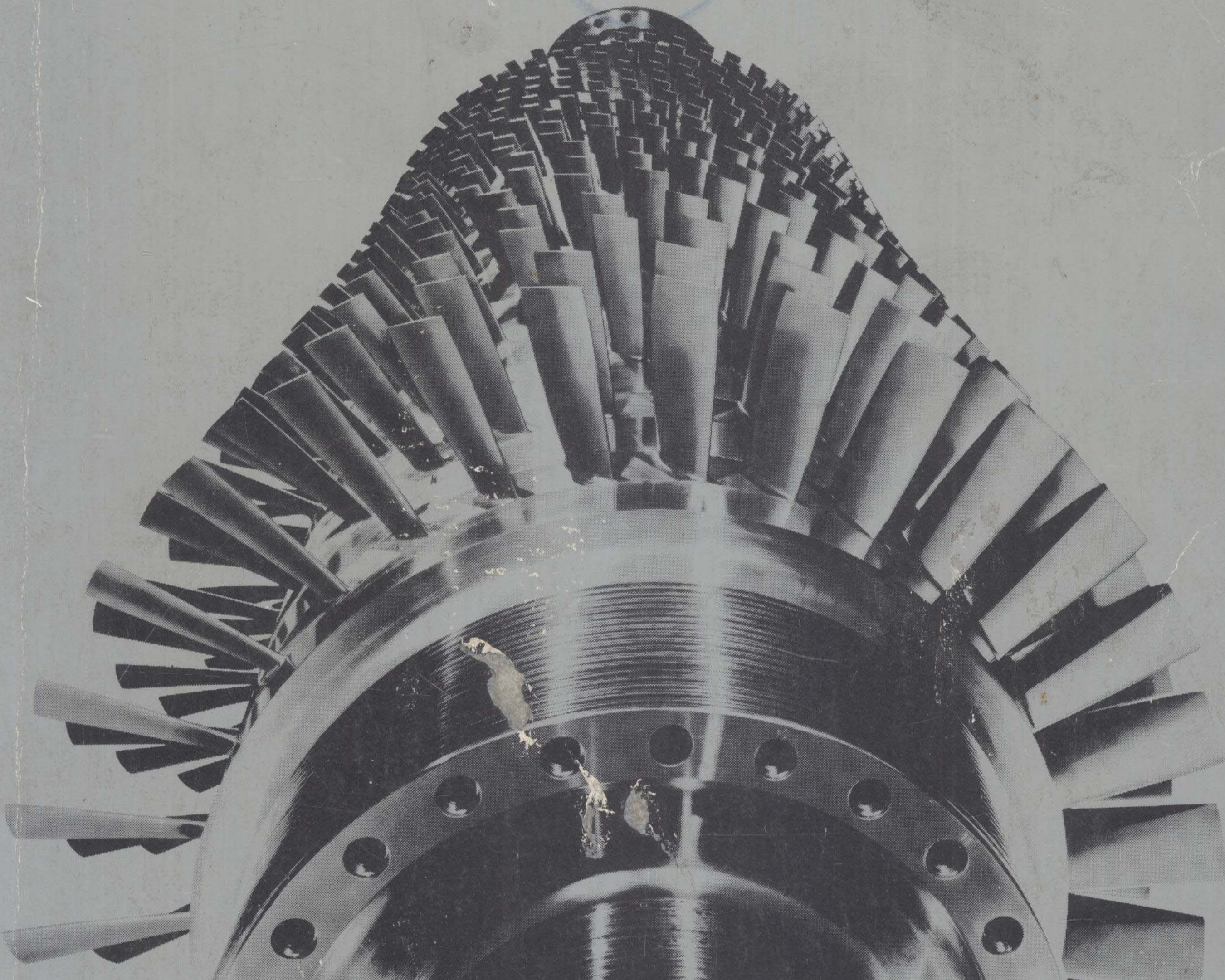
Fluid machinery for the oil, petrochemical and related industries



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IMechE 1984–2

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SECOND EUROPEAN CONGRESS ON FLUID MACHINERY FOR THE OIL, PETROCHEMICAL AND RELATED INDUSTRIES

