VISUAL STUDIES OF CAVITATION IN PUMPING MACHINERY

by

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ABSTRACT

The visual study of cavitation in pumping machinery now plays an important role in its development—particularly where high stage energies are concerned.

The incomplete picture provided by traditional head decay tests is outlined and the need for detailed visual study is presented. The methods can help differentiate good machines from bad, but can only hint at how long either one might last.

INTRODUCTION

Cavitation is one of the most crucial aspects of any pump's performance and cases of serious damage (Figure 1) or plant outage resulting from it are all too well documented. But how can cavitation be adequately defined for both the vendor and user alike? To answer this it is necessary to describe the relationship between pump performance and pump inlet pressure or net positive suction head available ($NPSH_A$). This is best shown as a three dimensional surface and net positive suction head available is portrayed in Figure 2. Two regimes are evident. First, there is Domain 1, in which pump performance is quite independent of the NPSH. Here, reductions in NPSH produce no perceptible change in the flow/head relationship of the machine. Secondly, there is Domain 2, in which the pump flow/head relationship is very strongly dependent upon NPSH. Here, reductions in NPSH result in simultaneous decays in pump output.

These two zones are loosely described as the "non-cavitating" and "cavitating" zones, respectively. The transition between

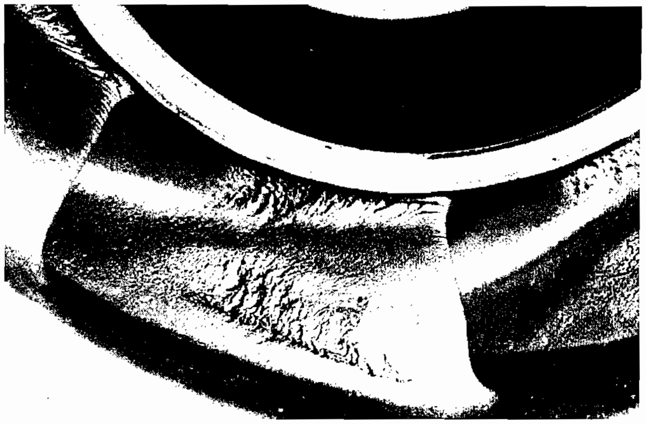

Figure 1. Typical Cavitation Damaged Impeller.

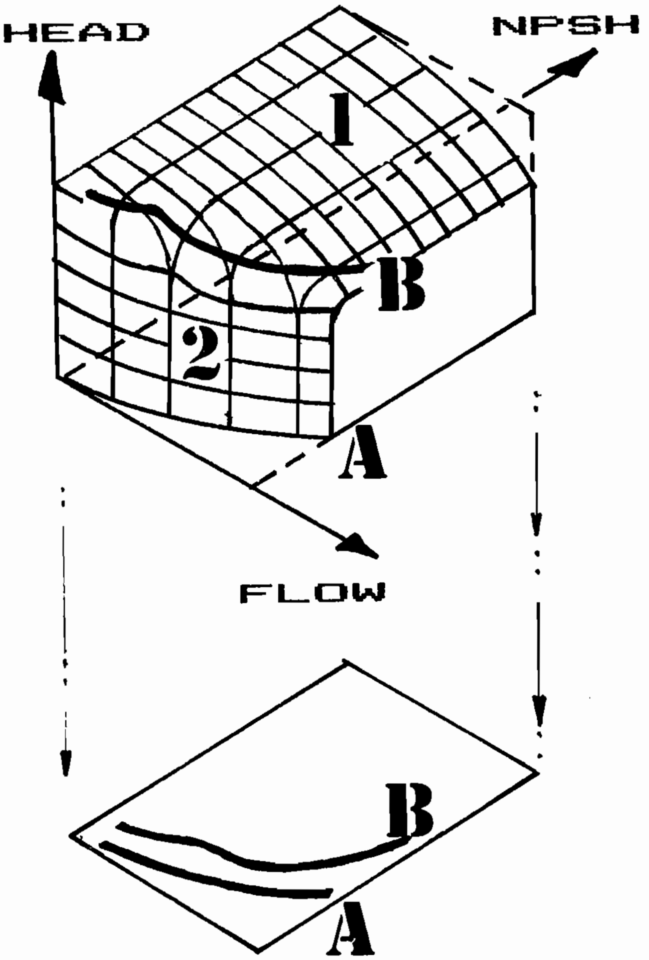

Figure 2. Complete Relationship between Pump Flow, Head and NPSH. Projected to show conventional NPSH curve presentation.

