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High Specific Speed in Circulating Water Pump Can Cause Cavitation, Noise and Vibration

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***Abstract*—**Excessive vibration means increased wear, increased repair efforts, bad product selection & quality and high energy consumption. This may be sometimes experienced by cavitation or suction/discharge recirculation which could occur only when net positive suction head available $NPSH_A$ drops below the net positive suction head required $NPSH_R$. Cavitation can cause axial surging, if it is excessive, will damage mechanical seals, bearings, possibly other pump components frequently, and shorten the life of the impeller. Efforts have been made to explain Suction Energy (SE), Specific Speed (Ns), Suction Specific Speed (Nss), $NPSH_A$, $NPSH_R$ & their significance, possible reasons of cavitation /internal recirculation, its diagnostics and remedial measures to arrest and prevent cavitation in this paper. A case study is presented by the author highlighting that the root cause of unwanted noise and vibration is due to cavitation, caused by high specific speeds or inadequate net- positive suction head available which results in damages to material surfaces of impeller & suction bells and degradation of machine performance, its capacity and efficiency too. Author strongly recommends revisiting the technical specifications of CW pumps to provide sufficient NPSH margin ratios >1.5, for future projects and Nss be limited to 8500 - 9000 for cavitation free operation.

***Keywords*—**Best efficiency point (BEP), Net positive suction head $NPSH_A$, $NPSH_R$, Specific Speed N_S, Suction Specific Speed $N_{ss.}$

I. Introduction

THE term 'cavitation' comes from the Latin word cavus, which means a hollow space or a cavity [1]. Cavitation is well recognized as a phenomenon that may cause serious pump malfunctioning due to improper pump inlet conditions. It is, therefore, important for the pump users to understand what cavitation is, what it potentially can cause, and how it can be controlled [2]. Sometimes cavitation has been so severe enough to wear holes in the impeller and damage the vanes to such a degree that the impeller becomes very ineffective. More commonly, the pump reliability and efficiency will decrease significantly during cavitation and continue to decrease further as damage to the impeller increases. Typically, when cavitation occurs, an audible sound similar to 'marbles' or 'crackling' is reported to be emitted from the pump. Cavitation is one of the most important causes that effect performance, operability, reliability, efficiency and pump life too [3].

According to [4], cavitation is the condition in which a more than 3% drop in the head pressure is experienced across a functioning pump. It is a kind of "heart failure" of a pump during operation. The pump suction side experiences a reduction in net-positive suction head (NPSH) pressure which is the main contributing factor in formation of bubbles while the pumping side is under high pressure. The effects of reduction in pressure resulting in cavitation will portray various imperfections. First, a pump experiencing this condition will have a reduced capacity. This is because; bubbles formed take up space which could otherwise have been taken up by the liquid. As a result, the delivery capacity of the pump is greatly reduced. In some cases, a big bubble can create itself at the eye of the impeller causing the pump to lose its ability to suction the liquid being pumped. Cavitation also causes a reduction of pump head or potential height which the pump can deliver the liquid being pumped. Bubbles are like balloons of air which are compressible in nature and this factor leads to reduction of the head and pressure of the pump. In actual fact, all these causes a drop in pump efficiency and its reliability to perform its desired function efficiently. When these bubbles pass into the region of higher pressure, they collapse causing noise and vibrations leading to a lot of damage to the pump and its components. This kind of cavitation is known as $NPSH_A$ insufficiency [5].

Insufficiency can be subsided by either improving the $NPSH_A$ or by reducing the $NPSH_{R,}$ by trimming the suction characteristics of impeller, which means increasing the Suction Specific Speed (Nss) (whereas impeller trimming reduces tip speed, which in turn directly lowers the amount of energy imparted to the system fluid and lowers both the flow and pressure generated by the pump .

A high Nss may indicate the impeller suction eye is somewhat larger than normal and consequently, the efficiency may be compromised to obtain a low $NPSH_{R.}$. Higher values of Nss may also require special designs and may also be operated with some degree of cavitation. A large impeller suction eye diameters can also generate excessive suction recirculation that sometimes leads to cavitation and reason for a higher number of failures. The suction recirculation increases as the Specific Speed (Ns) increases [6].

The best way to avoid cavitation due to suction recirculation problems is to select pumps having lower suction specific speed (Nss) not above 9,000 unless they have special designs. Many of above problems can be avoided by designing or selecting a pump for lower Suction Specific Speed (Nss) values and limiting the range of operation to capacities above the point of recirculation. Based on values of the Hydraulic Institute guidelines, if Suction Specific Speed (Nss) is above 8500-9000, pump reliability begins to suffer exponentially.

To a designer, Specific Speed is an indicator of impeller geometry; Suction Specific Speed is an indicator of impeller

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inlet geometry. Suction Specific Speed (Nss) accounts for changes in $NPSH_R$ characteristics that are created without a change in Specific Speed (Ns) [7].

The types of cavitation which can occur in circulating water pumps, their detection techniques, causes, possible ways of controlling and recommendations for operator/designer are described in detail along with conclusion by the author through a case study in this paper. Early detection of cavitation in circulating water pumps is mandatory because it can cause axial surging, pitting erosion, loss of capacity, head, and even complete damage to the impeller and reduction in pumps efficiency.

II. Suction Energy (SE), NS, NSS, $NPSH_A$, $NPSH_R$, BEP, N_{SSA}, N_{SSR}

A. Suction Energy (SE)

Suction Energy (SE) is another term for the liquid momentum in the suction eye of a pump impeller, which means that it is a function of the mass and velocity of the liquid in the inlet. Suction Energy is defined as

$$(\text{S.E.}) = D_e \text{ X N X S X S.G}, \tag{1}$$

where, D_e=Impeller eye diameter (mm), N = rotative speed of the impeller (rev/min), Suction specific speed = N x Q $^{(0.5)}$ / $NPSH_R$ $^{(0.75)}$, S = Suction specific speed = rpm x (Q m^3/h) $^{0.5}$/($NPSH_R$) $^{0.75}$, $NPSH_R$ = Head of the single stage of the pump at the best efficiency point, S.G. = Specific gravity of liquid pumped.

Using Suction Energy, pumps can be classified as "Low" "High," or "Very High" suction energy with the limits for each category somewhat variable depending on pump type. This guideline as shown in Table I recommends NPSH margin with respect to low, high, very high suction energy levels. One drawback of that guideline was the gradation between the different suction energy levels, however, these guidelines have since been withdrawn [6], [7].

B. Specific Speed (Ns)

Specific Speed (Ns) is the speed in rpm at which a given impeller would operate if reduced (or increased) proportionally in size so as to deliver a capacity at one gallon per minutes (GPM) at a head of one foot. By itself, this seems meaningless, but if taken into bigger picture, specific speed (Ns) become a dimensionless number that describes hydraulic features of a pump, and more specifically the pump's impeller(s). The "specific speed" refers to the discharge characteristics of a pump whereas "suction specific speed" (Nss) refers to the suction characteristics of the pump or impeller.

$$Ns = N \sqrt{Q_{(bep)}} / H_{(bep)}^{3/4} \tag{2}$$

where Ns = Specific Speed, N= rotative speed of the impeller (rev/min), $Q_{(bep)}$ = Capacity of the pump at the best efficiency point in m^3/h, $H_{(bep)}$= Head of the single stage of the pump at the best efficiency point in meter.

