

## Centrifugal Pumps: Basic Concepts of Operation, Maintenance, and Troubleshooting (Part- I)

### Introduction

The operating manual of any centrifugal pump often starts with a general statement, “Your centrifugal pump will give you completely trouble free and satisfactory service only on the condition that it is installed and operated with due care and is properly maintained.”

Despite all the care in operation and maintenance, engineers often face the statement “the pump has failed i.e. it can no longer be kept in service”. Inability to deliver the desired flow and head is just one of the most common conditions for taking a pump out of service. There are other many conditions in which a pump, despite suffering no loss in flow or head, is considered to have failed and has to be pulled out of service as soon as possible. These include seal related problems (leakages, loss of flushing, cooling, quenching systems, etc), pump and motor bearings related problems (loss of lubrication, cooling, contamination of oil, abnormal noise, etc), leakages from pump casing, very high noise and vibration levels, or driver (motor or turbine) related problems.

The list of pump failure conditions mentioned above is neither exhaustive nor are the conditions mutually exclusive. Often the root causes of failure are the same but the symptoms are different. A little care when first symptoms of a problem appear can save the pumps from permanent failures. Thus the most important task in such situations is to find out whether the pump has failed mechanically or if there is some process deficiency, or both. Many times when the pumps are sent to the workshop, the maintenance people do not find anything wrong on disassembling it. Thus the decision to pull a pump out of service for maintenance / repair should be made after a detailed analysis of the symptoms and root causes of the pump failure. Also, in case of any mechanical failure or physical damage of pump internals, the operating engineer should be able to relate the failure to the process unit's operating problems.

Any operating engineer, who typically has a chemical engineering background and who desires to protect his pumps from frequent failures must develop not only a good understanding of the process but also thorough knowledge of the mechanics of the pump. Effective troubleshooting requires an ability to observe changes in performance over time, and in the event of a failure, the capacity to thoroughly investigate the cause of the failure and take measures to prevent the problem from re-occurring.

The fact of the matter is that there are three types of problems mostly encountered with centrifugal pumps:

design errors

poor operation

poor maintenance practices

The present article is being presented in three parts, covering all aspects of operation, maintenance, and troubleshooting of centrifugal pumps. The article has been written keeping in mind the level and interests of students and the beginners in operation. Any comments or queries are most welcome.

## Working Mechanism of a Centrifugal Pump

A centrifugal pump is one of the simplest pieces of equipment in any process plant. Its purpose is to convert energy of a prime mover (a electric motor or turbine) first into velocity or kinetic energy and then into pressure energy of a fluid that is being pumped. The energy changes occur by virtue of two main parts of the pump, the impeller and the volute or diffuser. The impeller is the rotating part that converts driver energy into the kinetic energy. The volute or diffuser is the stationary part that converts the kinetic energy into pressure energy.

**Note:** All of the forms of energy involved in a liquid flow system are expressed in terms of feet of liquid i.e. head.

### Generation of Centrifugal Force

The process liquid enters the suction nozzle and then into eye (center) of a revolving device known as an impeller. When the impeller rotates, it spins the liquid sitting in the cavities between the vanes outward and provides centrifugal acceleration. As liquid leaves the eye of the impeller a low-pressure area is created causing more liquid to flow toward the inlet. Because the impeller blades are curved, the fluid is pushed in a tangential and radial direction by the centrifugal force. This force acting inside the pump is the same one that keeps water inside a bucket that is rotating at the end of a string. Figure A.01 below depicts a side cross-section of a centrifugal pump indicating the movement of the liquid.

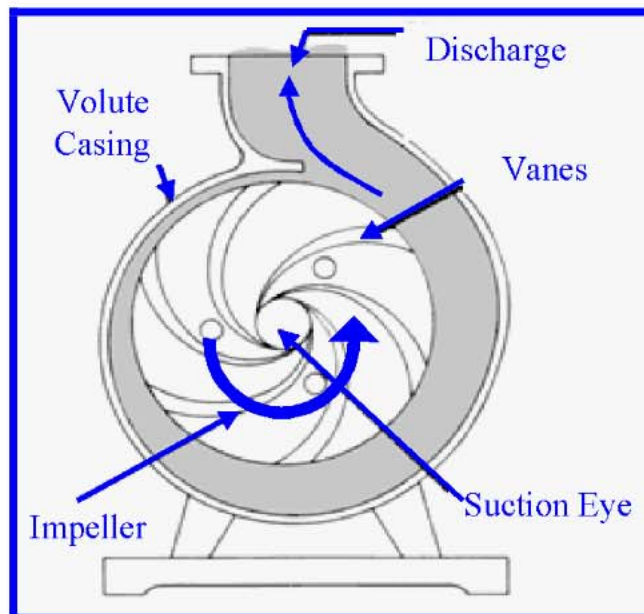


Figure A.01: Liquid flow path inside a centrifugal pump

### Conversion of Kinetic Energy to Pressure Energy

The key idea is that the energy created by the centrifugal force is *kinetic energy*. The amount of energy given to the liquid is proportional to the *velocity* at the edge or vane tip of the impeller. The faster the impeller revolves or the bigger the impeller is, then the higher will be the velocity of the liquid at the vane tip and the greater the energy imparted to the liquid.

This kinetic energy of a liquid coming out of an impeller is harnessed by creating a *resistance* to the flow. The first resistance is created by the pump volute (casing) that catches the liquid and slows it down. In the discharge nozzle, the liquid further decelerates and its velocity is converted to pressure according to Bernoulli's principle.

Therefore, the head (pressure in terms of height of liquid) developed is approximately equal to the velocity energy at the periphery of the impeller expressed by the following well-known formula:

$$H = \frac{v^2}{2g}$$

where

- **H = Total head developed in feet.**
- **v = Velocity at periphery of impeller in ft/sec.**
- **g = Acceleration due to gravity - 32.2 feet/Sec<sup>2</sup>**

A handy formula for peripheral velocity is:

$$v = \frac{N \times D}{229}$$

where

- **v = Velocity at periphery of impeller in ft/sec.**
- **N = The impeller RPM (revolutions per minute )**
- **D = Impeller diameter in inches**

This head can also be calculated from the readings on the pressure gauges attached to the suction and discharge lines.

**One fact that must always be remembered: A pump does not create pressure, it only provides flow. Pressure is a just an indication of the amount of resistance to flow.**

Pump curves relate flow rate and pressure (head) developed by the pump at different impeller sizes and rotational speeds. The centrifugal pump operation should conform to the pump curves supplied by the manufacturer. In order to read and understand the pump curves, it is very important to develop a clear understanding of the terms used in the curves. This topic will be covered later.

## General Components of Centrifugal Pumps

A centrifugal pump has two main components:

- I. A rotating component comprised of an impeller and a shaft
- II. A stationary component comprised of a casing, casing cover, and bearings.