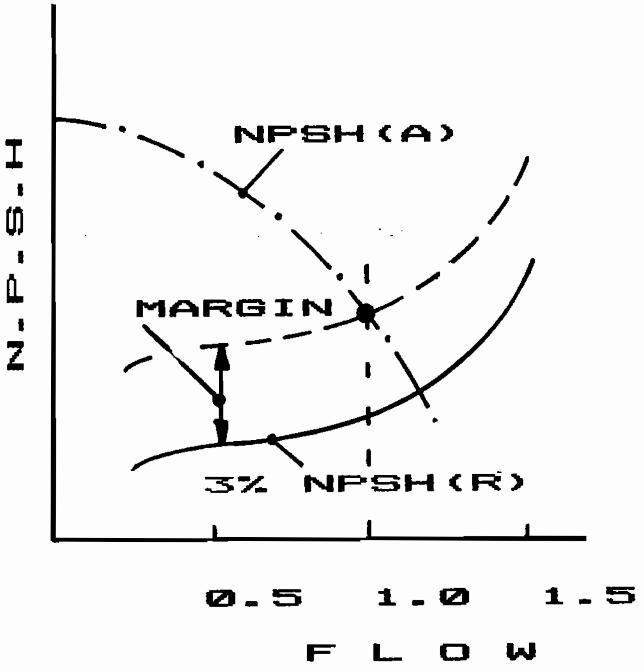

Figure 3. Early NPSH Margin Approach.

them is marked by a definite discontinuity on the three dimensional surface, and in the past this has conveniently helped describe the onset of cavitation. The most frequently invoked definition is that level of $NPSH_A$ at which the pump performance has decayed some three percent from the non-cavitating value [1, 2]. This is indicated by line B on Figure 2.

It would appear reasonable to suppose that, if some safety margin were applied to line 1, so as to bring it wholly on the the flat, so called "non-cavitating" domain, this would represent the threshold of freedom from cavitation damage. Such an approach was found to be quite effective in the past. However, it became apparent that:

- A constant margin (Figure 3), irrespective of pump type or speed, is not entirely satisfactory.
- A constant margin, irrespective of operating point, is not always effective, either.

FLOW VISUALIZATION STUDIES

Techniques

When designers became aware of the problem, they found a number of tools were available to help them towards a solution. Perhaps the most obvious technique was that of flow visualization. Such studies are difficult and expensive to conduct and actual production machinery can rarely be used because of inadequate access to the impeller eye. As a result, most cavitation studies have been carried out on special laboratory machines.

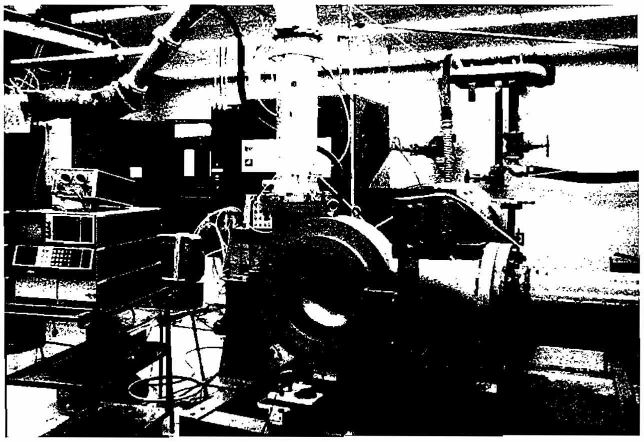

Figure 4. A Modern Flow Visualization Facility.

A typical flow visualization rig is shown in Figure 4. Visual access is obtained through a plexiglass cover that simulates the inlet duct on its wetted side. Illumination of cavitation events is achieved with a high intensity strobe light synchronized to the shaft speed in order to 'freeze" the image. Permanent records of the events may be made with conventional camera techniques or, in special cases, high speed movie cameras. Photographs and diagrams of several types of cavitation are presented in Figures 5, 6, 7 and 8.

Typical Results

Every impeller responds differently in detail, but a number of general similarities exist. The condition at which cavitation first becomes visible, when suction pressure is reduced, is known as the "point of inception." The cavitation inception curve (Figure 9) possesses a number of interesting properties, which can indicate several characteristics of the impeller inlet design.

- Cavitation inception invariably occurs at NPSH levels significantly higher than those for three percent performance decay.

