Centrifugal Pumps: Basic Concepts of Operation, Maintenance, and Troubleshooting (Part- II, Understanding Cavitation)

Introduction

In Part I of the article, two basic requirements for trouble free operation and longer service life of centrifugal pumps are mentioned in brief.

1. PREVENT CAVITATION
   Cavitation of the pump should not occur throughout its operating capacity range.

2. MINIMIZE LOW FLOW OPERATION
   Continuous operation of centrifugal pumps at low flows i.e. reduced capacities, leads to a number of unfavorable conditions. These include reduced motor efficiency, excessive radial thrusts, excessive temperature rise in the pumping fluid, internal re-circulation, etc. A certain minimum continuous flow (MCF) should be maintained during the pump operation.

Operating a pump under the condition of cavitation for even a short period of time an have damaging consequences for both the equipment and the process. Operating a pump at low flow conditions for an extended duration may also have damaging consequences for the equipment.

The condition of cavitation is essentially an indication of an abnormality in the pump suction system, whereas the condition of low flow indicates an abnormality in the entire pumping system or process. The two conditions are also interlinked such that a low flow situation can also induce cavitation.

The concept of cavitation is explored in detail under following topics:

1. Meaning of the term 'cavitation' in the context of centrifugal pumps.
2. Important definitions: Static pressure, Dynamic pressure, Total pressure, Static pressure head, Velocity Head, Vapor pressure.
3. Mechanism of cavitation.
4. General symptoms of cavitation and its effects on pump performance and pump parts.
5. Types of cavitation:
   a. Vaporous cavitation
      i. Classic cavitation
      ii. Internal re-circulation cavitation
   b. Gaseous cavitation
      i. Air ingestion induced cavitation
6. Methods to prevent cavitation.

The topics 1 to 4 are covered in detail in this part of the article. The topics 5 to 6 shall be explored in next part of the article.

Readers of Part I showed keen interest and appreciation about the approach in which the topic of Centrifugal Pumps has been discussed. The same enthusiasm, response and feedback are solicited from the readers.

Concept of Cavitation

Cavitation is a common occurrence but is the least understood of all pumping problems. Cavitation means different things to different people. Some say when a pump makes a rattling or knocking sound along with vibrations, it is cavitating. Some call it slippage as the pump discharge pressure slips and flow becomes erratic. When cavitating, the pump not only fails to serve its basic purpose of pumping the liquid but also may experience internal damage, leakage from the seal and casing, bearing failure, etc.

In summary, cavitation is an abnormal condition that can result in loss of production, equipment damage and worst of all, personnel injury.

The plant engineer's job is to quickly detect the signs of cavitation, correctly identify the type and cause of the cavitation and eliminate it. A good understanding of the concept is the key to troubleshooting any cavitation related pumping problem.

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1. Meaning of the term 'cavitation' in the context of centrifugal pumps

The term 'cavitation' comes from the Latin word cavus, which means a hollow space or a cavity. Webster's Dictionary defines the word 'cavitation' as the rapid formation and collapse of cavities in a flowing liquid in regions of very low pressure.

In any discussion on centrifugal pumps various terms like vapor pockets, gas pockets, holes, bubbles, etc. are used in place of the term cavities. These are one and the same thing and need not be confused. The term bubble shall be used hereafter in the discussion.

In the context of centrifugal pumps, the term cavitation implies a dynamic process of formation of bubbles inside the liquid, their growth and subsequent collapse as the liquid flows through the pump.

Generally, the bubbles that form inside the liquid are of two types: Vapor bubbles or Gas bubbles.

1. Vapor bubbles are formed due to the vaporisation of a process liquid that is being pumped. The cavitation condition induced by formation and collapse of vapor bubbles is commonly referred to as Vaporous Cavitation.
2. Gas bubbles are formed due to the presence of dissolved gases in the liquid that is being pumped (generally air but may be any gas in the system). The cavitation condition induced by the formation and collapse of gas bubbles is commonly referred to as Gaseous Cavitation.

Both types of bubbles are formed at a point inside the pump where the local static pressure is less than the vapor pressure of the liquid (vaporous cavitation) or saturation pressure of the gas (gaseous cavitation).

Vaporous cavitation is the most common form of cavitation found in process plants. Generally it occurs due to insufficiency of the available NPSH or internal recirculation phenomenon. It generally manifests itself in the form of reduced pump performance, excessive noise and vibrations and wear of pump parts. The extent of the cavitation damage can range from a relatively minor amount of pitting after years of service to catastrophic failure in a relatively short period of time.

Gaseous cavitation occurs when any gas (most commonly air) enters a centrifugal pump along with liquid. A centrifugal pump can handle air in the range of ½ % by volume. If the amount of air is increased to 6%, the pump starts cavitating. The cavitation condition is also referred to as Air binding. It seldom causes damage to the impeller or casing. The main effect of gaseous cavitation is loss of capacity.

The different types of cavitation, their specific symptoms and specific corrective actions shall be explored in the next part of the article. However, in order to clearly identify the type of cavitation, let us first understand the mechanism of cavitation, i.e. how cavitation occurs. Unless otherwise specified, the term cavitation shall refer to vaporous cavitation.