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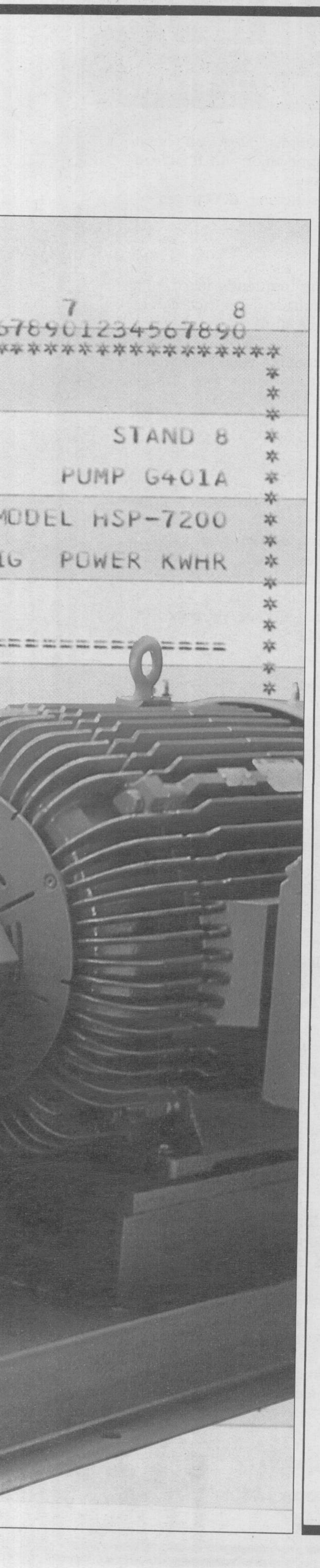

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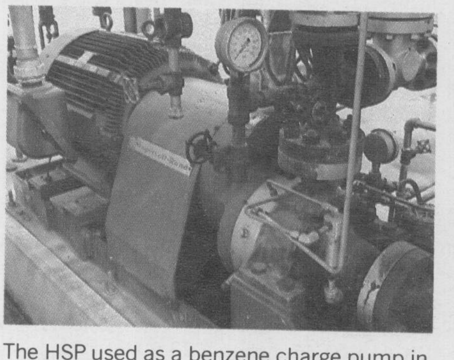

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CONTENTS

Erosion free operation of cavitating pumps

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SUMMARY

A limited amount of cavitation can be acceptable in an operating pump when it is ensured that no harmful effects will occur. A loss of hydraulic performance due to cavitation should however be avoided and the cavitation erosion rate should not exceed a given criterion.

The cavitation erosion resistance of materials differs substantially and careful selection is essential. It is suggested that material selection be related to the pump impeller eye peripheral speed in view of its relationship to the energy level in the pump. This approach complements a previously published design optimisation procedure; it appears that a cavitation erosion criterion can overrule an impeller eye diameter choice resulting from flow analysis but depends on the material selection and the blade cavitation factor.

The method presented is the result of a development process complemented by experience from the authors' company data bank.

1 INTRODUCTION

Cavitation is a phenomenon which limits the application of pumps; either performance is affected or life is reduced. The most economical pump selection (minimum size, maximum speed) should be very close to this physical limit, implying that basic knowledge of these limitations is required which should be combined with experimental experience.

A study of cavitation in pumps and valves has been undertaken in the VMF-Stork hydraulic laboratory and results of these studies have already been published (see refs. 4 and 5). These publications discussed the phenomenon of cavitation and design technique to reduce the formation of cavitation bubbles (decrease in cavitation inception). The authors now present their approach to the application of pumps with an acceptable amount of cavitation.

A limited amount of cavitation can be acceptable when it is ensured that no harmful effects will occur. The loss of hydraulic performance (pressure and/or efficiency drop) should however be avoided and thus determines the lower NPSH limit. If performance effects are excluded the main economic criterion becomes pump life related to cavitation erosion.

Erosion rate, however, is related to material which has a fixed resistance to cavitation erosion. It is proposed that this resistance be related to the impeller eye peripheral speed because of its relationship to the pump energy level. A threshold value U_{cr} has been established for various materials used in pump practice.