The Imperial Units (gpm) are converted to Metric Units (m^3/h, l/s) as follows:

- Nss (US gpm) =0.86 Nss (metric m^3/h)
- Nss (Metric l/s) = 0.614 Nss (US gpm)
- (1 gallon = 3.785411784 litre)
- (1 gallon/minute "gpm" = 0.227125 m^3/h)

Specific speed (Ns) is a function of a relationship between flow and total dynamic head and Suction Specific Speed (Nss) is a function of a relationship between flow and net positive suction head required ($NPSH_R$) and both will remain constant for a particular pump design regardless of its rotative speed [8].

A high Specific Speed value indicates a high rate of flow in relation to the amount of head developed. For instance, an axial flow pump, characterized by high flow and low head, is a high specific speed pump. Conversely, a radial impeller pump, characterized by low flow high head, is a low specific speed pump [9].

The head vs. capacity curve is shown in Fig. 1.

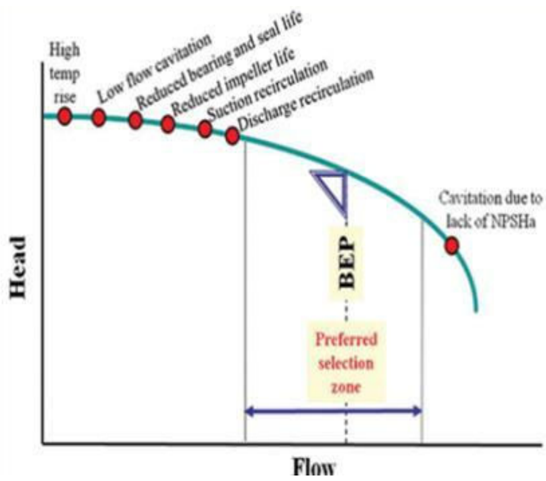

Fig. 1 Head vs. Capacity Curve [25]

As a rule of thumb, the steepness of the head/capacity curve increases as specific speed increases as shown in Fig. 2. A lower specific speed produces flatter curves, while higher specific speeds produce steeper ones. Lower specific speed pumps may have lower efficiency at their BEP, but at the same time will have lower power consumption at reduced flow than many of higher specific speed pump design. At medium specific speed power curve peaks at approximately the best efficiency point (BEP) [10].

The high specific speed pumps are more sensitive to the effects of cavitation because of relatively shorter blade lengths. When trimming the impeller diameter, the impeller blade length is also reduced. In some cases, the effects of cavitation blockage inside the impeller flow path can be more pronounced because they interface with pressure recovery. Therefore, the degree of cavitation must be reduced to ensure proper impeller hydraulic operation. Trimming the impeller diameter of some high specific speed pumps will require higher NPSH values. NPSH and impeller outside diameter were compared at a 3% head drop rate by Hydraulic Institute Standards (HIS) and found that when specific speed (Ns) is small, NPSH does not show significant variation, even when the impeller outer diameter has been trimmed. As it increases, NPSH is largely controlled by variation of the impeller outer diameter. The head drop patterns for low and high Ns impellers are completely different. In other words, the pump head drop falls off abruptly when Ns is low, it moves gradually when Ns is high. Cavitation could become a problem as the increase in speed means an increase in the N.P.S.H. required [11].

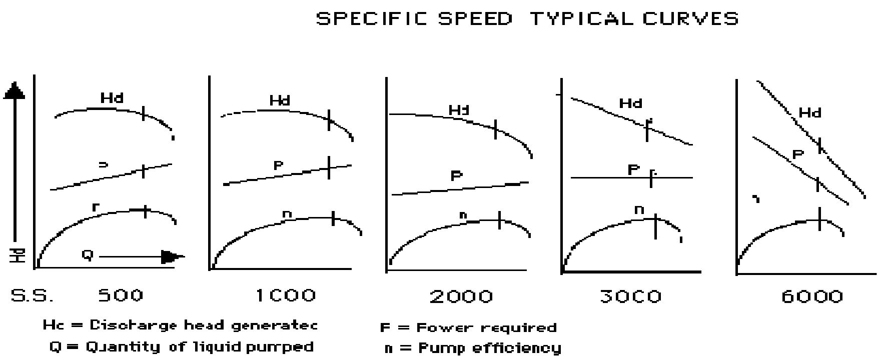

Fig. 2 Head vs. Specific Speed [10]

C. Suction Specific Speed (Nss)

Suction Specific Speed (Nss) is a number that is dimensionally similar to the pump specific speed and is used as a guide to prevent cavitation. The suction specific speed deals primarily with pump suction (inlet) side. The head (H) term in the denominator of the defining formula for the Ns is substituted by the $NPSH_R$.

$$Nss = RPM\ (N)\ \surd\ Q/\ (NPSH_{R)}\ ^{3/4} \qquad (3)$$

where flow is in the (m^3/h) at Best Efficiency Point (BEP) and $NPSH_R$ for the pump at the best efficiency point in meter. Also if the pump is double suction pump then the flow value to be used is one half the total pump output. The higher numerical values of Suction specific speed (Nss) or "(S)" are associated with better suction capabilities. The $NPSH_R$ is the denominator in the equation. The Nss rises as the $NPSH_R$ reduces. The Nss drops as the $NPSH_R$ rises. Low Nss reduces the pump's stress when operated to the left of best efficiency point. Low $NPSH_R$ is desirable to avoid cavitation.

In addition to pump specific speed, there exists two values of Suction Specific Speed depending on the form of NPSH used in (2). Suction specific speed required N_{SSR} is obtained when:

$$N_{SSR} = N\ \surd\ Q/\ (NPSH_R)^{3/4} \qquad (4)$$

Generally, the larger the numerical value of N_{SSR}, the more favorable the pump's suction capabilities are. Normal pump designs exhibit N_{SSR} values ranging from 6,000 to 9000 - 12000 (with special material). Greater values are not uncommon. It logically follows that the concept of suction specific speed available would be,

$$N_{SSA} = N\ \surd\ Q/\ (NPSH_A)^{3/4} \qquad (5)$$

It was mentioned earlier that Pump specific speed was primarily a pump designer's tool. As it turns out, N_{SSA} is a very useful number even to day-to-day applications. With this number, the on-set of cavitation can be predicted. N_{SSR} must exceed N_{SSA} in order to preclude liquid cavitation. The difference between the two quantities is known as margin [12]. Ideally,

$$N_{SSR} >> N_{SSA}$$

D. $NPSH_A$

The Net positive suction head available NPSH $_{available}$ to a pump combines the effect of atmospheric pressure, water temperature, supply elevation and the dynamics of the suction piping. The following equation illustrates this relationship:

$$NPSH_A = Ha +/- Hz - Hf + Hv - Hvp$$

where: Ha is the atmospheric or absolute pressure, Hz is the vertical distance from the surface of the water to the pump centerline, Hf is the friction formed in the suction piping, Hv is the velocity head at the pump's suction, Hvp is the vapour pressure of the water at its ambient temperature.