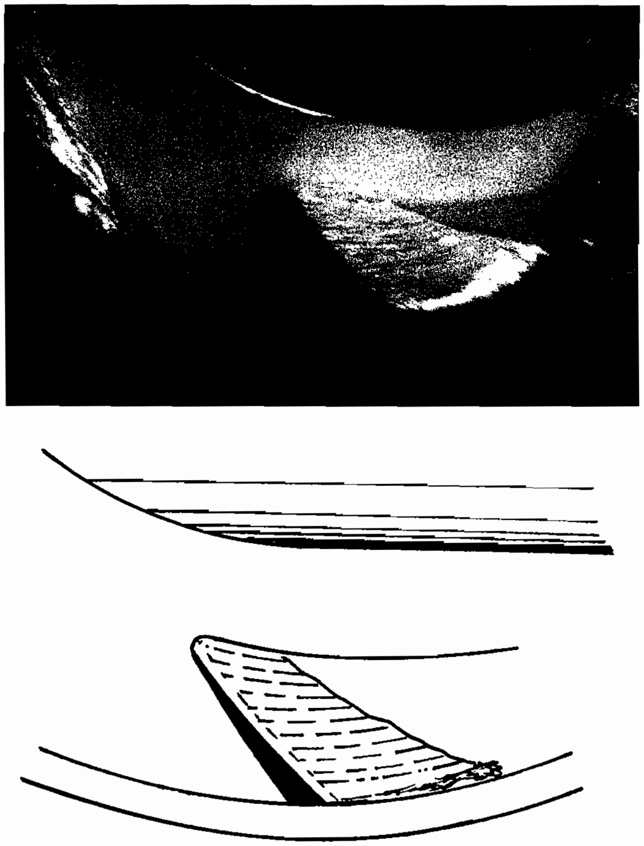

Figure 5. Sheet Cavitation.

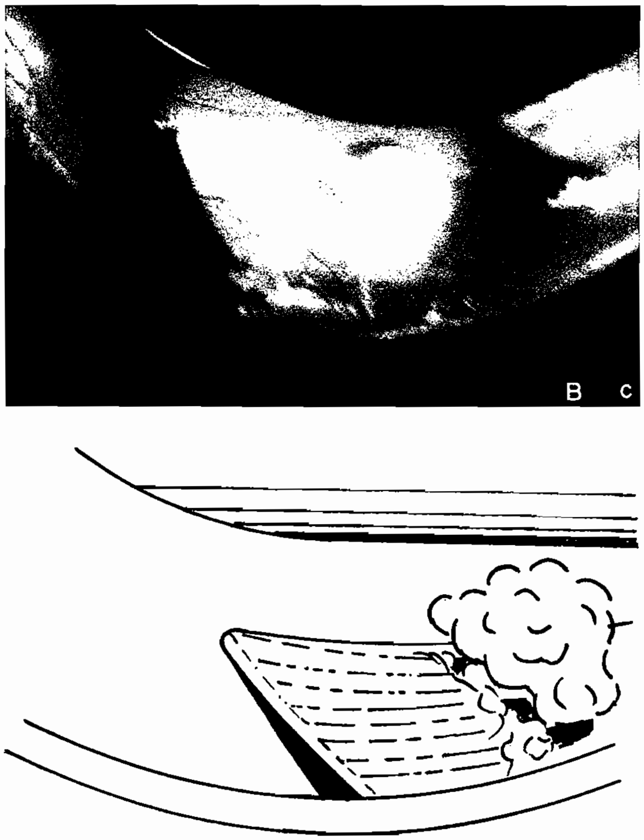

Figure 6. Sheet and Cloud Cavitation.

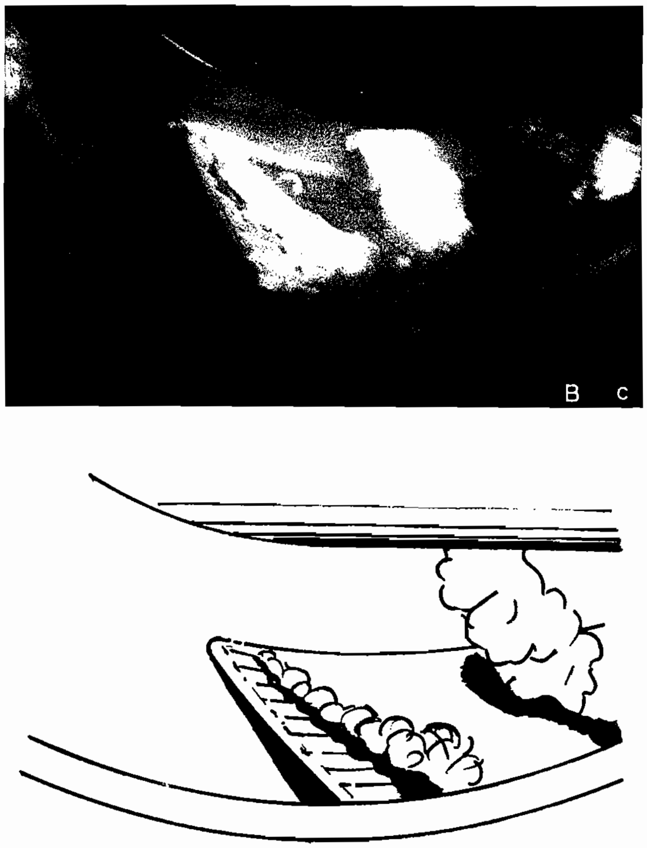

Figure 7. Vortex Cavitation.