2. Important Definitions: *To enable a clear understanding of mechanism of cavitation, definitions of following important terms are explored.*

- *Static pressure,*
- *Dynamic pressure,*
- *Total pressure,*
- *Static pressure head,*
- *Velocity head, and*
- *Vapor pressure.*

Static Pressure, p_s

The static pressure in a fluid stream is the normal force per unit area on a solid boundary moving with the fluid. It describes the difference between the pressure inside and outside a system, disregarding any motion in the system. For instance, when referring to an air duct, static pressure is the difference between the pressure inside the duct and outside the duct, disregarding any airflow inside the duct. In energy terms, the static pressure is a measure of the potential energy of the fluid.

Dynamic pressure, p_d

A moving fluid stream exerts a pressure higher than the static pressure due to the kinetic energy ($\frac{1}{2} mv^2$) of the fluid. This additional pressure is defined as the dynamic pressure. The dynamic pressure can be measured by converting the kinetic energy of the fluid stream into the potential energy. In other words, it is pressure that would exist in a fluid stream that has been decelerated from its velocity 'v' to 'zero' velocity.

Total pressure, p_t

The sum of static pressure and dynamic pressure is defined as the total pressure. It is a measure of total energy of the moving fluid stream. i.e. both potential and kinetic energy.

Relation between p_s, p_d & p_t

In an incompressible flow, the relation between static, dynamic and total pressures can be found out using a simple device called Pitot tube (named after Henri Pitot in 1732) shown in Figure 1.

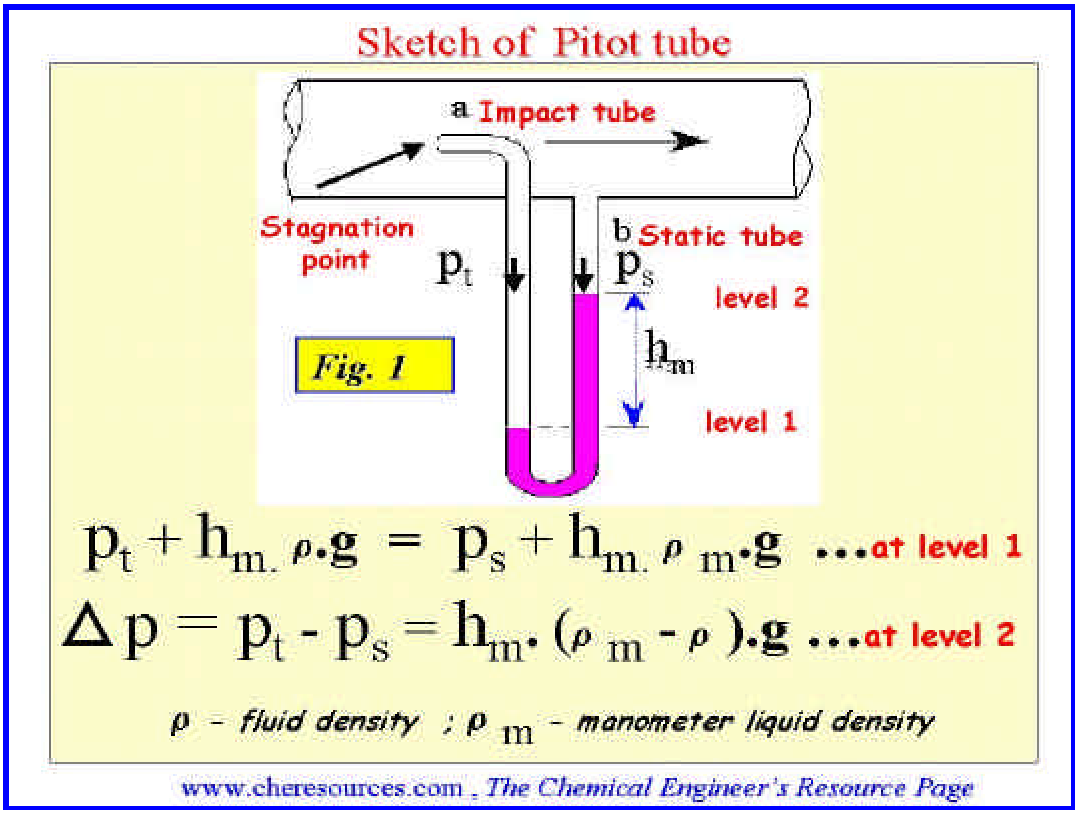

Figure 1: A Simple Sketch of a Pilot Tube

The Pitot tube has two tubes:

1. *Static tube* (b): The opening of the static tube is parallel to the direction of flow. It measures the static pressure, since there is no velocity component perpendicular to its opening.

2. *Impact tube* (a): The opening of the impact tube is perpendicular to the flow direction. The point at the entrance of the impact tube is called as the stagnation point .At this point the kinetic energy of the fluid is converted to the potential energy. Thus, the impact tube measures the total pressure (also referred to as stagnation pressure) i.e. both static pressure and dynamic pressure (also referred to as impact pressure).

The two tubes are connected to the legs of a manometer or equivalent device for measuring pressure.