E. $NPSH_R$

$NPSH_R$ is the head required at the pump inlet for satisfactory operation of a pump. $NPSH_R$ is typically included on manufacturers pump curves and is determined from performance testing. Whenever, the $NPSH_R$ increases, as the flow through the pump increases. In addition, as flow increases in the suction pipeline, friction losses also increase, giving a lower $NPSH_A$ at the pump inlet, both of which give a greater chances that cavitation will occur. $NPSH_R = (H_{suction} - H_{vapor})$ required to maintain 3% TDH loss.

F. NPSH Margin

Sufficient NPSH Margin is important for Pump Reliability.

The NPSH margin is the amount that the $NPSH_{available}$ to the pump exceeds the $NPSH_{required}$ of the pump, is shown in Fig. 3. The NPSH Margin ratio ($NPSH_A/NPSH_R$) should be of about 1.3 to 1.7 just to achieve the 100% rated head value. Much higher NPSH Margins are required in High Suction Energy pumps when the pump is at low flow rates in the suction recirculation region. The suction energy determines how much margin is required.

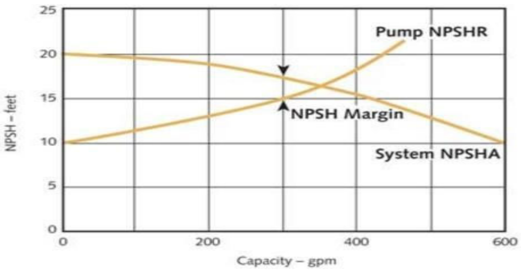

Fig. 3 NPSH Margin Ratio [13]

The following minimum NPSH Margin ratio values for the three Suction Energy levels (Low, High and Very High), above the start of suction recirculation is recommended and these are shown in Table I. NPSH Margin Ratio Guidelines is as follows: [13].

TABLE I
NPSH MARGIN RATIO GUIDELINES

SN	Suction Energy	NPSH Margin Ratio ($NPSH_A$ / $NPSH_R$)
1	Low	1.1-1.3
2	High	1.3-2.0
3	Very High	2.0-2.5

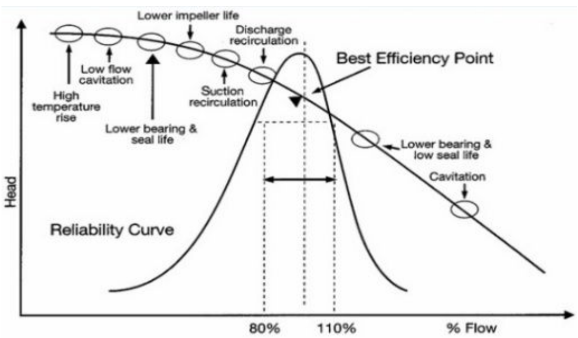

Fig. 4 Best Efficiency Point [15]

G.Best Efficiency Point

BEP is the point at which the impeller diameter provides the highest efficiency. BEP is an important parameter in that many parametric calculations are considered when calculating BEP, such as size, specific speed, viscosity correction, and head rise to shut-off. Professional users prefer that pumps operate within 80% to 110% of BEP for optimum performance [14]. While focusing on the best efficiency point (BEP), Barringer & Ed Nelson plotted eight traditional non-BEP problem areas on a representative H/Q curve. The plot supports the notion that pump reliability can approach zero as one operates farther away from the BEP. The Barringer-Nelson curve shows reliability impact of operation away from BEP (see in Fig. 4) [15].

III. SELECTION OF QUALITY PUMP

During selection of pump with quality, a user would prefer to provide as low $NPSH_A$ as possible, as it often relates to system costs: for example, higher level of liquid in the basin of the cooling water pumps requires taller basin walls, or deeper excavation to lower a pump centerline below the liquid level. A pump manufacturer, on the other hand, wants to have more $NPSH_A$, with an ample margin above the pump $NPSH_R$ to avoid cavitation, damage, and other similar problems. In other words, a wider margin (M) can be achieved either by increasing the $NPSH_A$, or decreasing the $NPSH_R$. Since M= $NPSH_A$- $NPSH_{R;}$ it may appear that a lower $NPSH_R$ design is preferential, and a competing pump manufacturer might present a lower $NPSH_R$ design as one that automatically translates into construction cost savings- not having to increase the $NPSH_A$. Since a lower $NPSH_R$ design means a higher value of suction specific speed (Nss), the design with highest suction specific speed (Nss) may seem like best option. In reality, however, this is not so, because if suction specific speed remains high, hydrodynamic cavitation and inlet eye recirculation will still occur [16]. Hydrodynamic cavitation problems that exist when the pump is operating at points below BEP may be suppressed partially if $NPSH_A$ is much higher than $NPSH_R$, [17].

The impeller eye is usually made larger to reduce suction static pressure near the impeller inlet as much as possible to lower the $NPSH_R$. However, in doing so, the larger eye becomes a problem- not near the best efficiency point (BEP) but at the low flow at which suction recirculation can occur (see Fig. 5). Recirculation also leads to cavitation. However, the cause of this type of cavitation is different from what causes classic cavitation that occurs at high flow rates. The recirculation produces a tornado-like pattern and a blade-to-blade flow separation pattern, which is a complex mechanism. The pressure drops as a result, and when that occurs, net positive suction head suffers. For this reason, suction specific speed is often limited to values below 8,500 (U.S units).

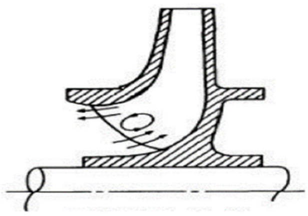

Fig. 5 Suction Recirculation [1]

At high flow, internal fluid velocities are higher, which result in reduction of static pressure, which may then become dangerously close to the fluid vapour pressure and cavitation. Thus, lower velocities result in higher localized static pressure, i.e. safe margin from the cavitating (i.e. evaporation) regime. Since, the velocity is equal to flow divided by the area, a larger area (for the given flow) reduces the velocity, -a desirable trend [16].

This is why a larger suction pipe is beneficial at the pump inlet. Cavitation usually occurs in the eye region of the impeller, and if the eye area is increased - velocities are decreased, and the resulting higher static pressure provides a better safeguard against vaporization (cavitation). Therefore, a larger impeller eye seems like a way to lower the $NPSH_R$ as shown in Fig. 6 [16].

Larger impeller eye results in lower $NPSH_R$ at BEP but certain problems arise at off-peak operation.