Figure 8. Three Percent Decay Cavitation.

Referring to the three dimensional surface concept (Figure 2), the inception points always appear to lie in the so called non-cavitating domain.

- The inception NPSH line is definitely *not* parallel to the three percent decay line, but rises steeply either side of some minimum value (Figure 9). At flows less than design, cavitation is usually limited to the low pressure (readily visible) surface of the impeller blade. At high flow, the cavity normally exists only on the pressure surface and, hence, requires special techniques to access its image.
- The minimum point on the inception curve indicates the optimum flowrate for that particular eye geometry. Here the flow incidence angle will be zero and the condition is often referred to as the shockless entry flow [3]. In a normal machine, this will closely coincide with the design flow.

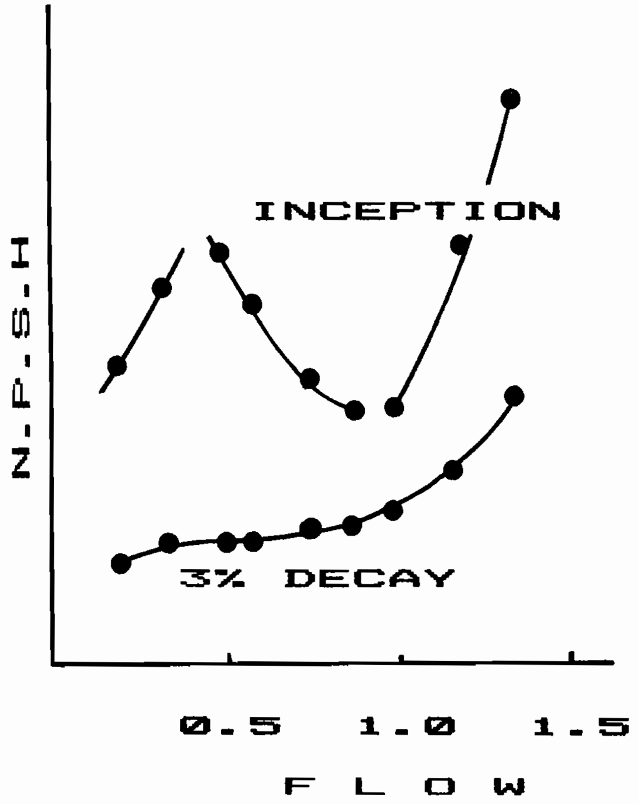

Figure 9. Typical Flow Visualization Results.

- At very low flowrates, the inception NPSH line begins to fall again. This is associated with the collapse of stable inlet flow conditions and the establishment of backflow or re-circulation [4, 5]. Simultaneously, there may be a shift in the cavity shape and position away from the impeller outer diameter and inwards towards the shaft axis.

What Results Indicate

- At the inception point, the head of the machine has not perceptibly decayed. In fact, the NPSH can be further reduced by a significant amount before head measurable decay occurs (Figure 10). In simple terms, the complete cavitation performance of a pump is comprised of two distinct mechanisms.
- As the NPSH is reduced below the inception point, the cavity grows in length without perceptible performance decay. This is the first mechanism, shown as "B" on Figure 10.
- As the downstream end of the cavitation begins to invade the vane to vane "throat," the machine begins to "choke" and performance decay is rapid. This is the second mechanism ("D" on Figure 10).

In practice, the three percent decay criterion is much more closely linked to the second "choke" mechanism; it is hardly surprising that it indicates very little about inception performance. In fact, machines with nominally similar three percent decay performance can often have significantly different inception curves.

- At flows within the "vee" shaped inception zone of Figure 9, cavitation is generally of a stable "sheet plus cloud" configuration (Figure 6). The cavity is located close to the maximum eye diameter and maximum damage occurs close to the "cloud" zone.
- On impellers operated at low flow (within the backflow or re-circulation regime), the cavity bubble configuration is highly unstable. The damage can be quite severe on the pressure side of the blade and is often located nearer to the minimum eye diameter. This agrees with the shift in cavity position noted previously.
- When impellers running within the backflow regime have their NPSH further reduced towards that for three percent head decay, then the relatively stable cavity becomes unstable as the impeller successively chokes and unchokes at very low frequency—typically only a few Hertz. The mechanism for this condition has been well documented [6, 7] and required flow visualization techniques to formulate its explanation. Further reduction of NPSH below the three percent head decay value tends to eliminate this "surging" and again produces a long stable cavity (Figure 8). Complete mapping of this so called "surge zone" adds a further detail to the three dimensional performance map (Figure 11).

