliers Association)

A general rule-of-thumb is to select an impeller that is one size smaller than the maximum size for the given pump casing, so that it can be replaced with a larger one without replacing the casing.

A common problem with rotating machinery is sealing the shaft penetration into the casing to prevent process fluid leaks, either by a packing or mechanical seal. *Packing* is used primarily in nonhazardous services, such as in pulp-and-paper plants, where fluid leaks are not a safety concern. *Mechanical seals* are the most widely used sealing method and must be selected carefully. Local environmental regulations will affect the seal type and arrangement for a particular service. Seal failure, by far, is the most common type of pump failure in the CPI. Using proper control schemes can keep the pump within design parameters and, if necessary, stop the pump to prevent irreparable damage.

An alternative to installing a seal is a sealless pump, for example, the magnetic-drive pump. The magnetic-drive pump uses a permanent magnetic coupling to transmit the torque to the impeller. This eliminates a shaft/casing penetration that must be sealed. A no-slip or synchronous torque-coupling-action is achieved without potential leakage. The other type of sealless pump is the canned motor pump, in which a portion of the pumped liquid is permitted to flow into the motor, but is isolated from parts such as the windings or insulation by a metal can. Both of these pumps should be considered where environmental regulations mandate zero leakage.

A seal flush system is generally incorporated to maintain a clean environment within the seal. Solids in the process fluid are detrimental to the life of a seal and must be flushed out before they damage the seal. There are a number of different seal-flush plans and fluids, and selection of the right plan and fluid depends upon the type of pump, its operating conditions, the type of fluid (hydrocarbon, nonhydrocarbon, flashing hydrocarbon), the temperature, whether it is hazardous/non-hazardous, etc. It is best to collaborate with the pump and seal suppliers for the correct sea, flush plan and fluid for a particular service.

## Control and operation

Pump control is often used to maintain a set process

flowrate by throttling the discharge, turning the pump on and off, or controlling its speed. Throttling is accomplished by placing a flow controller with a control valve on the discharge line. However, recirculation lines may be required. On-off control is achieved with level switches that have built-in deadbands used on the suction vessel to start and stop the pump. A high level will start the pump and a low level will stop it. Frequent starts and stops can damage the pump and driver, so the suction vessel must be sized to accommodate a sufficiently large inventory of liquid when using this option. Speed control is attained by using a variable-speed driver when the capacity of the pump may vary greatly. Many types are available, including electric, electromechanical, mechanical and hydraulic-power-recovery turbines. In choosing this type of pump driver, it is best to contact a supplier who can help determine the best one for the application, since the system curve determines whether a variable speed motor should be used.

Centrifugal pumps have a required minimum flow below which the pump can incur severe operational problems and damage. If the primary pump discharge-path can be blocked, a recirculation (kickback) line is required to accommodate the pump's minimum flow. Such lines can be designed either for continuous or controlled flows. Continuous flows are more common in smaller pumps and use a flow-restriction orifice in the kickback line to bleed-off the pressure gained from the pump. Controlled flows are normally used in higher-capacity systems where a continuous, minimum flow would lead to significantly higher operating costs or the selection of a larger pump. Controlled flows are most often ac-complished with a self-regulated pressure-control valve on the pump discharge or a flow-control valve and controller with the minimum flow configured as the setpoint.

Excess pumping energy increases the temperature of the fluid being pumped. In general, the temperature rise is negligible, except when the pump is operating near shutoff. For this reason, the minimum flow-recirculation line should be placed so that the outlet of the line connects to a vessel instead of the pump suction line, thus giving the fluid time to shed its excess heat. If the fluid is added to the suction line, the temperature increase will not be dissipated. A small heat exchanger may be placed ahead of the pump suction to achieve the same result for relatively high-head pumps (~500 ft) or when handling temperature-sensitive fluids.

Low-suction-pressure switches interlocked into the plant control system sometimes trip the pump or prevent its startup when the suction pressure is below a set value. High-pressure switches can be installed on the pump discharge so as not to exceed the maximum allowable output pressure (dead-heading the pump). The motor is usually tripped or is not allowed to start under these conditions. Similarly, low-flow switches on the discharge are used to alarm and trip the motor when a low-flow condition has occurred. This interlock is often by-passed (manually or with a timer) during pump startup to allow the flow to reach its normal operating point, at which time the bypass is removed. Currently, industry is changing from switches to transmitters for increased accuracy and easier failure diagnosis.                                           **CEP**

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## Further Reading

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