The relation between p_s*,* p_d *and* p_t *can be derived by applying a simple energy balance.*

Energy balance equation

Potential energy + Kinetic energy = total energy (constant)

As mentioned earlier, in the case of a fluid or gas the potential energy is represented by the static pressure and the kinetic energy by dynamic pressure. The kinetic energy is a function of the motion of the fluid, and of course it's mass. It is generally more convenient to use the density of the fluid (r) as the mass representation.

$$\therefore \quad \mathbf{K.E} = \mathbf{p_d} = \tfrac{1}{2}\,\mathbf{m\,v^2} = \tfrac{1}{2}\ r\ \mathbf{v^2}$$

The corresponding pressure balance equation is

static pressure + dynamic pressure = total pressure

$$\left(p_s + \rho \times \frac{V^2}{2}\right) = p_t$$

In place of the pressure terms as used above, it is more appropriate to speak of the energy during pumping as the energy per unit weight of the liquid pumped and the units of energy expressed this way are foot-pounds per pound (Newton-meters per Newton) or just feet (meters) i.e. the units of head. Thus the energy of the liquid at a given point in flow stream can be expressed in terms of head of liquid in feet.

The pressure term can be converted to head term by division with the factor ‘r **g**’. For unit inter-conversions the factor ‘r $\mathbf{g/g_c}$’ should be used in place of ‘r **g**’.

Static pressure head

The head corresponding to the static pressure is called as the static pressure head.

$$\textbf{Static pressure head} = \mathbf{p_s}\ /\ r\ \mathbf{g}$$

Velocity head

The head corresponding to dynamic pressure is called the velocity head.

$$\textbf{Velocity head} = p_d / \rho g = (\rho v^2/2) / \rho g = v^2/2g$$

From the reading h_m, of the manometer velocity of flow can be calculated and thus velocity head can be calculated. The pressure difference, dP ($p_t - p_s$) indicated by the manometer is the dynamic pressure.

$$dP = h_m (\rho_m - \rho) g = \rho v^2/2$$
$$\textbf{Velocity head} = dP / \rho g = h_m (\rho_m - \rho) / \rho$$

Vapor pressure, p_v

Vapor pressure is the pressure required to keep a liquid in a liquid state. If the pressure applied to the surface of the liquid is not enough to keep the molecules pretty close together, the molecules will be free to separate and roam around as a gas or vapor. The vapor pressure is dependent upon the temperature of the liquid. Higher the temperature, higher will be the vapor pressure.

3. Mechanism of Cavitation

The phenomenon of cavitation is a stepwise process as shown in Figure 2.

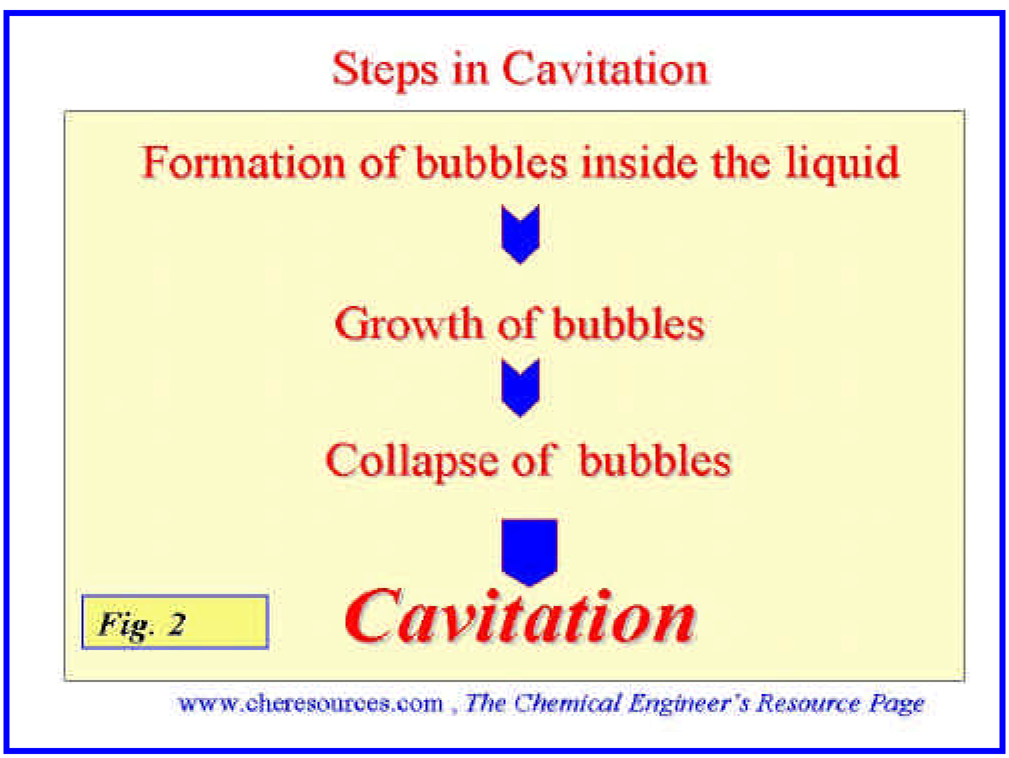

Figure 2: Phenomenon of Cavitation

***Step One**, Formation of bubbles inside the liquid being pumped.*

The bubbles form inside the liquid when it vaporises i.e. phase change from liquid to vapor. *But how does vaporization of the liquid occur during a pumping operation?*

Vaporization of any liquid inside a closed container can occur if either pressure on the liquid surface decreases such that it becomes equal to or less than the liquid vapor pressure at the operating temperature, or the temperature of the liquid rises, raising the vapor pressure such that it becomes equal to or greater than the operating pressure at the liquid surface. For example, if water at room temperature (about 77 ^oF) is kept in a closed container and the system pressure is reduced to its vapor pressure (about 0.52 psia), the water quickly changes to a vapor. Also, if the operating pressure is to remain constant at about 0.52 psia and the temperature is allowed to rise above 77 ^oF, then the water quickly changes to a vapor.