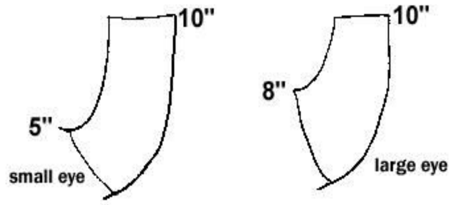

Fig. 6 Small & Large Impeller Eye [16]

Unfortunately, the flow of liquid at the impeller eye region is not as simple and uniform as it is in a straight run of a suction pipe. Impeller eye has a curvature, which guides the turning fluid, like a car along the sharp curves of the road, into the blades and towards the discharge. If a pump operates very close to its BEP, the inlet velocity profile becomes proportionally smaller, but the fluid particles stay within the same paths. If, however, a pump operates below its BEP, the velocity profile changes, and no longer can maintain its uniformity and order. Fluid particles then begin to separate from the path of the sharpest curvature (which is the impeller shroud area), and the resulting mixing and wakes produce a turbulent, disorderly flow regime, which makes matters difficult from the $NPSH_R$ standpoint [16].

The upshot of all this is that larger impeller eye does decrease the $NPSH_R$ at the BEP point, as shown in Fig. 7, but causes flow separation problems at the off-peak low-flow conditions. In other words, a high Suction Specific Speed (N_{SS}) design is better only if a pump does not operate significantly below its BEP point [16].

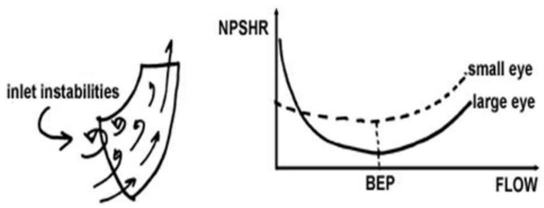

Fig. 7 Impeller Eye vs. $NPSH_R$ [16]

Interestingly, with very few exceptions, there is hardly a case where centrifugal pump operates strictly at the BEP. The flow demands at the plants change constantly, and operators throttle the pump flow via the discharge valve. High Nss designs are known to result in reliability problems because of such frequent operation in the undesirable low-flow region. Actual plant study has shown, that above Nss of 8500-9000, pumps reliability begins to suffer-exponentially [16].

Nss number is used to predict cavitation problems with your impeller selection. The flow angle of the inlet vanes and the number of vanes affect this number. A desired value would be below 8500 with impellers having a flow angle of about 17 degrees and five to seven vanes. The higher the flow angle number, the faster the liquid will travel and the lower suction head (pressure) we will get. The higher the suction specific speed numbers the narrower the stable window of operation which can be seen in Fig. 8, [24]

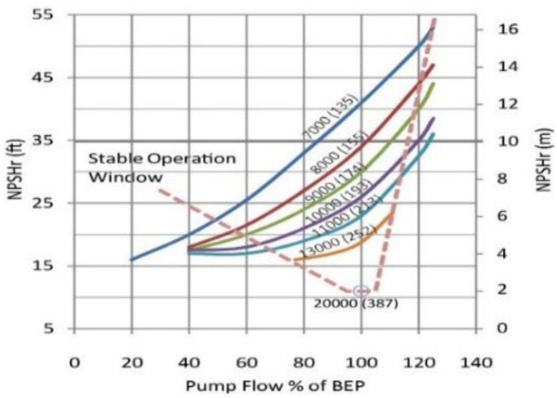

Fig. 8 Window Margin [24]

In their desire to quote a low NPSH required some manufacturers will cut away the impeller inlet vanes to reduce fluid drag and thereby lower the NPSH required. If this has been done, we must insure that the impeller to casing/volute clearance is adjusted correctly with open impeller designs and the wear ring clearance meets the manufacturers' specifications with closed impeller designs or you will experience internal recirculation problems and cavitation at the impeller outlet vane tips. If the suction specific speed number is kept below 8500, this problem should never come up.

While selection of pump, specific speed (Ns) always plays a vital role in deciding how much flow and head is required from the pump. The steepness of the head / capacity curve increases as specific speed (Ns) increases. Normally, Specific speed (Ns) is selected high for higher efficiency as shown in Fig. 9.

In case $NPSH_A$ is not sufficient to maintain NPSH margin ratio then manufacturers decide to increase Nss for reducing $NPSH_R$ because $NPSH_A$ cannot be increased after installation. Keep in mind that efficiency and power consumption are calculated at the best efficiency point (B.E.P.). Lower specific speed pumps may have lower efficiency at the B.E.P., but at the same time will have lower power consumption at reduced flow than many of the higher specific speed designs. *The result is that it might prove to be more economical to select a lower specific speed design if the pump had to operate over a broad range of capacity.*

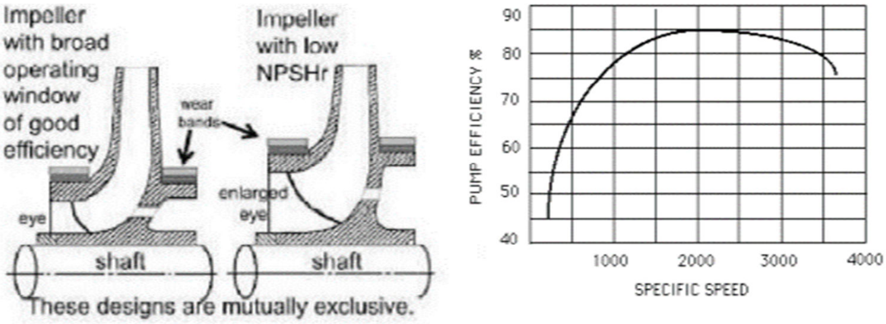

Fig. 9 Ns vs. High Efficiency [26]-[10]

Although opinions vary on the Nss value for a conservative vs. a marginal design, many engineers in industry have found the following to be desirable maximum:

- For cold water and general service applications, suction specific speeds are selected in the 8500 range and lower.
- For boiler feed pump and condensate applications, and for general hydrocarbon services, values of suction specific speeds typically range between 8500 and 11000.
- Pumps designed for suction specific speeds in excess of 12000 are generally for special application only [18].

A. Suction Specific Speed N_{SS} & Pump Reliability

A high suction speed design often results in reliability problems because of frequent operation in the undesirable low-flow range. If suction specific speeds (Nss) are above 8500 to 9000, pump reliability begins to suffer exponentially, can be seen in Fig. 10 [19].

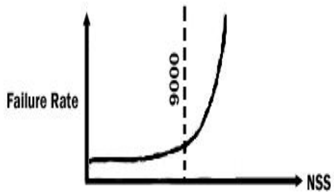

Fig. 10 Failure Rate vs. Nss [16]

For pumps of normal design, values of "Nss or S" vary from 6000 to 12000. In special designs, including inducers, higher values can be obtained, however, special material may be required for continuous operation. Actual plant studies have shown that above Nss of 8500-9000 have a poor reliability record. The reliability of a pump is meaningfully related to its suction specific speed (Nss). Fig. 11 shows the failure rate vs. Suction Specific Speed [19]-[24]. Realizing this, around mid-1980s, users started to limit the value of the suction specific speed and the Hydraulic Institute uses a suction specific speed of 8,500 as a typical guiding value.