In ref. 5 a calculation method is presented to determine the optimum impeller inlet geometry based on flow analysis. The criterion for erosion free operation is added here to finalise the optimisation process. By implication material choice is an important parameter in this process.

2 DEFINITIONS

2.1 Cavitation

Cavitation is the process of formation of vapour bubbles in a liquid when at a constant ambient temperature it is subjected to a static pressure which falls below the vapour pressure. The bubbles subsequently implode where the pressure is increased above the vapour pressure causing very high local pressures, vibration and noise. The zone in which cavitation occurs can be either steady or unsteady and usually disturbs the main flow.

Net Positive Suction Head (NPSH) is the total head at a given point reduced by the vapour pressure of the liquid:

$$NPSH = \frac{p_{static} - p_{vapour}}{\rho g} + \frac{V^2}{2g}$$

where p = pressure
V = velocity
ρ = density
g = acceleration of gravity

When the NPSH is related to the point at which vapour bubbles are formed it can be concluded that NPSH for cavitation inception is proportional to velocity squared ($p_{static} = p_{vapour}$).

2.2 Cavitation in pumps

Cavitation occurs in those pump regions where the local static pressure equals the vapour pressure, e.g.:

at the impeller inlet where the static pressure decreases because of the increased liquid velocity (see figure 1);

in the core of local whirls generated by rotational velocities in the flow and/or flow separations due to deviation of a flow pattern and passage geometry. This situation can be caused by incorrect geometry or a changed flow pattern (stable or unstable) at off design conditions;

in the gap between impeller blades and pump casing with unshrouded impellers.

Cavitation erosion occurs where vapour bubbles implode and where the intensity of the implosions generates an energy level in excess of that of the material threshold for cavitation erosion.

The cavitation behaviour of a pump is usually defined as the NPSH at the suction flange corrected by a static head to the centreline level of the pump. During cavitation, it is assumed that the vapour bubbles form at the impeller inlet. It is obvious, therefore, that the defined NPSH is not related to the point in the pump at which cavitation occurs. For analysis of pump cavitation, the definition of NPSH becomes: (see figure 1)

$$NPSH = \frac{p_{stat\ f} - p_{vapour}}{\rho g} + \frac{C_f^2}{2g}$$

$$NPSH = \frac{p_{stat\ o} - p_{vapour}}{\rho g} + (1+k_1)\frac{C_o^2}{2g} + k_2\frac{W_o^2}{2g}$$

where: p = pressure
C = absolute velocity
W = relative velocity
k_1= loss coefficient inlet passage
k_2= blade cavitation coefficient

For incipient cavitation it is assumed that vapour pressure equals static pressure, therefore:

$$NPSH_i = (1 + k_1)\frac{C_o^2}{2g} + k_2\frac{W_o^2}{2g} \quad \text{------ (1)}$$

From this formula we conclude that NPSH is proportional to velocity squared. The indicated velocities are proportional to the dominant peripheral velocity 'U', indicating that:

$NPSH_i$ is proportional to U^2

When related to a pressure drop criterion, this relationship of NPSH to speed is less clear; experiments show that:

$NPSH_\beta$ is proportional to $U^{1.6}$ to U^2

Two NPSH concepts are in common use:

NPSH(R) = NPSH required, defined by the pump geometry and related to a specified criterion e.g. visual cavitation, efficiency or pressure drop, or erosion-free.

NPSH(A) = NPSH available in the system in which the pump is to operate.

For satisfactory pump operation, it is essential that NPSH(A) is greater than or equal to NPSH(R).

When considering a cavitation criterion for a pump for which it is ensured that no harmful effects will occur, the definition of NPSH(R) should be:

$NPSH(R)_{e.f.}$ = NPSH required at which the pump operates smoothly and trouble-free.

Trouble free operation means:

No unacceptable vibration or pressure pulsations due to cavitation;
No pressure or efficiency drop;
No unacceptable cavitation erosion damage.

When this definition is used it is permitted that $NPSH(A) = NPSH(R)_{e.f.}$

This definition of $NPSH(R)_{e.f.}$ however is not complete. Acceptance criteria for vibration, pressure pulsation and erosion must be stated as must the operating flow limitation for the pump and its required life.