Just like in a closed container, vaporization of the liquid can occur in centrifugal pumps when the local static pressure reduces below that of the vapor pressure of the liquid at the pumping temperature.

NOTE: The vaporisation accomplished by addition of heat or the reduction of static pressure without dynamic action of the liquid is excluded from the definition of cavitation. For the purposes of this article, only pressure variations that cause cavitation shall be explored. Temperature changes must be considered only when dealing with systems that introduce or remove heat from the fluid being pumped.

To understand vaporization, two important points to remember are:

1. We consider only the static pressure and not the total pressure when determining if the system pressure is less than or greater than the liquid vapor pressure. The total pressure is the sum of the static pressure and dynamic pressure (due to velocity).
2. The terms pressure and head have different meanings and they should not be confused. As a convention in this article, the term "pressure" shall be used to understand the concept of cavitation whereas the term "head" shall be used in equations.

Thus, the key concept is - vapor bubbles form due to vaporization of the liquid being pumped when the local static pressure at any point inside the pump becomes equal to or less than the vapor pressure of the liquid at the pumping temperature.

How does pressure reduction occur in a pump system?

The reduction in local static pressure at any point inside the pump can occur under two conditions:

1. The actual pressure drop in the external suction system is greater than that considered during design. As a result, the pressure available at pump suction is not sufficiently high enough to overcome the design pressure drop inside the pump.
2. The actual pressure drop inside the pump is greater than that considered during the pump design.

The mechanism of pressure reduction in the external and internal suction system of a pump system is explored next.

- *Pressure reduction in the external suction system of the pump*

A simple sketch of a pump 'external suction system' is shown in Figure 3.