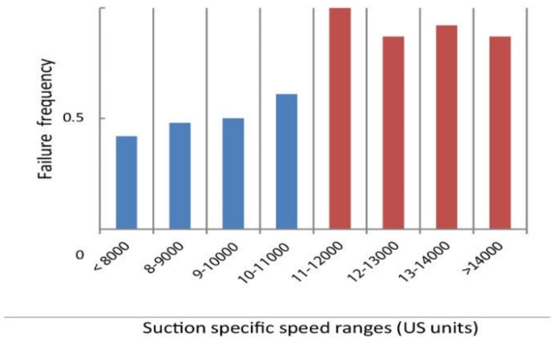

Fig. 11 Failure Frequency vs. Suction Specific Speed [24]

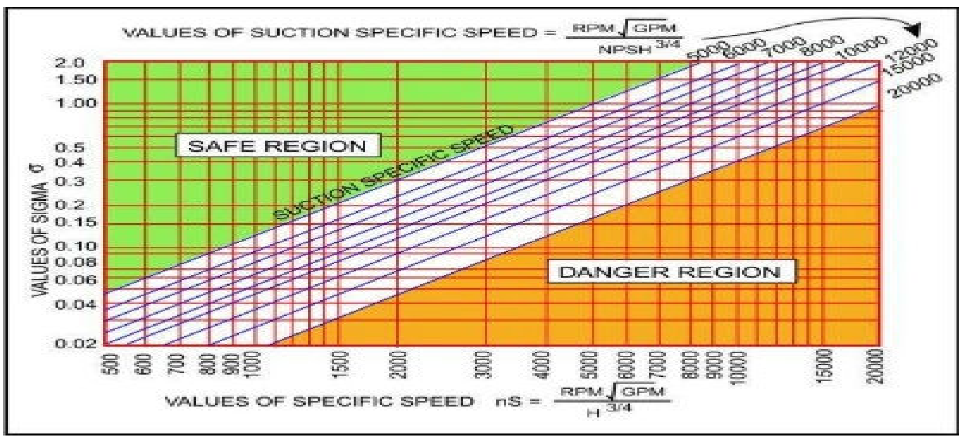

Fig. 12 Cavitation Parameter σ (sigma) vs. Ns & Nss [20]

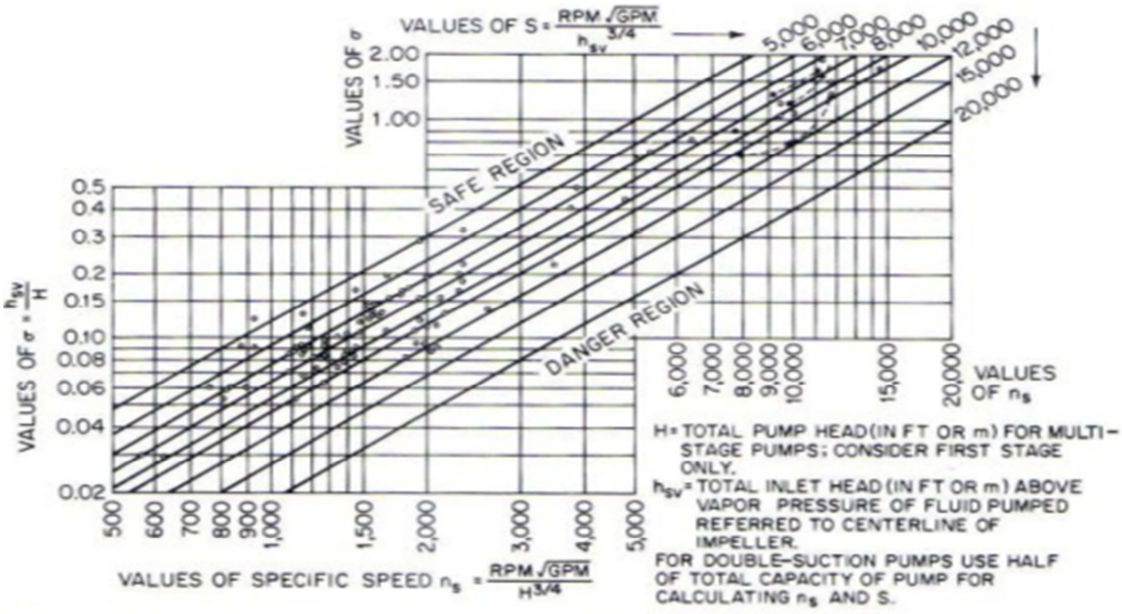

Fig. 13 Cavitation Regions [20]

Figs. 20 and 21 represent the value of the Thoma cavitation parameter σ (sigma) vs. the pump specific speed (Ns) and the suction specific speed (Nss). This chart can be found in the Pump Handbook published by McGraw Hill. It can predict the onset of cavitation and we can use it to help us diagnose if pump is cavitating. The value of the Thoma sigma number σ is given in the image from the Pump Handbook shown in Fig. 12.

Value of Thoma sigma σ = (NPSH/H); NPSH or Hsv (Total inlet head in FT or meter) above vapor pressure of the fluid pumped referred to centerline of the impeller. H= Total pump head in FT or Meter for multi stage pumps: consider first stage only. As we can see, there is a safe region in the upper left corner of the graph. If calculations for the specific speed and the suction specific speed indicate that designer/operators are in that region then everything should be fine. The lower right region is unsafe and if in that region there is no doubt that the pump will cavitate. In the middle is a gray zone where pump may or may not cavitate is shown in Fig. 13, [20].

B. NPSH$_R$ Testing

Suction specific speed is used as a measure of cavitation performance of a pump. Pump manufacturers determine the characteristic shape of the NPSH$_R$ curve for each impeller through carefully controlled shop testing, hydraulic modelling and computer simulation. Reference [4] gives strict guidelines for conducting shop testing and it is used by most pump manufactures. Pumps are normally connected to closed-loop piping circuit where water flows from a suction tank (or sump) through the pump and then back to the tank. The discharge flow rate, temperature, and pressure are carefully measured and controlled throughout the test. Basically, the test is conducted at a fixed flow rate and speed while the suction pressure is reduced. By reducing the suction pressure a point is reached when the water begins to vaporize thus causing the pump to cavitate. The characteristic "cavitation" point is the flow rate that is exhibited by a small drop in head. The test is conducted again at another fixed flow rate and again the resulting suction pressure and flow rate value are recorded at the "cavitation" point. Once the series of tests are completed, a smooth line is drawn through the recorded data and plotted. Fig. 14 illustrates a typical series of test results and the resulting NPSH$_R$ curve.

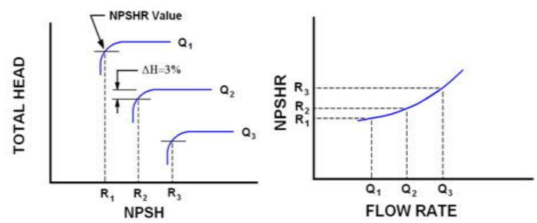

Fig. 14 NPSH$_R$ Curve [21]

A pump cavitation point can be difficult to define. The formation of vapour bubbles is a gradual process, starting slowly and increasing with flow rate.