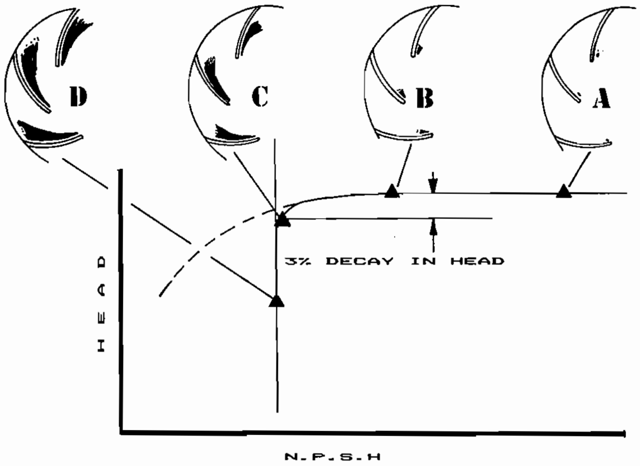

Figure 10. Cavity Growth Related to Head Decay.

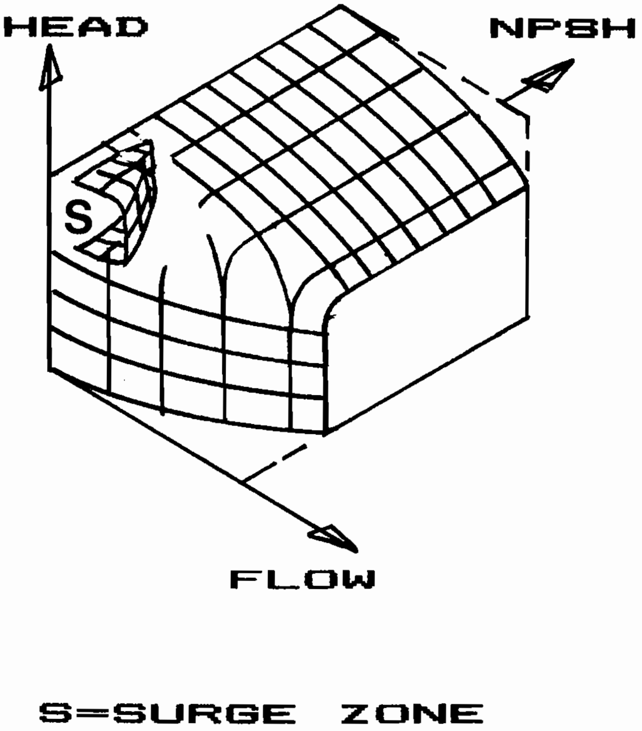

Figure 11. Cavitating Surge Regime Related to Flow/Head/NPSH.

What Results Do Not Indicate

Since the principle objective of visual studies is to lead to improved impeller reliability, it is perhaps surprising that the technique on its own can give no direct indication of finite life expectancy. In other words, assessment of a particular cavity geometry cannot be readily transformed to a damage rate. Only two definite factors emerge from the technique.

- The site NPSH required for zero damage and infinite cavitation life. This should correspond to the inception NPSH line.
- Different designs may be ranked in order of relative life probability, but no *absolute* scale of life can be attached to them.

The technique adds little to the understanding of three percent decay performance, because the flow patterns at these conditions are very irregular and confused. However, since the relevance of three percent data is questionable in any event, this is perhaps of no consequence.

Cavitation Damage Investigation

Flow visualization is not an absolutely essential ingredient in formulating impeller life estimates. Any manufacturer with a substantial and detailed service history can analyze its database to equate service life with impeller geometry and fluid conditions. Such a study shows that the threshold line for finite impeller life (five years) is similar to, but lower than, the inception line (Figure 12). This line may then be related to the three percent decay line by a margin factor "R" or to the inception performance by a factor "r". Both "R" and "r" are found to depend on impeller materials, fluid properties and fluid/impeller inlet velocity [8].