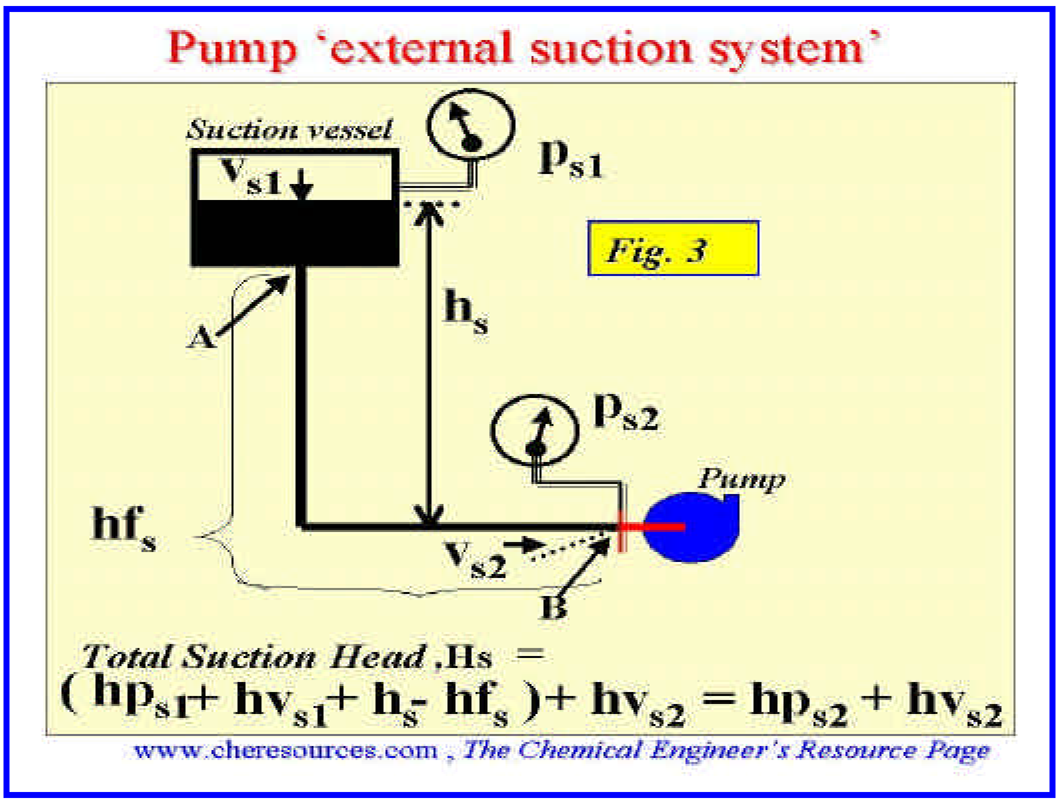

Figure 3: External Suction System

Nomenclature used for Figure 3

- ρ - Liquid density in lb_m / ft^3
- G - Acceleration due to gravity in ft / s^2
- Psn - p refers to local static pressure (absolute). Subscript s refers to suction and subscript n refers to the point of measurement. The pressure at any point can be converted to the head term by division with the factor - ρ g
- p_{s1} - Static pressure (absolute) of the suction vessel in psia
- hp_{s1} - Static pressure head i.e. absolute static pressure on the liquid surface in the suction vessel, converted to feet of head ($p_{s1}/ \rho\ g/g_c$). If the system is open, hp_{s1} equals the atmospheric pressure head.
- v_{s1} - Liquid velocity on the surface in the suction vessel in ft/s
- hv_{s1} - Velocity head i.e. the energy of a liquid as a result of its motion at some velocity 'v_{s1}'. (v^2_{s1} / 2g). It is the equivalent head in feet through which the liquid would have to fall to acquire the same velocity, or the head necessary to accelerate the liquid to velocity v_{s1}. In a large suction vessel, the velocity head is practically zero and is typically ignored in calculations.
- h_s - Static suction head. . . . i.e. head resulting from elevation of the liquid relative to the pump centerline. If the liquid level is above pump centerline, h_S is positive. If the liquid level is below pump centerline, h_S is negative. A negative h_S condition is commonly referred to as "suction lift".
- hf_s - Friction head i.e. the head required to overcome the resistance to flow in the pipe, valves and fittings between points A and B, inclusive of the entrance losses at the point of connection of suction piping to the suction vessel (point A in Figure 1). The friction head is dependent upon the size, condition and type of pipe, number and type of fittings, valves, flow rate and the nature of the liquid. The friction head varies as the square of the average velocity of the flowing fluid.
- p_{s2} - Absolute static pressure at the suction flange in psia
- hp_{s2} - Static pressure head at the suction flange i.e. absolute pressure of the liquid at the suction flange, converted to feet of head - p_{s2} / ρ g/g_c
- v_{s2} - Velocity of the moving liquid at the suction flange in ft/s. The pump suction piping is sized such that the velocity at the suction remains low.
- hv_{s2} - Velocity head at suction flange i.e. the energy of a liquid as a result of its motion at average velocity 'v_{s2}' equal to v^2_{s2} / 2g.
- p_v - Absolute vapor pressure of the liquid at operating temperature in psia.
- hp_v - Vapor Pressure head i.e. absolute vapor pressure converted to feet of head (p_v / ρ. g/g_c).
- H_s - Total Suction Head available at the suction flange in ft.

Note: As pressure is measured in absolute, total head is also in absolute.

The pump takes suction from a vessel having a certain liquid level. The vessel can be pressurised (as shown in the Figure 3) or can be at atmospheric pressure or under vacuum.

Calculation of the Total Suction Head, $\mathbf{H_s}$

The external suction system of the pump provides a certain amount of head at the suction flange. This is referred to as Total Suction Head (TSH), H_s.

TSH can be calculated by application of the energy balance. The incompressible liquid can have energy in the form of velocity, pressure or elevation. Energy in various forms is either added to or subtracted from the liquid as it passes through the suction piping. The head term in feet (or meters) is used as an expression of the energy of the liquid at any given point in the flow stream.

As shown in Figure 3, the total suction head, H_s, available at the suction flange is given by the equation,

$$\mathbf{H_s = hp_{s1} + hv_{s1} + h_s - hf_s + hv_{s2}} \qquad \mathbf{(1)}$$

For an existing system, Hs can also be calculated from the pressure gauge reading at pump suction flange,

$$\mathbf{H_s = hp_{s2} + hv_{s2}} \qquad \mathbf{(2)}$$

Equations 1 and 2 above include the velocity head terms hv_{s1} and hv_{s2}, respectively.

A word about the velocity head term:

There is a lot of confusion as to whether the velocity head terms should be added or subtracted in the head calculations. To avoid any confusion remember the following:

- Just like a static tube of Pitot, a pressure gauge can measure only the static pressure at the point of connection. It does not measure the dynamic pressure as the opening of the gauge impulse pipe is parallel to the direction of flow and there is no velocity component perpendicular to its opening.

In Figure 4 below, flow through a pipe of varying cross section area is shown.