The general components, both stationary and rotary, are depicted in Figure B.01. The main components are discussed in brief below. Figure B.02 shows these parts on a photograph of a pump in the field.

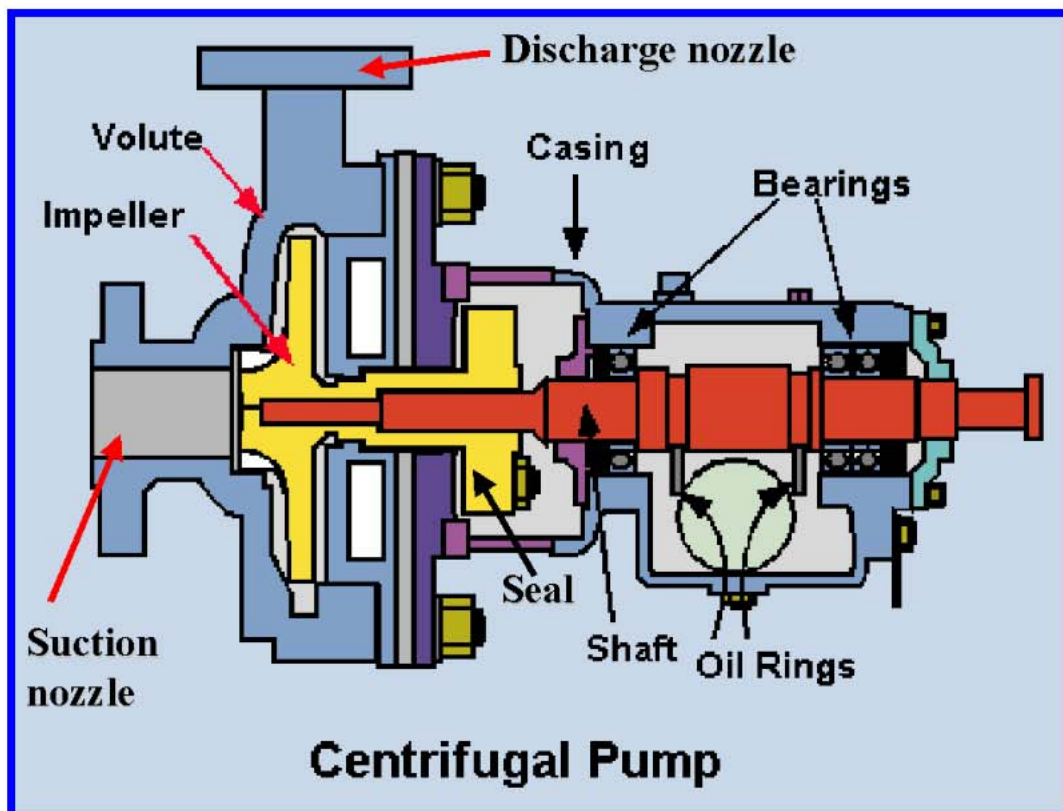


Figure B.01: General components of Centrifugal Pump

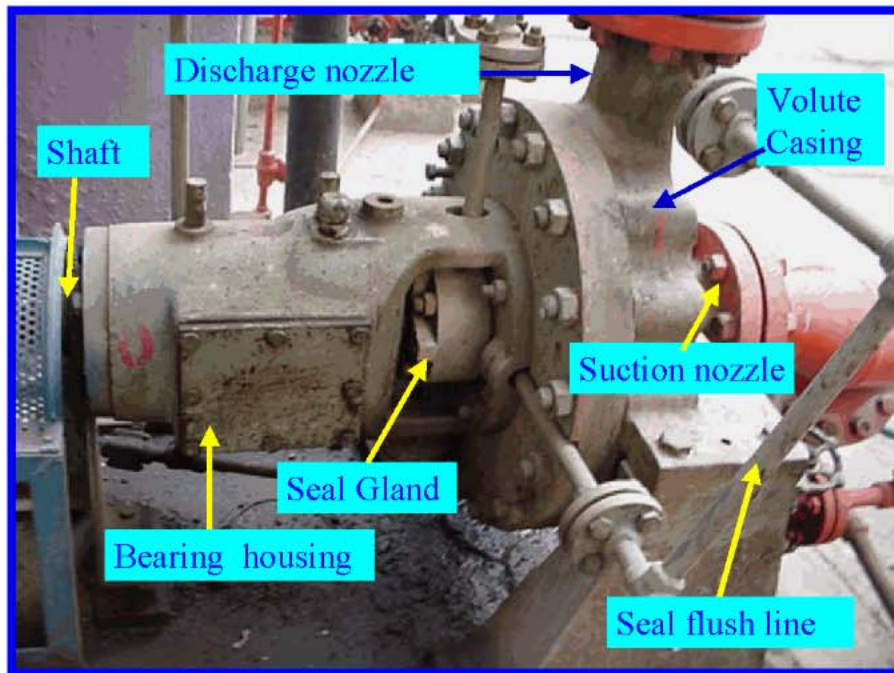


Figure B.02: General components of a Centrifugal Pump

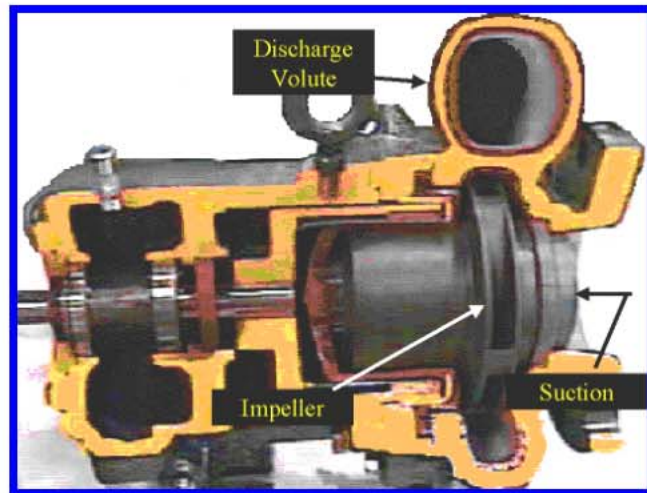
## Stationary Components

### Casing

Casings are generally of two types: volute and circular. The impellers are fitted inside the casings.

1. **Volute casings** build a higher head; *circular casings* are used for low head and high capacity.

- A *volute* is a curved funnel increasing in area to the discharge port as shown in Figure B.03. As the area of the cross-section increases, the volute reduces the speed of the liquid and increases the pressure of the liquid.