Acceptable pump vibration levels are defined by International Standards. However, like noise and pressure pulsations, the acceptance criteria are not related to cavitation behaviour. It is important, therefore, that the required levels are agreed in the pump contract.

There is, similarly, no standard acceptance criterion for cavitation erosion. The following combination of criteria is proposed and is the basis for the method presented in Chapter 4.4.:

An acceptable amount of cavitation erosion after 40 000 hours' operation permits an impeller weight loss given by the following formula:

$$\Delta G = 1,5 \times 10^3 \times z \times D_1$$

where ΔG = weight loss (gr.)
z = number of blades
D_1 = impeller eye diameter (m)

Cavitation erosion after 40 000 hours' operation should not lead to a head loss greater than 1%.

3 CAVITATION DETECTION

The phenomena which characterise cavitation also influence the method used for its detection and the criteria used in its quantification. (see figure 2).

3.1 Visual observation of cavitation bubbles

The development of vapour bubbles and their implosion can be observed by directing stroboscopic light through an observation window into a pump. This is usually only possible in a model pump. The NPSH value at which the first bubbles become visual is defined as "incipient visual cavitation", $NPSH_{i.v.}$ This condition is difficult to establish so the criterion "visual cavitation" is also used in which the NPSH value is defined as that at which visual cavitation occurs over a given surface area of the pump, normally the impeller blade.

3.2 Noise analysis

During cavitation a crackling noise can be heard due to bubble implosion. It should be possible, therefore, to detect cavitation acoustically if the measured noise level is related to that under non cavitating conditions. Acoustic detection of cavitation can clearly establish its inception: $NPSH_{i.a.}$: This NPSH level, however, depends upon the frequency considered; also the shape of the noise level curve related to the NPSH depends upon the frequency.

3.3 Determination of performance reduction

During cavitation a pump impeller handles a mixture of fluid and vapour or gas. The presence of bubbles affects the performance by blocking the impeller channels causing a head drop. In high specific speed pump impellers, however, wide flow passages can handle a large quantity of bubbles before a noticeable head drop occurs; here efficiency drop is more dominant.

The head drop criterion, however is the most widely recognised result of cavitation and it can be accurately determined and compared with a standard.

The pressure drop is is defined by:

$$\beta = \frac{\Delta H}{H} \cdot 100\% \quad (Q = \text{constant})$$

The characteristic of pressure drop related to flow can show substantial differences when compared with visual cavitation data. At flow rates greater than best efficiency flow, when cavitation occurs on the pressure side of the impeller blades, the characteristics are comparable. At lower flow rates, however, the curves diverge; impeller blade suction side cavitation only affects the pump head when a large quantity of bubbles is generated.

4 CAVITATION EROSION RATE

Cavitation bubbles implode in areas where static pressure exceeds vapour pressure, resulting in very high local pressures. When an implosion occurs close to the solid boundary of a flow channel, the material can be damaged and cavitation erosion occurs.

Table 1 lists various parameters which influence the cavitation erosion rate. The interaction between abrasive erosion and corrosion with cavitation erosion will not be discussed here. (See, however, ref. 18).

The method presented here for the determination of NPSH(R) for erosion-free operation of a pump, is the result of an extended development process. Information obtained concerning cavitation in pumps delivered by the author's company, has been gathered in a data bank and when full operating conditions are known, the data have been used as the basis for this analysis. The majority of available data refers to cast iron and bronze impellers which have operated in water. Additional information is also available from boiler feed pumps involving a combination of high water temperature, high speed and stainless steels.
During the last decade, the application of aluminium bronze has increased because of its superior resistance to cavitation erosion. However, very little data are available at present which can be used for cavitation erosion analysis.