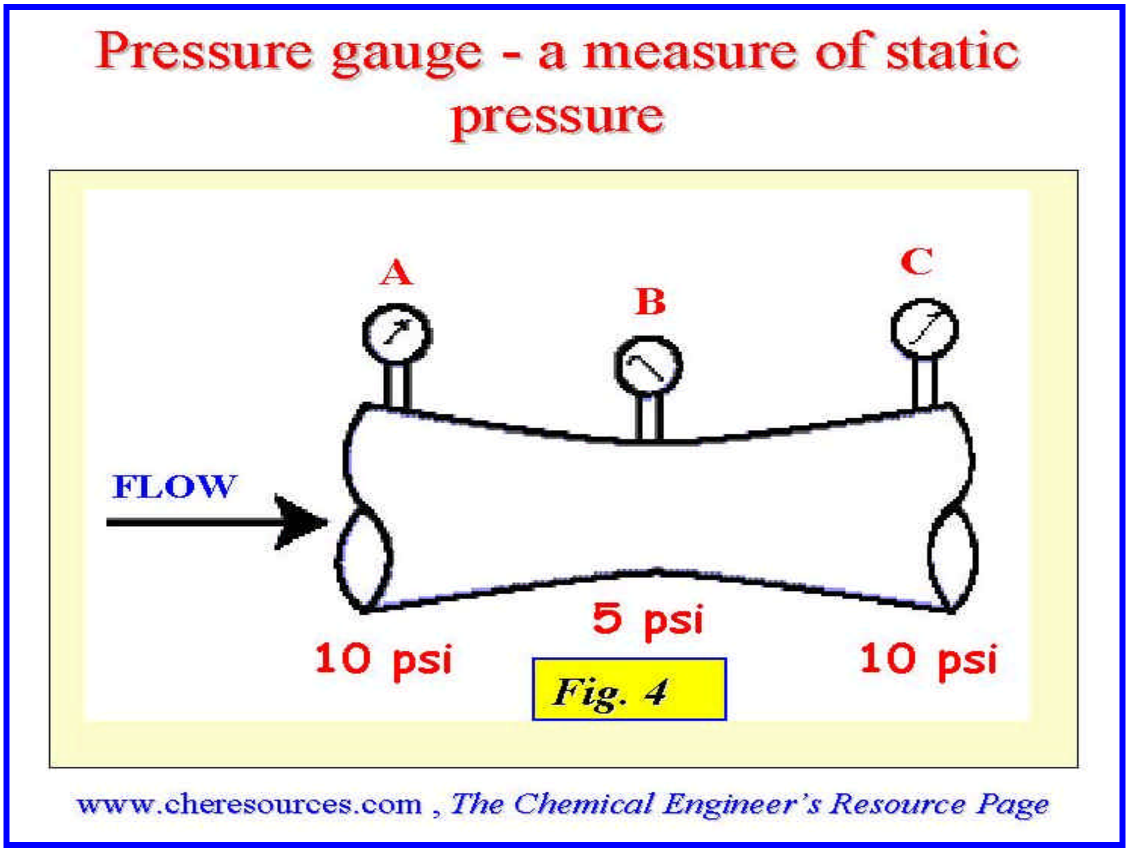

Figure 4: Measuring Static Pressure

As the cross section at point B reduces, the velocity of flow increases. The rise in kinetic energy happens at the expense of potential energy. Assuming that there are no friction losses, the total energy (sum of potential energy and kinetic energy) of fluid at point A, B and C remains constant. The pressure gauges at point A, B and C measure only the potential energy i.e. the static pressures at respective points. The drop in static pressure from 10 psi (point A) to 5 psi (point B) occurs owing to rise the dynamic pressure by 5 psi i.e. increase in velocity at point B. However the gauge at point B records only the static pressure. The velocity decreases from point B to C and the static pressure is recovered again to 10 psi.

- At a particular point of flow, the total pressure is the sum of the static pressure and the dynamic pressure.

Thus, theoretically, the velocity head terms must always be added and not subtracted, in calculating Total Suction Head (TSH), H_S.

However, practically speaking, the value of these terms is not significant in comparison to the other terms in the equation.

- hv_{s1} : In industrial scale suction vessels, the value of hv_{s1} is practically zero and it can be safely ignored.
- $hv_{s2:}$ It is good piping design practice to reduce the friction losses and prevent unnecessary flow turbulence by sizing the suction pipes for fluid velocities in the three to five feet per second range only. The velocity head corresponding to a velocity of 5 ft/s at the suction flange is only about 0.4 ft. Thus, for all practical purposes, in high head systems the velocity head at the suction flange is not significant and can be safely ignored. Only in low head systems does the factor need to be considered.

Therefore, neglecting the velocity head terms, Equations 1 and 2 simplify to:

$$\mathbf{H_s = hp_{s1} + h_s - hf_s} \qquad (3)$$

$$\mathbf{H_s = hp_{s2}} \qquad (4)$$

Two important inferences can be drawn from the above equations:

- The pressure reduction in the external suction system is primarily due to frictional loss in the suction piping (Equation 3).
- For all practical purposes, the total head at the suction flange is the static pressure head at the suction flange (Equation 4).

Therefore the pump's external suction system should be designed such that the static pressure available at the suction flange is always positive and higher than the vapor pressure of the liquid at the pumping temperature.

∴ For no vaporization at pump suction flange,

$$\mathbf{(p_{s2} > p_{v}) \text{ or } (p_{s2} - p_v) \text{ or } (hp_{s2} - hp_v) > 0} \qquad (5)$$

As the liquid enters the pump, there is a further reduction in the static pressure. If the value of p_{s2} is not sufficiently higher than p_v, at some point inside the pump the static pressure can reduce to the value of p_v. In pumping terminology, the head difference term corresponding to Equation 5 (hp_{s2} - hp_v) is called the Net Positive Suction Head or NPSH. The NPSH term shall be explored in detail in the next part of the article. For now, the readers should focus only on how the static pressure within the pump may be reduced to a value lower than that of the liquid vapor pressure.

- *Pressure reduction in the internal suction system of the pump*

The pressure of the fluid at the suction flange is further reduced inside the internal suction system of the pump.

Flow path of fluid inside the pump

The internal suction system is comprised of the pump's suction nozzle and impeller. Figures 5 and 6 depict the internal parts in detail. A closer look at the graphic is a must in understanding the mechanism of pressure drop inside the pump.