**Figure B.03: Cut-away of a pump showing volute casing**

- One of the *main purposes of a volute casing* is to help balance the hydraulic pressure on the shaft of the pump. However, this occurs best at the manufacturer's recommended capacity. Running volute-style pumps at a lower capacity than the manufacturer recommends can put lateral stress on the shaft of the pump, increasing wear-and-tear on the seals and bearings, and on the shaft itself. Double-volute casings are used when the radial thrusts become significant at reduced capacities.
2. **Circular casing** have stationary diffusion vanes surrounding the impeller periphery that convert velocity energy to pressure energy. Conventionally, the diffusers are applied to multi-stage pumps.
- The casings can be designed either as solid casings or split casings. **Solid casing** implies a design in which the entire casing including the discharge nozzle is all contained in one casting or fabricated piece. A **split casing** implies two or more parts are fastened together. When the casing parts are divided by horizontal plane, the casing is described as horizontally split or axially split casing. When the split is in a vertical plane perpendicular to the rotation axis, the casing is described as vertically split or radially split casing. Casing Wear rings act as the seal between the casing and the impeller.



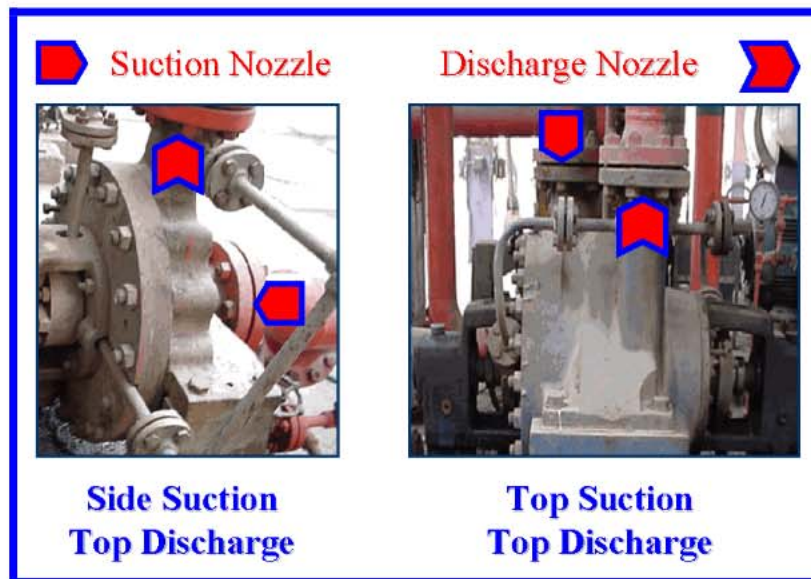
**Figure B.04: Solid Casing**

#### Suction and Discharge Nozzle

The suction and discharge nozzles are part of the casings itself. They commonly have the following configurations.

1. End suction/Top discharge (Figure B.05) - The suction nozzle is located at the end of, and concentric to, the shaft while the discharge nozzle is located at the top of the case perpendicular to the shaft. This pump is always of an overhung type and typically has lower NPSHr because the liquid feeds directly into the impeller eye.
2. Top suction Top discharge nozzle (Figure B.05) -The suction and discharge nozzles are located at the top of the case perpendicular to the shaft. This pump can either be an overhung type or between-bearing type but is always a radially split case pump.



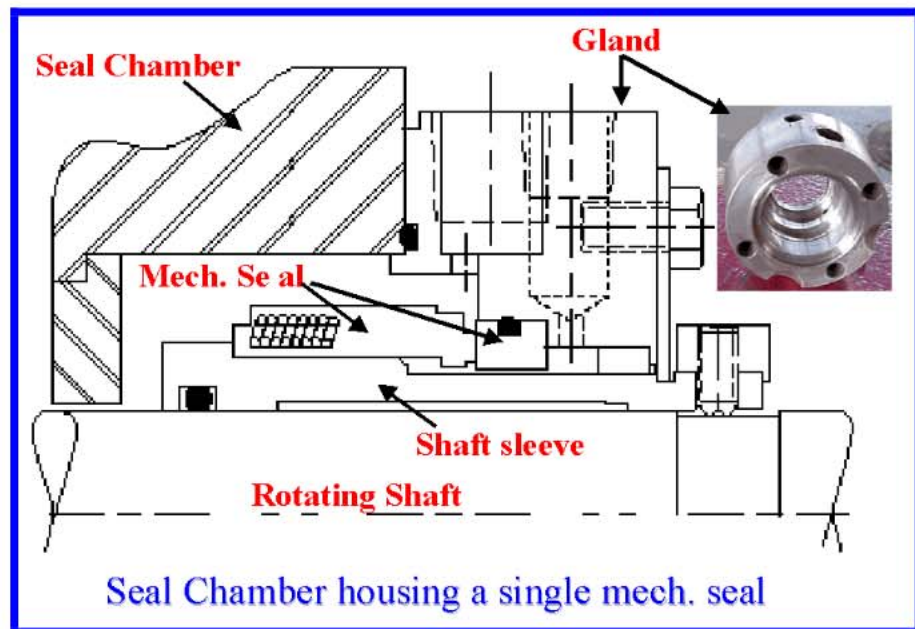


**Figure B.05: Suction and Discharge Nozzle Locations**

3. *Side suction / Side discharge nozzles* - The suction and discharge nozzles are located at the sides of the case perpendicular to the shaft. This pump can have either an axially or radially split case type.

#### Seal Chamber and Stuffing Box

Seal chamber and Stuffing box both refer to a chamber, either integral with or separate from the pump case housing that forms the region between the shaft and casing where sealing media are installed. When the sealing is achieved by means of a mechanical seal, the chamber is commonly referred to as a Seal Chamber. When the sealing is achieved by means of packing, the chamber is referred to as a Stuffing Box. Both the seal chamber and the stuffing box have the primary function of protecting the pump against leakage at the point where the shaft passes out through the pump pressure casing. When the pressure at the bottom of the chamber is below atmospheric, it prevents air leakage into the pump. When the pressure is above atmospheric, the chambers prevent liquid leakage out of the pump. The seal chambers and stuffing boxes are also provided with cooling or heating arrangement for proper temperature control. Figure B.06 below depicts an externally mounted seal chamber and its parts.



**Figure B.06: Parts of a simple Seal Chamber**

- **Gland:** The gland is a very important part of the seal chamber or the stuffing box. It gives the packings or the mechanical seal the desired fit on the shaft sleeve. It can be easily adjusted in axial direction. The gland comprises of the seal flush, quench, cooling, drain, and vent connection ports as per the standard codes like API 682.
- **Throat Bushing:** The bottom or inside end of the chamber is provided with a stationary device called throat bushing that forms a restrictive close clearance around the sleeve (or shaft) between the seal and the impeller.
- **Throttle bushing** refers to a device that forms a restrictive close clearance around the sleeve (or shaft) at the outboard end of a mechanical seal gland.
- **Internal circulating device** refers to device located in the seal chamber to circulate seal chamber fluid through a cooler or barrier/buffer fluid reservoir. Usually it is referred to as a pumping ring.
- **Mechanical Seal:** The features of a mechanical seal will be discussed in Part-II of the article.