The API-610 defines the cavitation point as a three percent drop in head. This is not to say that pump cavitation does not occur at smaller values, it is just difficult to accurately measure at smaller values. To obtain a single point it is necessary to run a pump for a period of time and allow the testing circuit to stabilize to the reducing suction pressure. Remember that vapour bubbles are forming and instruments need time to react to the fluid dynamics, [21].

C. Impeller Diameter & Head Relationship

Larger pump impellers produce greater values of head for a given speed. This is because the head is proportional to the tip speed. The relationship of head to tip speed can be approximated by

$$H= V^2/2g \quad (5)$$

Tip velocity can also be related to impeller diameter and rotating speed i.e.

$$V= \pi Dn /A \quad (6)$$

From (5) and (6), it can be seen that changes in impeller diameter will have a direct effect on the pump head. For example, reducing the impeller diameter will lower the pump head by a factor of four. Since the cavitation point is identified by a three percent drop in pump head, it is logical that any change in impeller diameter will have a direct effect on the $NPSH_R$ value. For this reason, most pump manufacturers provide a single $NPSH_R$ curve for a given impeller diameter. Inlet tip speed: values below ≈15 m/s are considered low, while values exceeding ≈ 30 m/s are considered high and should be evaluated for adequate NPSH margin [21].

IV. Low & High Specific Speed (Ns) vs. NPSH

The change in pump performance with changes in impeller diameter can be predicted similarly to that with speed change utilizing the affinity Laws:-

- Pump Flow rate Q varies directly with the diameter (D) & flow is proportional to speed i.e. Q1/Q2= (D1/D2) (N1/N2)
- Pump head (H) varies with square of the diameter (D) & Head is proportional to the square of the speed. i.e. $H1/H2= (D1/D2)^2 \sim N1^2/N2^2$.
- Power absorbed varies with the cube of the diameter (D) & power is proportional to cube of speed i.e. $P1/P2 = (D1/D2)^3 \sim N1^3/N2^3$

Low Ns and High Ns impellers are compared with 3% head drop condition. With a low-specific speed impeller, the outer diameter is essentially large, and the blade length is greater than in case of a high specific speed Ns impeller. Thus, the impeller flow passages of a low Ns pump are not as apt to be blocked, even when cavitation develops, because there is more distance between the impeller inlet and outlet. For this reason, trimming the impeller to an extent that will not adversely affect pump efficiency will not cause NPSH to notably change [11].

In case of high specific speed (Ns) pumps, the impeller outside diameter is relatively small in comparison to the diameter of a low specific speed (Ns) impeller. Therefore, the distance between the impeller outlet and cavitating zone of a high Ns pump is shorter. In other words, the relationship between impeller outside diameter and the blockage of flow passage produced by the cavities become more sensitive in high-Ns impeller. Depending on the amount of trimming, the impeller outside diameter approaches the cavitating zone and the complete restoration of pressure after the cavities have collapsed does not become sufficient. This results in a relatively large head drop and marked deterioration in the suction performance, when compared with low-Ns impeller [11].

The impeller diameter of a mixed flow pump has a strong influence on the pump NPSH and that the rate of NPSH variation is largely controlled by specific speed Ns. Therefore, we may conclude that impeller diameter and NPSH are related and the relationship becomes more acute as suction specific speed increases for reduction of $NPSH_R$.

V. Cavitation

Cavitation occurs when the pump cannot get enough fluid flow into the impeller & the resulting reduction in pressure causes the liquid to vaporize and form bubbles. These bubbles can grow dramatically & choke an inlet, further reducing the flow of liquid & the performance of the pump. In addition, the bubbles can implode with tremendous force, literally tearing away at the metal surface. The resulting increase in stresses, vibration and noise can lead to premature component replacement and in some cases complete pump failure.

A. Types of Cavitation

Two main types of cavitation may occur in a pump, suction cavitation, and discharge cavitation. Suction cavitation occurs when there is low pressure at the impeller eye providing a region in which the pumped liquid can vaporize. Subsequently the formed vapour bubbles move into regions of higher pressure as they travel towards the discharge and collapse.

Discharge cavitation occurs when a pump is operating towards the high head end of its pump curve resulting in the majority of the pumped fluid circulating around the pump impeller. When this occurs, the fluid is forced through the clearance between the impeller and the pump housing at high velocity resulting in formation of a low pressure region in which cavitation can occur. To avoid cavitation when designing a pump system, one should pay special attention to Net Positive Suction Head requirements $NPSH_R$ [22].

B. Cavitation Symptoms

- The high frequency random vibration.
- Sounds like pump is pumping gravel.
- Although amplitudes may or may not be high enough to affect bearing life significantly, cavitation causes excessive wear on the impeller and other internal components.
- May come and go from one collection to the next as load varies.

First step should be assessed operational parameters.-flow rates and pressure- that can influence this vibration. Second step should be an inspection of internal components for excessive wear with particular attention paid to the impeller vanes [23].

C. Cavitation Detection Technique

Role of vibration along with making that loud popping sound, the collapsing vapour bubbles create certain vibration patterns - and the vibration analysis rules for detecting cavitation are fairly well understood. The ability to detect high frequency energy at a pump and determine whether this

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energy is increasing or decreasing is one key to recognizing cavitation. If the high frequency energy is increasing, the cavitation is getting worse, and the impeller and seals are probably sustaining damage. Increasing vibration can also place added stress on the pump bearings, causing accelerated wear on these components as well. Too low a liquid in a suction tank /sump can very quickly reduce suction pressure below the $NPSH_R$ of the pump, thereby causing pump failure. In addition, if antivortex baffles are badly designed or even missing from the suction tank, then vapour/air can be drawn into the suction vortex resulting in pumps problems similar to, and including, cavitation and surging.

The mechanical problems could be caused by poor mechanical design and /or an incorrect or oversized pump selection. Insufficient shaft stiffness can be the reason for bending of the shaft and /or high vibration amplitudes, causing failures of the mechanical shaft seals and /or wear of wear rings. The following spectrum visually shows the difference between these two phenomena.

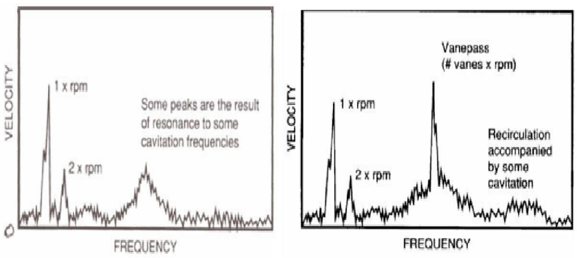

Fig. 15 Cavitation & Recirculation [22]

The area of cavitation is within the eye of the impeller, therefore, there are no vane pass frequencies. Cavitation can cause axial surging, which, if excessive, will cause damage to both bearings and seals. The spectra produced have a very broad frequency range with low amplitude. The highest amplitudes are most often found in the suction area of the pump and are usually highest in the axial direction. It is also significant to note that in cavitation, the peaks are non-synchronous, and there is also a lot of broadband noise is shown in Fig. 15.