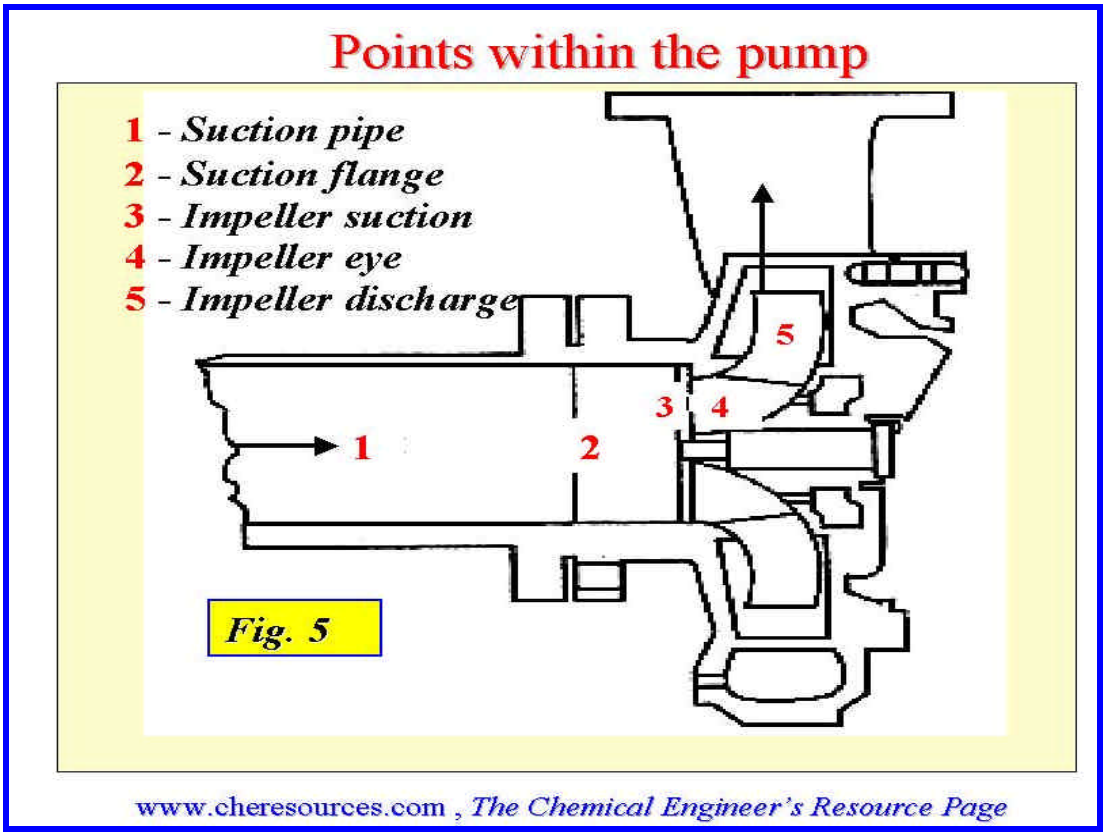

Figure 5: Internal Pump Locations

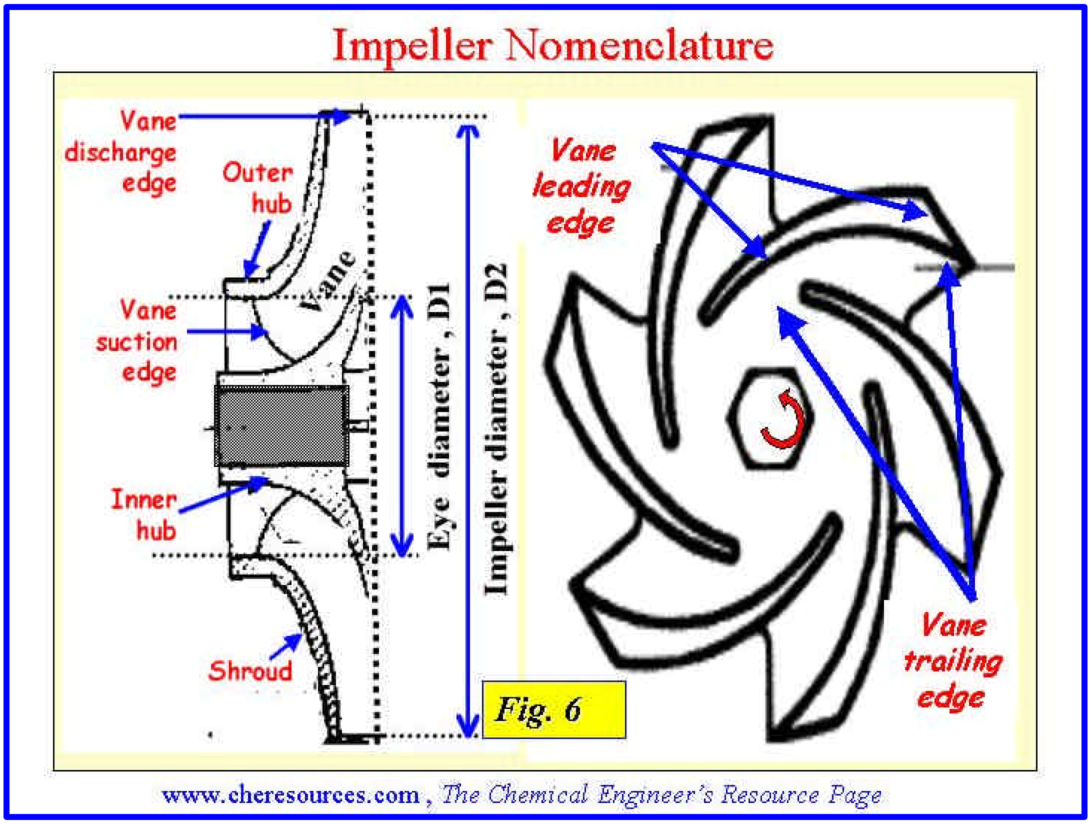

Figure 6: Impeller Nomenclature

In Figure 7, it can be seen that the passage from the suction flange (point 2) to the impeller suction zone (point 3) and to the impeller eye (point 4) acts like a venturi i.e. there is gradual reduction in the cross-section area.