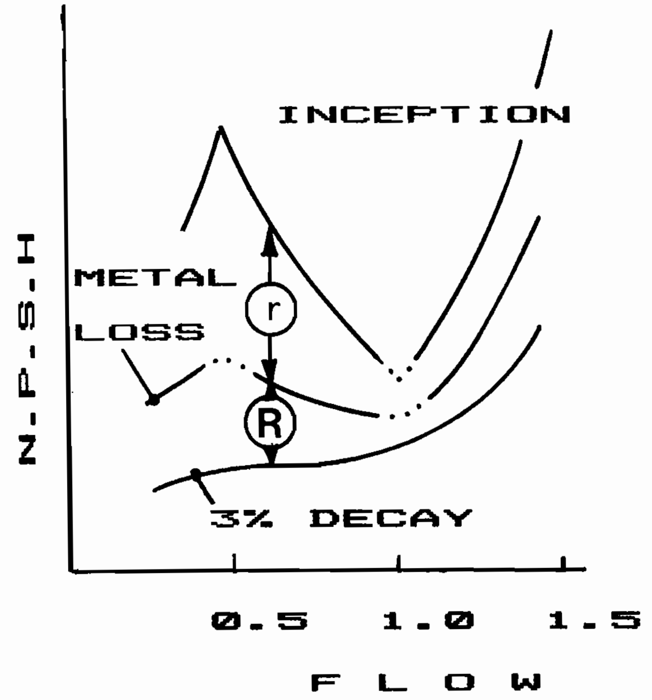

Figure 12. Finite Metal Loss Curve Related to Inception and Three Percent Decay Curves.

The influence of materials is obvious. Everyone would anticipate that under identical visual cavitation conditions, a cast iron impeller would be damaged more readily than a stainless steel impeller.

Various laboratory techniques exist for ranking materials according to resistance to a standard cavitation situation. Typical results from a vibratory tester are shown in Figure 13 [9].

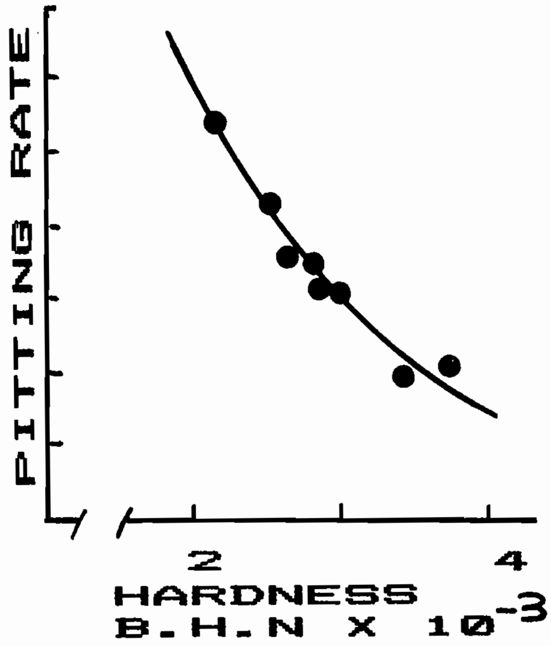

Figure 13. Correlation of Vibratory Cavitation Test Results for Martensitic Stainless Steels with Brinell Hardness Numbers. This correlation is not necessarily the same for other types of materials.

This relative reference framework does not easily help put visual cavitation data into perspective in terms of true impeller metal loss rates. This is because several types of cavitation or bubbles can coexist in different combinations within a pump impeller and the combination will change with flowrate (relative to the design point). The different types are: sheet cavitation, cloud cavitation, and vortex cavitation.

Within the "vee" of Figure 9, stable sheet cavitation is most commonly observed (Figure 5). At the downstream boundary of the sheet, bubble clouds are often seen (Figure 6) and it is when these bubbles collapse on or near the impeller surface that the high impact pressures predicted by Rayleigh [10] are experienced. Damage is most often observed to occur at these collapse points—rarely on the blade areas covered by sheet cavitation. To the left of the "vee", an even more complex cavity system is established (Figure 7). Here the interface between the rejected backflow at the outer eye diameter and the incoming flow near the hub generates highly unstable "shear vortices." At the vortex core, the fluid vaporizes into conglomerations of bubbles, and this "vortex cavitation" has much the same damaging potential as cloud cavitation. Given the unstable and uncertain path of the vortices, the bubbles collapse and do damage at unexpected locations, such as on the blade pressure surface, or in the blade-shroud fillet area.

A number of analogue techniques have been developed to address the problem of relating such observations to impeller life.

Coatings

With this technique, the visible blade surface is coated with ink or paint—occasionally two layers of different colors may be applied to slightly refine the measurements. Under cavitating conditions, the top layer is removed and with some experience it is possible to correlate the removal rate with field experience.

Accelerated Erosion

An alternative strategy is to manufacture the impeller in a material that is highly susceptible to cavitation damage—

aluminum is a popular choice. This technique can be a good indicator of the field damage location or intensity and shows that the vibratory data portrayed in Figure 13 is only qualitative when it comes to predicting life.