Note the difference between cavitation and re-circulation. It is very noticeable that there is now a clear peak at the impeller vane pass frequency. The cure for re-circulation is to operate the pump at or close to its rated capacity for the operating conditions and to avoid excessive throttling on the discharge side. Re-circulation can also be identified by washout of the impeller exit faces. This usually shows up as a polished, sharp edge on the impeller exit face. *It should be noted that cavitation because of internal recirculation is not eliminated by increasing the suction head* [22].

D. Prevent Cavitation in Existing Installation

Cavitation may be avoided by increasing the $NPSH_A$ and/or reducing the $NPSH_R$ (See Table II):-

1. The $NPSH_A$ may be increased through the following methods
- Reduce the length or increasing the diameter of the pump suction line and reducing the number of fittings in the suction line. This will reduce the suction piping friction head.
- Increase the height of the pumping fluid to increase the static pressure head.
- Reduce the temp of the pumping fluid at the pump entrance for example moving a pump to the return line of a heating fluid system. This will reduce the vapor pressure head.
- Pressurize the pumping fluid supply tank. This will increase the head at the liquid surface.
- Reduce the flow rate and/or fluid velocity. This can be achieved by reducing the pump speed and will reduce the suction piping friction head.
2. The $NPSH_R$ can be reduced through the following methods
- Throttle the pump discharge using a throttling valve or a restriction orifice. This will increase the pump head by reducing the flow rate & operate the pump in a lower NPSHR region.
- Use of an oversized pump & use of an impeller with a larger diameter eye.

TABLE II
PREVENT CAVITATION FROM EXISTING INSTALLATION

SN	Eliminate Cavitation	Reduce $NPSH_R$ or increase $NPSH_A$	Performance & Efficiency
1	Reduce $NPSH_R$	• Raise discharge • Oversize pump • Use impeller with larger eye (inlet)	• All affect efficiency so be careful. • The cavities or bubbles will collapse when they pass into the higher regions of pressure, causing noise, vibration and damage to many of the components. • We experience a loss in capacity • The pump can no longer build the same head (pressure) • The pump's efficiency drops.
2	Increase $NPSH_A$	• Raise height of sources fluids • Lower pump • Reduce pipe friction • Pressurize supply tank • Reduce pump speed.	

VI. CASE STUDY EXPERIENCED AT STATIONS "A"&"B"

Two similar super thermal power stations one having capacity of 3 units of 500 MW rating (Station "A") and other having two units of 500 MW rating (Station "B") which are located in two different States of India. While one of the Super Thermal Power Stations "A" Stage-I (3X500MW) having six CW pumps were facing high vibration problem, the other power Station "B" Stage-II (2X500MW) having five CW pumps of the same make but did not have any such problem as far as vibration is concerned. Although technical stipulations for both the stations are the same, the same pump supplier assumed different specific speeds while selecting the pumps for these two stations. The data sheet provided by the pump supplier for the two stations is as in Tables III & IV, [27].

TABLE III
DATA SHEET

Motor	Make BHEL
KW	3000
Voltage	11 kV
Current	200 A
over speed	490
Speed	373
Noise level	85 dBA
Motor top	75 µm (micrometer)

TABLE IV
TECHNICAL SPECIFICATION OF STATION "A" & "B"

Pump Suppliers	WPIL	
Stations	(A)	(B)
Guaranteed design capacity (m^3/hr)	31000	30000
Guaranteed Total Head (MWC)	25.7	27.2
Shutoff head of the pump	39.15	39.78
No of Pumps	5 +1 pumps	4+1 pumps
Impeller type	Mixed low	Mixed Flow
Impeller dia at inlet (DI), outlet D(O) mm,	1397-1614	1172-1576
Impeller eye mm	Small-217	Large-404
Specific speed	4978*	4669**
Suction specific speed (NPSH)A	8111	7709
Suction specific speed (NPSH)R	10106	9889
Combined 1st Critical speed	1400	1400
2nd Critical speeds	2160	2160
NPSH (A) avail. at min. water level	13.4	13.93
NPSH (R) required	9.6	9.5
Thoma sigma σ	0.52	0.51
NPSH Margin Ratio	1.4	1.4

*High Specific speed pump; ** Low Specific speed pump

Study of High Noise & Vibration Problem

CW pumps at Station "A" have been experiencing high vibration and noise problems since commissioning of the units whereas CW pumps commissioned at Station "B" are working satisfactorily.

From the above technical specification, it is evident that specific speed selected for Station "A" pumps was high (i.e. 4978) whereas the selected specific speed for Station "B" was low (i.e. 4669). Hence, the major difference between the two specifications is specific speed only although the supplier for the pumps in both of these stations happened to be the same.

As has been brought out earlier while Specific Speed refers to the discharge characteristics of a pump, Suction Specific Speed, as the name implies, refers to the suction characteristics. The high specific speed generates high flow and low head whereas low specific speed generates low flow and high head.

In order to identify the root cause for high vibration and noise levels in the pumps at Station "A", one of the pumps was physically inspected and it was found to have high cavitation as shown in Fig. 16 and that too within a very short span of plant operation.

Fig. 16 Cavitation of Impeller

In order to ascertain the reasons for cavitation in the pump impeller, an exercise was conducted on CW pumps at Station "A" by raising the water level in the fore-bay to 8.0 meters from 7.6 meters. During this exercise of gradually increasing the water level in the sump, the vibration behavior of pump was recorded and it was observed at different load conditions that the overall vibration data at CW Pump#1A Motor NDE & DE bearings were exhibiting decreasing trend at 0% recirculation. The reduction in vibration levels to 488 µm peak to peak from 662µm peak to peak was observed by raising the sump level by 0.4 meter which is an indication that NPSH margin ratio ($NPSH_A/NPSH_R$) is improving. Further, with increase of water level in the sump, a reduction in noise levels was also noticed. This is an additional indication that the pump had started getting sufficient $NPSH_A$.

The vibration data and corresponding operational parameters were recorded at 470 MW at CW Pump # 1A at Station "A" on 19th July 2013 at two different sump levels namely at 7.6 meters and 8 meters level respectively are shown in Table V.

It is clearly shown that increase in sump level to 8.0 meters from 7.6 meters resulted in an appreciable reduction in vibration & noise levels. The pump was also cheeked for abnormal vibration if any by opening the recirculation valve 10% also.

It means that suction head $NPSH_A$ may be insufficient for particular impeller profile, (DI-1397 mm & DO-1614 mm), which is having high specific speed (Ns-4978). In other words, discharge head generated by this impeller profile (Ns-4978) selected by the pump supplier, was critical with available suction head ($NPSH_A$) which was leading to cavitation. Whereas, Station "B" pumps which had been commissioned with lower specific speed (Ns-4669) and having larger impeller eye diameter (DI -1172 mm & DO-1576 mm), are operating satisfactorily without any sign and symptoms of cavitation/internal recirculation. The impeller profile of CW pump at Station "B" is an example wherein impeller eye area is large and therefore there is no cavitation can be seen from Table VI and Fig. 17 (b), [27].