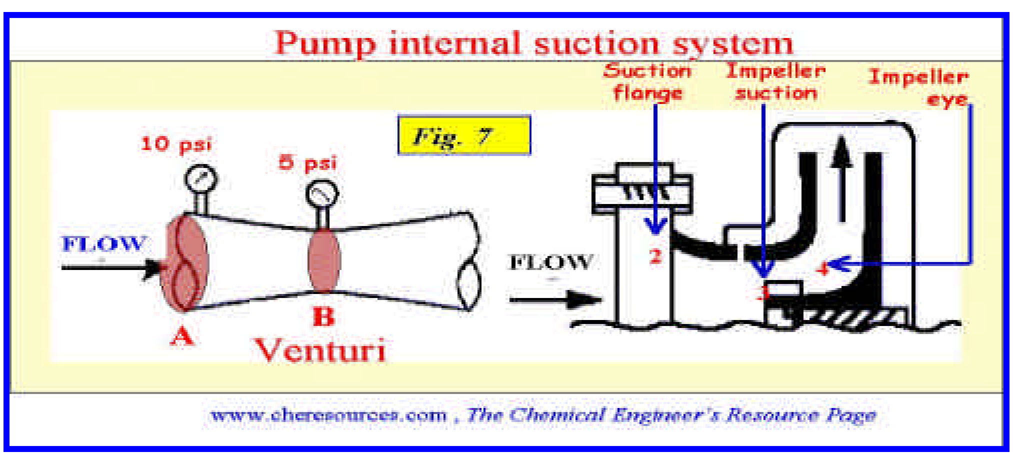

Figure 7: Pump Internal Suction System

In the impeller, the point of minimum radius (r_{eye}) with reference to pump centerline is referred to as the “eye” of the impeller (Figure 8).

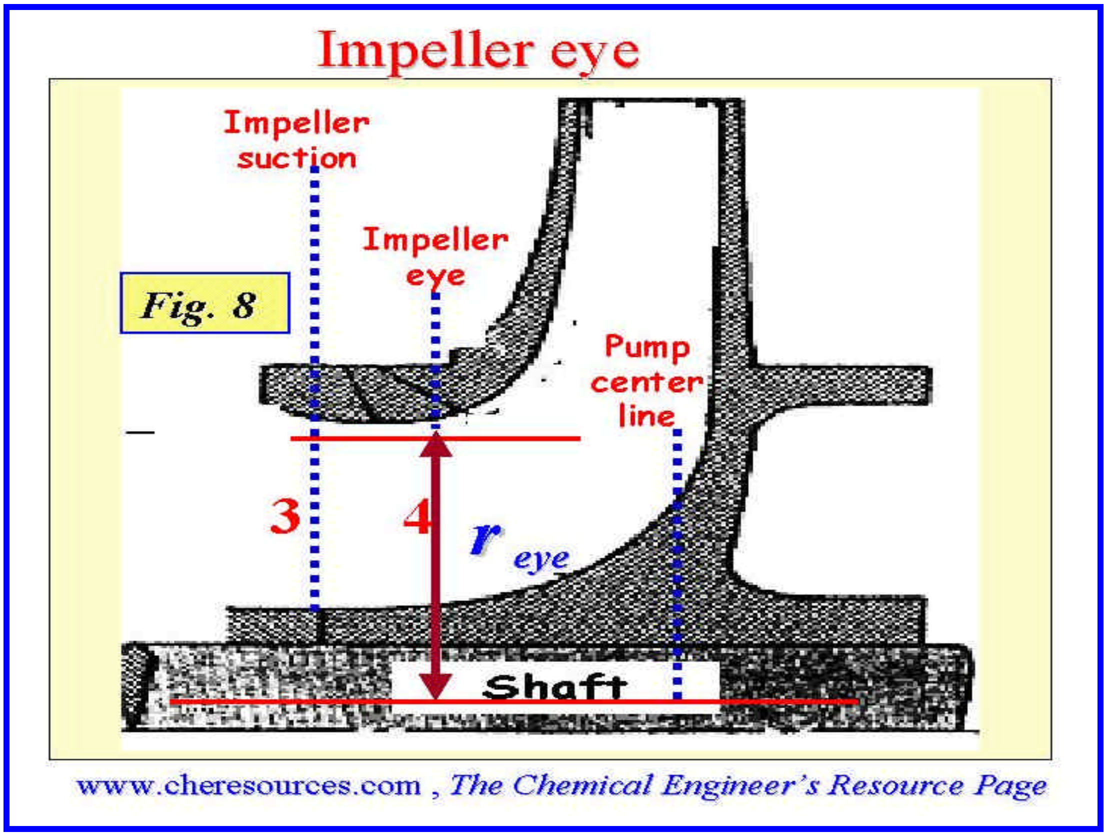

Figure 8: Impeller Eye

How pressure reduction occurs as the fluid flows inside the pump?

According to Bernoulli’s principle, when a constant amount of liquid moves through a path of decreasing cross-section area (as in a venturi), the velocity increases and the static pressure decreases. In other words, total system energy i.e. sum of the potential and kinetic energy, remains constant in a flowing system (neglecting friction). The gain in velocity occurs at the expense of pressure. At the point of minimum cross-section, the velocity is at a maximum and the static pressure is at a minimum.

The pressure at the suction flange, p_{s2} (Point 2) decreases as the liquid flows from the suction flange, through the suction nozzle and into the impeller eye. This decrease in pressure occurs not only due to the venturi effect but also due to the friction in the inlet passage. However, the pressure drop due to friction between the suction nozzle and the impeller eye is comparatively small for most pumps. However the pressure reduction due