Hydraulic Design Implications

The general pressure field near the impeller blade inlet edge can be expressed in NPSH terms as:

$$NPSH_i = Cb(i) \times \frac{Wl(t)^2}{2g} + Ca \times \frac{Cml^2}{2g} \qquad (1)$$

where

$NPSH_i$ = required NPSH at inception
$Wl(t)$ = relative inlet velocity
$Cb(i)$ = a blade cavitation co-efficient
Cml = mean absolute inlet velocity
Ca = entry coefficient (typically 1 to 2)

Visual studies confirm theoretical predictions [11, 12] that the Cb(i) value should lie between 0.25 and 0.4, but also show that in small, poorly cast impellers, this value may reach 0.7 to 0.9!

At a given shaft speed and flow, the fluid relative velocity W1(t) is a function of the impeller eye diameter. Equation 1, therefore, may be evaluated for a range of eye diameters, in order to determine the eye diameter for minimum $NPSH_i$ (Figure 14). The corresponding vane angle will ensure that the minimum of the resulting inception curve lies at the design flow. As ever, the success of this approach depends on the correct choice of coefficients. Typical values derived for a range of blade thickness distributions are shown in Figure 15.

TYPICAL Cb (i)	PROFILE
0.45 TO 0.7	
0.35 TO 0.45	
0.20 TO 0.35	
0.10 TO 0.20	

Figure 15. Typical Blade Inception Coefficients for Different Inlet Edge Profiles.

Cb(i) values as low as 0.25 require some form of manual finishing, whereas commercially cast impellers might achieve 0.35 at best. Sand castings in large machines may achieve 0.45 to 0.55.

This data may be translated into practical guidelines of interest to pump designer and user alike, simply by using Equation (1) to express the relationship between blade inlet angle, inception specific speed, and blade cavitation coefficient. This is shown in Figure 16 for over hung impellers having no shaft obstruction through the eye.

$$Nss(A) = \frac{N\,Q}{(NPSH_A)^{0.75}} \qquad (2)$$

where

N = shaft speed cpm
Q = flow/eye usgpm
NPSH(A) = true site NPSH available, (with no margin) ft

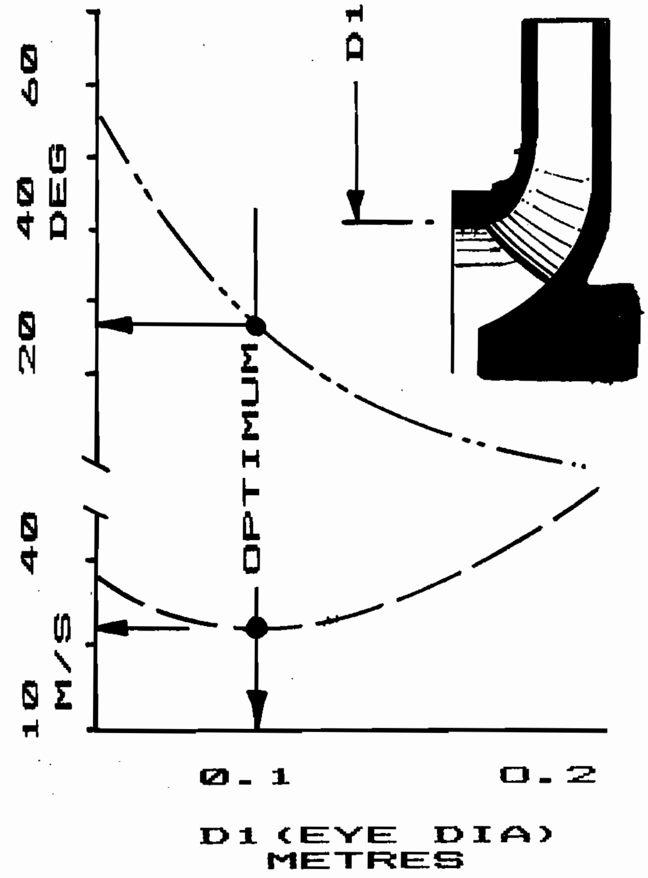

Figure 14. Optimization of Eye Diameter for Minimum Relative Velocity (W1) and, Hence, Minimum Inception NPSH.

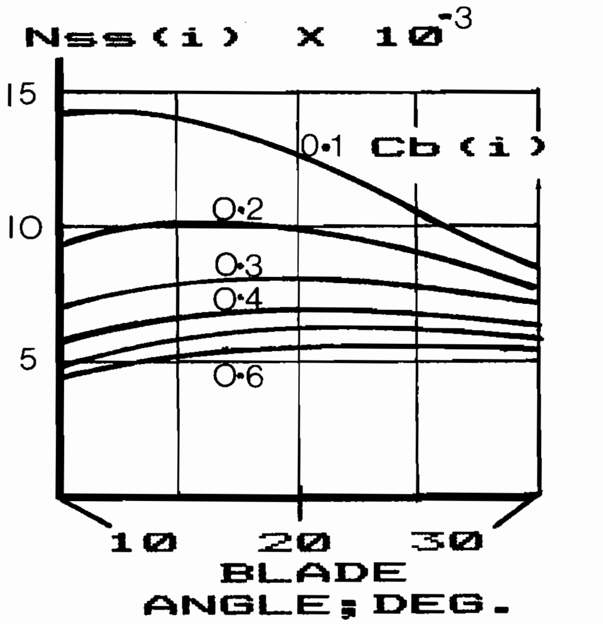

Figure 16. Simplified Zero Incidence Inception Performance for Overhung Impellers.