### Bearing housing

The bearing housing encloses the bearings mounted on the shaft. The bearings keep the shaft or rotor in correct alignment with the stationary parts under the action of radial and transverse loads. The bearing house also includes an oil reservoir for lubrication, constant level oiler, jacket for cooling by circulating cooling water.

## Rotating Components

### 1. Impeller

The impeller is the main rotating part that provides the centrifugal acceleration to the fluid. They are often classified in many ways.

- Based on major direction of flow in reference to the axis of rotation
  - || Radial flow
  - || Axial flow
  - || Mixed flow
- Based on suction type
  - || Single-suction: Liquid inlet on one side.
  - || Double-suction: Liquid inlet to the impeller symmetrically from both sides.
- Based on mechanical construction (**Figure B.07**)
  - || Closed: Shrouds or sidewall enclosing the vanes.
  - || Open: No shrouds or wall to enclose the vanes.
  - || Semi-open or vortex type.

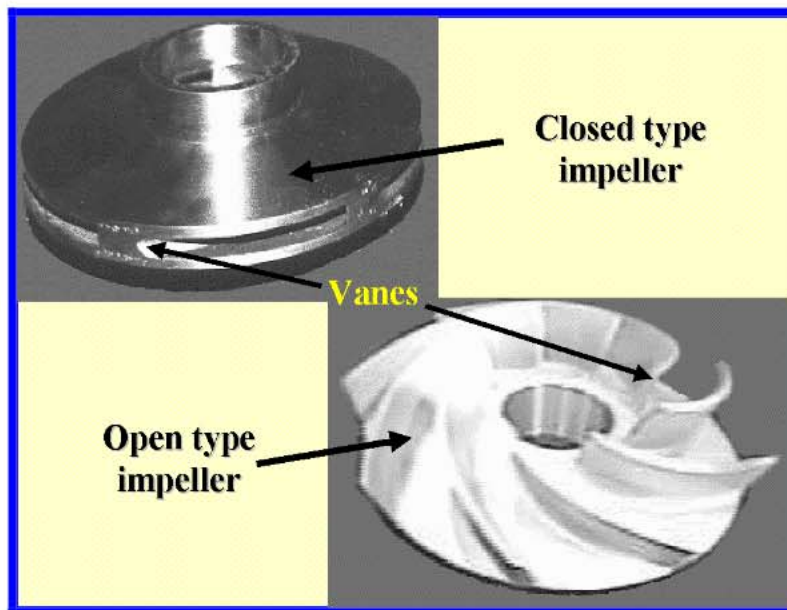


Figure B.07: Impeller types

Closed impellers require wear rings and these wear rings present another maintenance problem. Open and semi-open impellers are less likely to clog, but need manual adjustment to the volute or back-plate to get the proper impeller setting and prevent internal re-circulation. Vortex pump impellers are great for solids and "stringy" materials but they are up to 50% less efficient than conventional designs. The number of impellers determines the number of stages of the pump. A single stage pump has one impeller only and is best for low head service. A two-stage pump has two impellers in series for medium head service. A multi-stage pump has three or more impellers in series for high head service.

- Wear rings: Wear ring provides an easily and economically renewable leakage joint between the impeller and the casing. clearance becomes too large the pump efficiency will be lowered causing heat and vibration problems. Most manufacturers require that you disassemble the pump to check the wear ring clearance and replace the rings when this clearance doubles.

## 2. Shaft

The basic purpose of a centrifugal pump shaft is to transmit the torques encountered when starting and during operation while supporting the impeller and other rotating parts. It must do this job with a deflection less than the minimum clearance between the rotating and stationary parts.

- **Shaft Sleeve (Figure B.08):** Pump shafts are usually protected from erosion, corrosion, and wear at the seal chambers, leakage joints, internal bearings, and in the waterways by renewable sleeves. Unless otherwise specified, a shaft sleeve of wear, corrosion, and erosion-resistant material shall be provided to protect the shaft. The sleeve shall be sealed at one end. The shaft sleeve assembly shall extend beyond the outer face of the seal gland plate. (Leakage between the shaft and the sleeve should not be confused with leakage through the mechanical seal).



**Figure B.08: A view of a shaft sleeve**

- **Coupling:** Couplings can compensate for axial growth of the shaft and transmit torque to the impeller. Shaft couplings can be broadly classified into two groups: rigid and flexible. Rigid couplings are used in applications where there is absolutely no possibility or room for any misalignment. Flexible shaft couplings are more prone to selection, installation and maintenance errors. Flexible shaft couplings can be divided into two basic groups: elastomeric and non-elastomeric
  - || Elastomeric couplings use either rubber or polymer elements to achieve flexibility. These elements can either be in shear or in compression. Tire and rubber sleeve designs are elastomer in shear couplings; jaw and pin and bushing designs are elastomer in compression couplings.
  - || Non-elastomeric couplings use metallic elements to obtain flexibility. These can be one of two types: lubricated or non-lubricated. Lubricated designs accommodate misalignment by the sliding action of their components, hence the need for lubrication. The non-lubricated designs accommodate

misalignment through flexing. Gear, grid and chain couplings are examples of non-elastomeric, lubricated couplings. Disc and diaphragm couplings are non-elastomeric and non-lubricated.

## Auxiliary Components

Auxiliary components generally include the following piping systems for the following services:

- Seal flushing , cooling , quenching systems
- Seal drains and vents
- Bearing lubrication , cooling systems
- Seal chamber or stuffing box cooling, heating systems
- Pump pedestal cooling systems

Auxiliary piping systems include tubing, piping, isolating valves, control valves, relief valves, temperature gauges and thermocouples, pressure gauges, sight flow indicators, orifices, seal flush coolers, dual seal barrier/buffer fluid reservoirs, and all related vents and drains.

All auxiliary components shall comply with the requirements as per standard codes like API 610 (refinery services), API 682 (shaft sealing systems) etc.

## Definition of Important Terms

The key performance parameters of centrifugal pumps are capacity, head, BHP (Brake horse power), BEP (Best efficiency point) and specific speed. The pump curves provide the operating window within which these parameters can be varied for satisfactory pump operation. The following parameters or terms are discussed in detail in this section.