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TABLE V
VIBRATION DATA & OPERATION PARAMETERS TAKEN DURING THE STUDY

Motor NDE µm (micrometer)			Motor DE µm (micrometer)			Forebay Level in m	Recirculation			Operation parameters MW	Hz	m^3/h	Discharge Pressure in kg/cm^2
(H)	(V)	(A)	H	V	A	Meter	%	ΔP	ΔT°C	500	50.00	30000	1.9 ksc
218	662	146	86	488	22	7.6	0%	4.8	14.0	470	49.80	X	1.7 ksc
206	488	130	98	298	112	8.0	0%,	7.0	14.0	470	49.80	X+2500	1.8 ksc
150	452	144	98	314	110	8.0	10%,	4.0	11.5	*326	50.17	X	1.79 ksc

H-Perpendicular to discharge, V-Parallel to discharge, A-Axial,
*Load in Megawatt reduced, Flow in Quantity X =30,000 m^3/h : Discharge Pressure in ksc ; ΔP: MWC stands for Meter of Water Column (Pressure Unit)
For BHEL design 500 MW; Vibration in µm –micrometer (peak to peak); Velocity in mm/s peak.

TABLE VI
DIMENSIONS BEFORE & AFTER IMPELLER REPLACEMENT

Specific Speed (Ns) & Status	Impeller DI in mm	Impeller DO in mm
Station "A" 4978 (with cavitation)	1397	1614
Station "B" 4669 (with no cavitation)	1172	1576
Modified Impeller installed at Station "A" similar to Station "B" (with no cavitation)	1172	1540

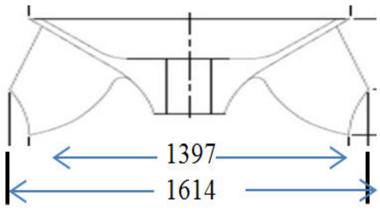

Fig. 17 (a) High Ns impeller [27]

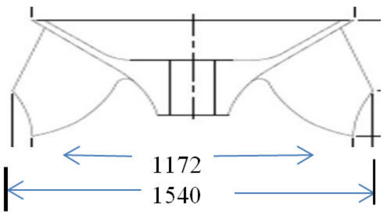

Fig. 17 (b) Low Ns impeller [27]

"Cavitation usually occurs in the eye region of the impeller, and if the eye area is increased - velocities are decreased, and the resulting higher static pressure provides a better safeguard against vaporization (cavitation). Therefore, a larger impeller eye seems like a way to lower the "$NPSH_R$". Accordingly, it was decided to use larger impeller eye at Station "A" similar to that at Station "B". Subsequently, one of the CW Pumps has been replaced with a new modified impeller having dimensions i.e. DI-1172 mm & DO-1540 mm, (as shown above larger impeller eye), which is operating within just satisfactorily vibration limits since last almost one year.

The maximum vibration readings recorded on 15th October 2014 at Motor NDE bearing of the same Pump were 193 µm peak to peak and velocity i.e. 6.42 mm/sec peak at 8 meter sump level and 175 µm peak to peak and velocity i.e. 6.55 mm/sec peak at 7.8 meter sump level respectively as shown in Fig. 18.

The motor solo run had slightly high vibration of the order of 146 µm peak to peak which could have been brought down to an acceptable limit to reduce pump vibration further. The impeller replacement resulted in substantial reduction of noise level, but slight increase in current consumption to 190 ampere from 180 ampere.

Fig. 18 Sump Levels

In order to check effect of system resistance, total pressure drop across the condenser of similar machines was collected and compared against the normally specified value of 4.05 MWC for 500 MW units' condenser. From the analysis of the operational data (pressure drops across condenser) at Stations "A" and "B", it is evident that although the pressure drop across the condenser in Station "B" is higher than that at Station "A". The CW pumps of Station "B" experiencing a higher system resistance but they are not facing vibration on account of cavitation. (See in Table VII).

TABLE VII
PRESSURE DROPS IN CONDENSERS AT STATION "A" & "B"

Pressure Drops				Normal ΔP MWC	
Units		PASS (A)	PASS (B)	4.0	4.0
Station "A" Stage-I,	Unit #1	4.8	4.8	Normal	Normal
Station "B" Stage-II,	Unit #6	6.4	7.0	Moderate chocking	

VII. CONCLUSION

The reason is very evident; NPSH margin ratio was critical at high Ns pump impeller at Station "A" however, the same was suitable for low Ns pump impeller. Pump was not getting enough suction, as a result vaporization was taking place at low pressure areas inside the impeller which led to bubble formation. These bubbles created in the suction side normally go to discharge side where pressure is high. Implosion is taking place creating pitting on the suction components as well as on the impeller which resulted in cavitation, exhibiting high noise and vibration too. The raising water level in forebay by

0.4 meter improves NPSH margin ratio which resulted in reduction of noise and vibration levels. It is confirmed that the larger impeller eye helped in improvement of NPSH margin ratio although with marginal increase in power consumption.

Methods for Improvement of NPSH Margin Ratio

The improvement in NPSH Margin are generally limited in an existing installation, there are still some choices available. Changes to the system that will increase the NPSH available include:

- Increase the supply tank elevation or the water level in sump & Lower the pump elevation.
- Eliminate any flow restrictions in the suction piping (such as a strainer).
- Operate at a flow rate less than the pump BEP.
- Install an inducer, if available.
- Change to low $NPSH_R$ impeller, if available.
- Operate the pump at a slower speed (if driven by a VFD), or install a VFD.
- Lower the water temperature thus reducing vapour pressure or add booster pump.

VIII. Recommendations

Investigations established that cavitation was taking place in the pump which is due to high Ns or inadequate $NPSH_A$. The impeller profile should be selected in such a way to suit available suction head to avoid cavitation.

A. Civil Aspects

As discussed in the foregoing, the general concept is that $NPSH_A$ should be greater than $NPSH_{R,}$ to avoid suction recirculation / cavitation. The question then arises, how much margin of $NPSH_A$ over $NPSH_R$ is enough, the answer to the question is that it should be greater than >1.5. Inadequate NPSH margin may affect pump head, noise, and vibration – all leading to reduced pump service life and higher maintenance costs. For adequate $NPSH_A$ deepening of suction trench is required, not the entire sump.

B. System Engineering Aspects

Technical specifications of CW pumps for new projects may be revisited for keeping enough NPSH margin ratio for better pump reliability & efficiency. Based on the experience gained at Station "A", it is generally good practice to add an additional 3-5 feet of $NPSH_A$ over the margin values to account for disparities between test data and actual site conditions.

C. Condition Monitoring Aspects

Root cause failure analysis has to be done before deciding action for replacement of pump & its profile. Condition Monitoring is probably the most important tool in these pump problem and has become accepted and proven worldwide in various industries.

D. Selection of Quality Pump Aspects

Actual plant studies have shown that N_{SS} above 9000, pumps reliability begins to suffer – exponentially, therefore, while selecting a pump care must be taken to keep suction specific speed (Nss) value below 8500 for cavitation- free operation.

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