Table 1. Design Differences for Axial and Side Entries.

	B_1 TIP	B_1 HUB
OPTIMUM, AXIAL ENTRY	18°	22°
OPTIMUM SIDE ENTRY	21°	16°

Should site NPSH conditions dictate a suction specific speed in excess of 10,000 (i.e. if site $NPSH_A$ is used in Equation (2) instead of $NSPH_i$, then Figure 16 would indicate that some cavitation is unavoidble, because Cb(i) levels lower than 0.2 prove difficult to achieve. This does *not* mean that significant damage is also inevitable. On the other hand, if $N_{ss}(i)$ turns out to be around 6000, then cavitation free performance should be possible from all but the smallest or poorest designs.

One important disclosure of visual studies is the critical nature of the inlet duct ahead of the impeller. Axisymmetric conditions are obviously ideal (i.e., end suction entry). However, the effect of side entry conditions (typical of most high energy machines) can be quite dramatic. Such entry approaches substantially modify the radial velocity distribution and may also introduce some degree of swirl into the flow field. Consequently, the optimum inlet geometry for side entry conditions may not be the same as that for axial entry. This is demonstrated in Table 1, which shows the geometry of the same boiler feed pump impeller optimized for axial entry and then side entry conditions. This emphasizes that the full wetted inlet profile must be modelled if the results of rig testing are to have any validity.

CONCLUSIONS

The impeller eye of any pump is perhaps the most critical design zone since failure at this location means failure to the entire machine. Success is not assured just by meeting the three percent decay criterion—often this must be bettered by substantial amounts, if long term damage avoidance is to be guaranteed.

Flow visualization can indicate site NPSH levels that virtually assure damage free operation. It must be said, however, that such levels would be considered excessive by many users, who are usually prepared to relax the approach in return for finite impeller life.

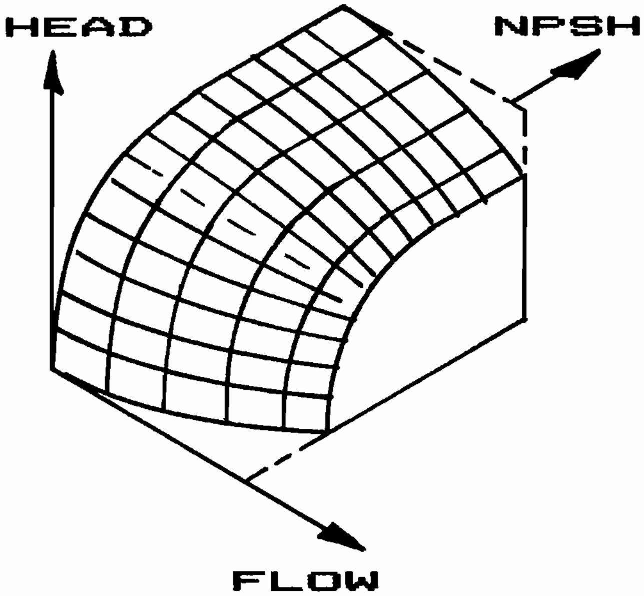

Figure 17. Complete Pump Flow, Head, NPSH Relationship for Low Solidity Impellers, Typical of Mixed/Axial Flow Machines and Sewerage/Self Priming Pumps.

The pump designer would want to run flow visualization testing in several areas, the most notable would be those where very high reliability is called for—typically boiler feed applications. On the other hand, high speed machines operating under marginal suction conditions (i.e., seawater injection pumps) would also be candidates. The techniques may also be appropriate for less sophisticated machines. For example, sewage pumps and/or self priming pumps are often of such extreme hydraulic design that they do not demonstrate clearly defined cavitation onset (there is no distinct break in the three dimensional head, flow, NPSH surface, only a steady reduction as shown in Figure 17. With such machines and all others having low solidity impellers (i.e., mixed and axial flow pumps), flow visualization may be the only sure way of defining the cavitation threshold.

There is little doubt that flow visualization testing has had a significant influence on mainstream hydraulic design. Achievement of even higher speeds and/or reliability will require deeper insights into the cavitation process. Visual cavitation studies will continue to be one of the essential tools required in reaching this goal.

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