Capacity

Head

- Significance of using Head instead of Pressure
- Pressure to Head Conversion formula
- Static Suction Head,  $h_s$
- Static Discharge Head,  $h_d$
- Friction Head,  $h_f$

- Vapor pressure Head, **h<sub>vp</sub>**
- Pressure Head, **h<sub>p</sub>**
- Velocity Head, **h<sub>v</sub>**
- Total Suction Head **H<sub>s</sub>**
- Total Discharge Head **H<sub>d</sub>**
- Total Differential Head **H<sub>T</sub>**

#### NPSH

- Net Positive Suction Head Required **NPSH<sub>r</sub>**
- Net Positive Suction Head Available **NPSH<sub>a</sub>**

Power (Brake Horse Power, B.H.P) and Efficiency (Best Efficiency Point, B.E.P)

Specific Speed (N<sub>s</sub>)

Affinity Laws

## Capacity

Capacity means the flow rate with which liquid is moved or pushed by the pump to the desired point in the process. It is commonly measured in either gallons per minute (gpm) or cubic meters per hour (m<sup>3</sup>/hr). The capacity usually changes with the changes in operation of the process. For example, a boiler feed pump is an application that needs a constant pressure with varying capacities to meet a changing steam demand.

The capacity depends on a number of factors like:

Process liquid characteristics i.e. density, viscosity

Size of the pump and its inlet and outlet sections

Impeller size

Impeller rotational speed RPM

Size and shape of cavities between the vanes

Pump suction and discharge temperature and pressure conditions

For a pump with a particular impeller running at a certain speed in a liquid, the only items on the list above that can change the amount flowing through the pump are the pressures at the pump inlet and outlet. The effect on the flow through a pump by changing the outlet pressures is graphed on a pump curve.

As liquids are essentially incompressible, the capacity is directly related with the velocity of flow in the suction pipe. This relationship is as follows:

$$Q = 449 \times V \times A$$

where

- $Q$  = Capacity in gallons per minute (GPM).
- $V$  = Velocity of flow in ft/sec.
- $A$  = Area of pipe in ft<sup>2</sup>

## Head

### Significance of using the “head” term instead of the “pressure” term

The pressure at any point in a liquid can be thought of as being caused by a vertical column of the liquid due to its weight. The height of this column is called the static head and is expressed in terms of feet of liquid.

The same *head* term is used to measure the kinetic energy created by the pump. In other words, head is a measurement of the height of a liquid column that the pump could create from the kinetic energy imparted to the liquid. Imagine a pipe shooting a jet of water straight up into the air, the height the water goes up would be the head.

The head is not equivalent to pressure. Head is a term that has units of a length or feet and pressure has units of force per unit area or pound per square inch. **The main reason for using head instead of pressure** to measure a centrifugal pump's energy is that the pressure from a pump will change if the specific gravity (weight) of the liquid changes, but the head will not change. Since any given centrifugal pump can move a lot of different fluids, with different specific gravities, it is simpler to discuss the pump's head and forget about the pressure.

A given pump with a given impeller diameter and speed will raise a liquid to a certain height regardless of the weight of the liquid.

So a centrifugal pump's performance on any Newtonian fluid, whether it's heavy (sulfuric acid) or light (gasoline) is described by using the term 'head'. The pump performance curves are mostly described in terms of head.



### Pressure to Head Conversion formula

The static head corresponding to any specific pressure is dependent upon the weight of the liquid according to the following formula:

$$\text{Head (ft)} = \frac{\text{Pressure (psi)} \times 2.31}{\text{Specific Gravity}}$$

Newtonian liquids have specific gravities typically ranging from 0.5 (light, like light hydrocarbons) to 1.8 (heavy, like concentrated sulfuric acid). Water is a benchmark, having a specific gravity of 1.0.

This formula helps in converting pump gauge pressures to head for reading the pump curves. The various head terms are discussed below.

**Note:** The Subscripts 's' refers to suction conditions and 'd' refers to discharge conditions.

- Static Suction Head, **h<sub>s</sub>**
- Static Discharge Head, **h<sub>d</sub>**
- Friction Head, **h<sub>f</sub>**
- Vapor pressure Head, **h<sub>vp</sub>**
- Pressure Head, **h<sub>p</sub>**
- Velocity Head, **h<sub>v</sub>**
- Total Suction Head **H<sub>s</sub>**
- Total Discharge Head **H<sub>d</sub>**
- Total Differential Head **H<sub>T</sub>**
- Net Positive Suction Head Required **NPSH<sub>r</sub>**
- Net Positive Suction Head Available **NPSH<sub>a</sub>**

*Static Suction Head ( $h_s$ )*: Head resulting from elevation of the liquid relative to the pump center line. If the liquid level is above pump centerline,  $h_s$  is positive. If the liquid level is below pump centerline,  $h_s$  is negative. Negative  $h_s$  condition is commonly denoted as a “suction lift” condition

*Static Discharge Head ( $h_d$ )*: It is the vertical distance in feet between the pump centerline and the point of free discharge or the surface of the liquid in the discharge tank.

*Friction Head ( $h_f$ )*: The head required to overcome the resistance to flow in the pipe and fittings. It is dependent upon the size, condition and type of pipe, number and type of pipefittings, flow rate, and nature of the liquid.

*Vapor Pressure Head ( $h_{vp}$ )*: Vapor pressure is the pressure at which a liquid and its vapor co-exist in equilibrium at a given temperature. The vapor pressure of liquid can be obtained from vapor pressure tables. When the vapor pressure is converted to head, it is referred to as vapor pressure head,  $h_{vp}$ . The value of  $h_{vp}$  of a liquid increases with the rising temperature and in effect, opposes the pressure on the liquid surface, the positive force that tends to cause liquid flow into the pump suction i.e. it reduces the suction pressure head.

*Pressure Head ( $h_p$ )*: Pressure Head must be considered when a pumping system either begins or terminates in a tank which is under some pressure other than atmospheric. The pressure in such a tank must first be converted to feet of liquid. Denoted as  $h_p$ , pressure head refers to absolute pressure on the surface of the liquid reservoir supplying the pump suction, converted to feet of head. If the system is open,  $h_p$  equals atmospheric pressure head.

*Velocity Head ( $h_v$ )*: Refers to the energy of a liquid as a result of its motion at some velocity ‘v’. It is the equivalent head in feet through which the water would have to fall to acquire the same velocity, or in other words, the head necessary to accelerate the water. *The velocity head is usually insignificant and can be ignored* in most high head systems. However, it can be a large factor and must be considered in low head systems.

*Total Suction Head ( $H_s$ )*: The suction reservoir pressure head ( $h_{ps}$ ) plus the static suction head ( $h_s$ ) plus the velocity head at the pump suction flange ( $h_{vs}$ ) minus the friction head in the suction line ( $h_{fs}$ ).

$$H_s = h_{ps} + h_s + h_{vs} - h_{fs}$$

The total suction head is the reading of the gauge on the suction flange, converted to feet of liquid.

*Total Discharge Head ( $H_d$ )*: The discharge reservoir pressure head ( $h_{p_d}$ ) plus static discharge head ( $h_d$ ) plus the velocity head at the pump discharge flange ( $h_{v_d}$ ) plus the total friction head in the discharge line ( $h_{f_d}$ ).

$$H_d = h_{p_d} + h_d + h_{v_d} + h_{f_d}$$

The total discharge head is the reading of a gauge at the discharge flange, converted to feet of liquid.

*Total Differential Head ( $H_T$ )*: It is the total discharge head minus the total suction head or

$$H_T = H_d + H_s \text{ (with a suction lift)}$$

$$H_T = H_d - H_s \text{ (with a suction head)}$$

## NPSH

When discussing centrifugal pumps, the two most important head terms are NPSHr and NPSHa.

### Net Positive Suction Head Required, NPSHr

NPSH is one of the most widely used and least understood terms associated with pumps. Understanding the significance of NPSH is very much essential during installation as well as operation of the pumps.

#### *Pumps can pump only liquids, not vapors*

The satisfactory operation of a pump requires that vaporization of the liquid being pumped does not occur at any condition of operation. This is so desired because when a liquid vaporizes its volume increases very much. For example, 1 ft<sup>3</sup> of water at room temperature becomes 1700 ft<sup>3</sup> of vapor at the same temperature. This makes it clear that if we are to pump a fluid effectively, it must be kept always in the liquid form.

#### *Rise in temperature and fall in pressure induces vaporization*

The vaporization begins when the vapor pressure of the liquid at the operating temperature equals the external system pressure, which, in an open system is always equal to atmospheric pressure. Any decrease in external pressure or rise in operating temperature can induce vaporization and the pump stops pumping. Thus, the pump always needs to have a sufficient amount of suction head present to prevent this vaporization at the lowest pressure point in the pump.

### *NPSH as a measure to prevent liquid vaporization*

The manufacturer usually tests the pump with water at different capacities, created by throttling the suction side. When the first signs of vaporization induced cavitation occur, the suction pressure is noted (the term cavitation is discussed in detail later). This pressure is converted into the head. This head number is published on the pump curve and is referred as the "net positive suction head required (NPSHr) or sometimes in short as the NPSH. **Thus the Net Positive Suction Head (NPSH) is the total head at the suction flange of the pump less the vapor pressure converted to fluid column height of the liquid.**

#### *NPSHr is a function of pump design*

NPSH required is a function of the pump design and is determined based on actual pump test by the vendor. As the liquid passes from the pump suction to the eye of the impeller, the velocity increases and the pressure decreases. There are also pressure losses due to shock and turbulence as the liquid strikes the impeller. The centrifugal force of the impeller vanes further increases the velocity and decreases the pressure of the liquid. The NPSH required is the positive head in feet absolute required at the pump suction to overcome these pressure drops in the pump and maintain the majority of the liquid above its vapor pressure.

The NPSH is always positive since it is expressed in terms of absolute fluid column height. The term "Net" refers to the actual pressure head at the pump suction flange and not the static suction head.

#### *NPSHr increases as capacity increases*

The NPSH required varies with speed and capacity within any particular pump. The NPSH required increase as the capacity is increasing because the velocity of the liquid is increasing, and as anytime the velocity of a liquid goes up, the pressure or head comes down. Pump manufacturer's curves normally provide this information. The NPSH is independent of the fluid density as are all head terms. **Note:** It is to be noted that the net positive suction head required (NPSHr) number shown on the pump curves is for fresh water at 20°C and not for the fluid or combinations of fluids being pumped.

## Net Positive Suction Head available, NPSHa

### *NPSHa is a function of system design*

Net Positive Suction Head Available is a function of the system in which the pump operates. It is the excess pressure of the liquid in feet absolute over its vapor pressure as it arrives at the pump suction, to be sure that the pump selected does not cavitate. It is calculated based on system or process conditions.

### *NPSHa calculation*

The formula for calculating the NPSHa is stated below:

$$NPSHa_S = hp_S + h_S - hvp_S - hf_S$$

- $hp_S$  - Pressure Head i.e Barometric Pressure of the suction vessel converted to Head
- $h_S$  - Static suction Head i.e.the vertical distance between the eye of the first stage impeller centerline and the suction liquid level.
- $hvp_S$  - Vapor pressure Head i.e. vapor pressure of liquid at its max. pumping temperature converted to Head
- $hf_S$  - Friction Head i.e. friction and entrance pressure losses on the suction side converted to Head

### Note:

1. It is important to correct for the specific gravity of the liquid and to convert all terms to units of "feet **absolute**" in using the formula.
2. Any discussion of NPSH or cavitation is only concerned about the suction side of the pump. There is almost always plenty of pressure on the discharge side of the pump to prevent the fluid from vaporizing.

### ***NPSHa in a nutshell***

In a nutshell, NPSH available is defined as:

NPSHa = Pressure head + Static head - Vapor pressure head of your product – Friction head loss in the piping, valves and fittings.

“All terms in feet absolute”

In an existing system, the NPSHa can also be approximated by a gauge on the pump suction using the formula:

$$\text{NPSHa} = h_{ps} - h_{vps} + h_{gs} + h_{vs}$$

- **$h_{ps}$**  = Barometric pressure in feet absolute.
- **$h_{vps}$**  = Vapor pressure of the liquid at maximum pumping temperature, in feet absolute.
- **$h_{gs}$**  = Gauge reading at the pump suction expressed in feet (plus if above atmospheric, minus if below atmospheric) corrected to the pump centerline.
- **$h_{vs}$**  = Velocity head in the suction pipe at the gauge connection, expressed in feet.

### ***Significance of NPSHr and NPSHa***

The NPSH available must always be greater than the NPSH required for the pump to operate properly. It is normal practice to have at least 2 to 3 feet of extra NPSH available at the suction flange to avoid any problems at the duty point.

## **Power and Efficiency**

### Brake Horse Power (BHP)

The work performed by a pump is a function of the total head and the weight of the liquid pumped in a given time period.

*Pump input or brake horsepower (BHP)* is the actual horsepower delivered to the pump shaft.

*Pump output or hydraulic or water horsepower (WHP)* is the liquid horsepower delivered by the pump. These two terms are defined by the following formulas.

$$BHP = \frac{Q \times H_T \times Sp.Gr.}{3960 \times Eff.}$$

where

- $Q$  = Capacity in gallons per minute (GPM).
- $H_T$  = Total Differential Head ,ft
- $Sp.Gr.$  = Specific Gravity of the liquid
- $Eff.$  = Pump efficiency , %

$$WHP = \frac{Q \times H_T \times Sp.Gr.}{3960}$$

where

- $Q$  = Capacity in gallons per minute (GPM).
- $H_T$  = Total Differential Head ,ft
- $Sp.Gr.$  = Specific Gravity of the liquid

The constant 3960 is obtained by dividing the number of foot-pounds for one horsepower (33,000) by the weight of one gallon of water (8.33 pounds).

**BHP** can also be read from the pump curves at any flow rate. Pump curves are based on a specific gravity of 1.0. Other liquids' specific gravity must be considered.

The brake horsepower or input to a pump is greater than the hydraulic horsepower or output due to the mechanical and hydraulic losses incurred in the pump.

Therefore the pump efficiency is the ratio of these two values.

$$Pump\ Efficiency\ (Eff.) = \frac{WHP}{BHP}$$

## Best Efficiency Point (BEP)

The H, NPSHr, efficiency, and BHP all vary with flow rate, Q. **Best Efficiency Point (BEP)** is the capacity at maximum impeller diameter at which the efficiency is highest. All points to the right or left of BEP have a lower efficiency.

### **Significance of BEP**

#### *BEP as a measure of optimum energy conversion*

When sizing and selecting centrifugal pumps for a given application the pump efficiency at design should be taken into consideration. The efficiency of centrifugal pumps is stated as a percentage and represents a unit of measure describing the change of centrifugal force (expressed as the velocity of the fluid) into pressure energy. The B.E.P. (best efficiency point) is the area on the curve where the change of velocity energy into pressure energy at a given gallon per minute is optimum; in essence, the point where the pump is most efficient.

#### *BEP as a measure of mechanically stable operation*

The impeller is subject to non-symmetrical forces when operating to the right or left of the BEP. These forces manifest themselves in many mechanically unstable conditions like vibration, excessive hydraulic thrust, temperature rise, and erosion and separation cavitation. Thus the operation of a centrifugal pump should not be outside the furthest left or right efficiency curves published by the manufacturer. Performance in these areas induces premature bearing and mechanical seal failures due to shaft deflection, and an increase in temperature of the process fluid in the pump casing causing seizure of close tolerance parts and cavitation.

#### *BEP as an important parameter in calculations*

BEP is an important parameter in that many parametric calculations such as specific speed, suction specific speed, hydrodynamic size, viscosity correction, head rise to shut-off, etc. are based on capacity at BEP. Many users prefer that pumps operate within 80% to 110% of BEP for optimum performance.



## Specific Speed

### Specific speed as a measure of the geometric similarity of pumps

Specific speed ( $N_s$ ) is a non-dimensional design index that identifies the geometric similarity of pumps. It is used to classify pump impellers as to their type and proportions. Pumps of the same  $N_s$  but of different size are considered to be geometrically similar, one pump being a size-factor of the other.

### Specific speed Calculation

The following formula is used to determine specific speed:

$$N_s = \frac{N \times Q^{0.5}}{H^{0.75}}$$

where

- $Q$  = Capacity at best efficiency point (BEP) at maximum impeller diameter, GPM
- $H$  = Head per stage at BEP at maximum impeller diameter, ft
- $N$  = Pump speed, RPM

As per the above formula, it is defined as the speed in revolutions per minute at which a geometrically similar impeller would operate if it were of such a size as to deliver one gallon per minute flow against one-foot head.

The understanding of this definition is of design engineering significance only, however, and specific speed should be thought of only as an index used to predict certain pump characteristics.

### Specific speed as a measure of the shape or class of the impellers

The specific speed determines the general shape or class of the impellers. As the specific speed increases, the ratio of the impeller outlet diameter,  $D_2$ , to the inlet or eye diameter,  $D_1$ , decreases. This ratio becomes 1.0 for a true axial flow impeller. *Radial flow impellers* develop head principally through centrifugal force. Radial impellers are generally low flow high head designs. Pumps of higher specific speeds develop head partly by centrifugal force and partly by axial force. A higher specific speed indicates a pump design with head generation more by axial forces and less by centrifugal forces. An axial flow or propeller pump with a specific speed of 10,000 or greater generates its head exclusively through axial forces. Axial flow impellers are high flow low head designs.

Specific speed identifies the approximate acceptable ratio of the impeller eye diameter (D1) to the impeller maximum diameter (D2) in designing a good impeller.

Ns: 500 to 5000;  $D1/D2 > 1.5$  - radial flow pump

Ns: 5000 to 10000;  $D1/D2 < 1.5$  - mixed flow pump

Ns: 10000 to 15000;  $D1/D2 = 1$  - axial flow pump

Specific speed is also used in designing a new pump by size-factoring a smaller pump of the same specific speed. The performance and construction of the smaller pump are used to predict the performance and model the construction of the new pump.

#### Suction specific speed (Nss)

Suction specific speed (Nss) is a dimensionless number or index that defines the suction characteristics of a pump. It is calculated from the same formula as Ns by substituting H by NPSHr.

In multi-stage pump the NPSHr is based on the first stage impeller NPSHR.

#### Specific speed as a measure of the safe operating range

Nss is commonly used as a basis for estimating the safe operating range of capacity for a pump. The higher the Nss is, the narrower is its safe operating range from its BEP. The numbers range between 3,000 and 20,000. Most users prefer that their pumps have Nss in the range of 8000 to 11000 for optimum and trouble-free operation.

## The Affinity Laws

The Affinity Laws are mathematical expressions that define changes in pump capacity, head, and BHP when a change is made to pump speed, impeller diameter, or both. According to *Affinity Laws*:

**Capacity, Q** changes in direct proportion to impeller diameter **D** ratio, or to speed **N** ratio:

$$Q_2 = Q_1 \times [D_2/D_1]$$

$$Q_2 = Q_1 \times [N_2/N_1]$$

**Head, H** changes in direct proportion to the square of impeller diameter **D** ratio, or the square of speed **N** ratio:

$$H_2 = H_1 \times [D_2/D_1]^2$$

$$H_2 = H_1 \times [N_2/N_1]^2$$

**BHP** changes in direct proportion to the cube of impeller diameter ratio, or the cube of speed ratio:

$$BHP_2 = BHP_1 \times [D_2/D_1]^3$$

$$BHP_2 = BHP_1 \times [N_2/N_1]^3$$

Where the subscript: 1 refers to initial condition, 2 refer to new condition

If changes are made to both impeller diameter and pump speed the equations can be combined to:

$$Q_2 = Q_1 \times [(D_2 \times N_2)/(D_1 \times N_1)]$$

$$H_2 = H_1 \times [(D_2 \times N_2)/(D_1 \times N_1)]^2$$

$$BHP_2 = BHP_1 \times [(D_2 \times N_2)/(D_1 \times N_1)]^3$$

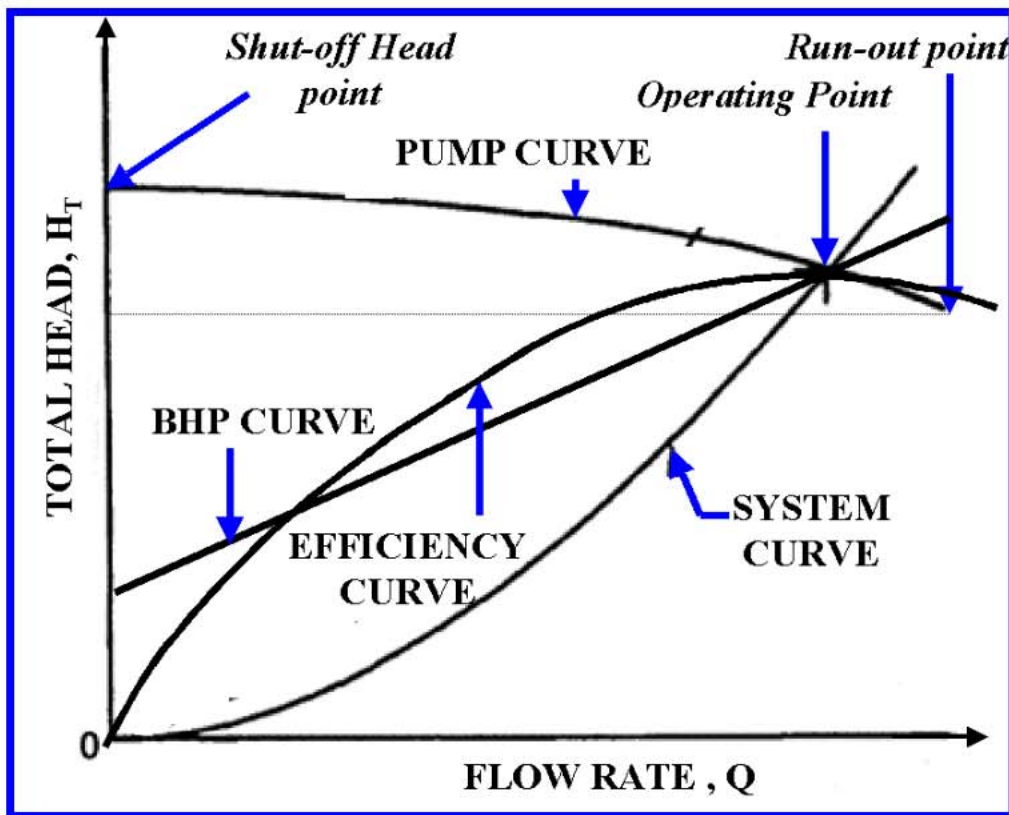
This equation is used to hand-calculate the impeller trim diameter from a given pump performance curve at a bigger diameter.

**The Affinity Laws are valid only under conditions of constant efficiency.**

## Understanding Centrifugal Pump Performance Curves

The capacity and pressure needs of any system can be defined with the help of a graph called a *system curve*. Similarly the capacity vs. pressure variation graph for a particular pump defines its characteristic *pump performance curve*.

The pump suppliers try to match the system curve supplied by the user with a pump curve that satisfies these needs as closely as possible. A pumping system operates where the pump curve and the system resistance curve intersect. The intersection of the two curves defines the operating point of both pump and process. However, it is impossible for one operating point to meet all desired operating conditions. For example, when the discharge valve is throttled, the system resistance curve shift left and so does the operating point.



**Figure D.01: Typical system and pump performance curves**

## Developing a system curve

The *system resistance or system head curve* is the change in flow with respect to head of the system. **It must be developed by the user based upon the conditions of service.** These include physical layout, process conditions, and fluid characteristics. It represents the relationship between flow and hydraulic losses in a system in a graphic form and, since friction losses vary as a square of the flow rate, the system curve is parabolic in shape. Hydraulic losses in piping systems are composed of pipe friction losses, valves, elbows and other fittings, entrance and exit losses, and losses from changes in pipe size by enlargement or reduction in diameter.

## Developing a Pump performance Curve

A pump's performance is shown in its characteristics performance *curve* where its capacity i.e. flow rate is plotted against its developed head. The pump performance curve also shows its efficiency (BEP), required input power (in BHP), NPSHr, speed (in RPM), and other information such as pump size and type, impeller size, etc. This curve is plotted for a constant speed (rpm) and a given impeller diameter (or series of diameters). **It is generated by tests performed by the pump manufacturer.** Pump curves are based on a specific gravity of 1.0. Other specific gravities must be considered by the user.

## Normal Operating Range

A typical performance curve (Figure D.01) is a plot of Total Head vs. Flow rate for a specific impeller diameter. The plot starts at zero flow. The head at this point corresponds to the shut-off head point of the pump. The curve then decreases to a point where the flow is maximum and the head minimum. This point is sometimes called the run-out point. The pump curve is relatively flat and the head decreases gradually as the flow increases. This pattern is common for radial flow pumps. Beyond the run-out point, the pump cannot operate. The pump's range of operation is from the shut-off head point to the run-out point. Trying to run a pump off the right end of the curve will result in pump cavitation and eventually destroy the pump.

In a nutshell, by plotting the system head curve and pump curve together, you can determine:

1. Where the pump will operate on its curve?
2. What changes will occur if the system head curve or the pump performance curve changes?

## Two Basic Requirements for Trouble-Free Operation of Centrifugal Pumps

Centrifugal pumps are the ultimate in simplicity. In general there are two basic requirements that have to be met at all the times for a trouble free operation and longer service life of centrifugal pumps.

The **first** requirement is that no cavitation of the pump occurs throughout the broad operating range and the **second** requirement is that a certain minimum continuous flow is always maintained during operation.

A clear understanding of the concept of cavitation, its symptoms, its causes, and its consequences is very much essential in effective analyses and troubleshooting of the cavitation problem.

Just like there are many forms of cavitation, each demanding a unique solution, there are a number of unfavorable conditions which may occur separately or simultaneously when the pump is operated at reduced flows. Some include:

- Cases of heavy leakages from the casing, seal, and stuffing box
- Deflection and shearing of shafts
- Seizure of pump internals
- Close tolerances erosion
- Separation cavitation
- Product quality degradation
- Excessive hydraulic thrust
- Premature bearing failures

Each condition may dictate a different minimum flow low requirement. The final decision on recommended minimum flow is taken after careful “techno-economical” analysis by both the pump user and the manufacturer.

The consequences of prolonged conditions of cavitation and low flow operation can be disastrous for both the pump and the process. Such failures in hydrocarbon services have often caused damaging fires resulting in loss of machine, production, and worst of all, human life.

Thus, such situations must be avoided at all cost whether involving modifications in the pump and its piping or altering the operating conditions. Proper selection and sizing of pump and its associated piping can not only eliminate the chances of cavitation and low flow operation but also significantly decrease their harmful effects.

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