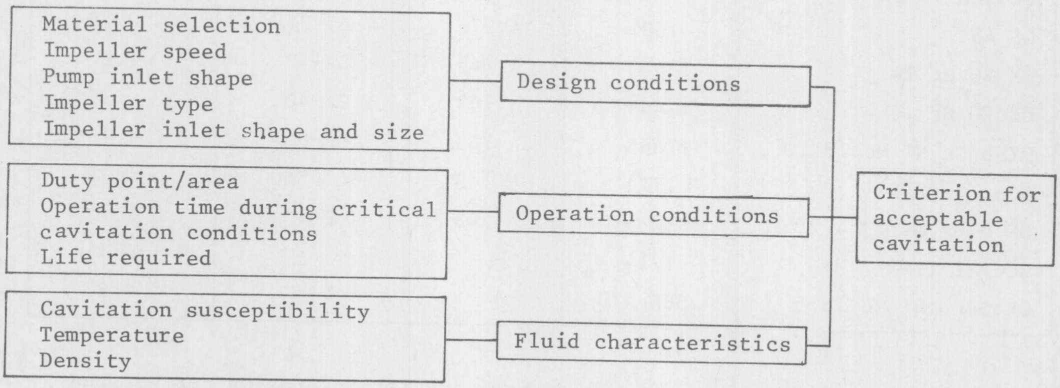

Table 1 Parameters for the determination of the criterion for acceptable cavitation.

The photographs shown in figure 3 give an example of the data bank information for a stainless steel impeller. This pump operated at 80% of its best efficiency flow, pumping brine at 35°C and at an impeller inlet peripheral speed U_1 = 23,5 m/s. The pictures refer to various operating times; the development of cavitation erosion is clearly illustrated.

4.1 Design conditions

Impeller material selection

Resistance to cavitation erosion varies substantially depending upon the material selected; the correct choice of material for this application is therefore very important as it will determine the pump life. For applications involving high cavitation intensity, superior quality alloys must be used. Whilst the cause of damage in such applications would not be removed, the probability of damage occurring can be reduced or even eliminated by the correct choice of material.

A critical peripheral speed has been established for materials most frequently used for pump impellers and this has been chosen as the threshold value for cavitation erosion damage. Unacceptable cavitation damage as defined in chapter 2 will not occur if the peripheral speed of the impeller eye is less than the aforementioned threshold value when the pump is operating at the following conditions:

- NPSH = $NPHS(R)_{1\%}$, i.e. 1% head drop;
- a shrouded impeller is used;
- pump duty at the pump design flow;
- continuous operation;
- uniform velocity distribution into the impeller eye.

In Table 2 various materials are listed and the peripheral speed ratio's given related to that for cast steel. These data assume a consistent casting quality.

Speed

When the impeller eye peripheral speed exceeds the threshold speed for a particular material, cavitation damage will occur if the pump is operated continuously at $NPSH(R)_{1\%}$.

It is important to point out that, when considering the cavitation erosion rate, the speed - NPSH relationship given in chapter 2 must be treated with caution. Cavitation erosion intensity is proportional to between U_1^5 and U_1^7, indicating that the effect of speed is dramatically greater than the effect of pressure drop (see refs. 6, 7 and 8).

For otherwise identical operating conditions the impeller peripheral speed U_1 can be increased over the threshold speed U_{cr} if the NPSHA is also increased. The required $NPSHR_{e.f.}$ for increased speed can be determined from figure 4. The characteristics of various materials are given indicating separately the conditions where cavitation damage will occur and those where erosion damage is not expected. The relationships given refer to the same conditions as used for the definition of the maximum impeller speed for the various materials. When the actual conditions differ from those as defined, correction factors must be used to establish a new value for U_1.

In figure 4 NPSH(R) for erosion free operation has been related to the NPSH for a 1% head drop. This value should be established by testing the actual pump as a function of flow.

Pump inlet geometry

The geometry of the pump inlet passage determines the velocity at the impeller eye as well as the pressure loss to this point. The pressure loss has already been taken into account in the calculation of NPSH, i.e. the loss factor k_1 in formula 1. However, the effect of velocity distribution has not been considered.

DIN		ASTM		$\frac{U_{cr}}{U_{cr\ ref.}}$
Designation	Sheet	Sheet	Grade	
GG 20	1691	A 48	Class 20	0.65
GGG Ni Cr 20.2	1694	A 439	Type D2	0.71
GCu Sn 10 Zn	1705	B 584	C 90500	0.76
GS 45	1681	A 27	65-35	0.76
GX 20 Cr 14 g	17445	A 743	CA-40	1.0
GX 20 Cr 14 h	17445	A 743	CA-40	1.10
GX 6 Cr Ni Mo 18.10	17445	A 743	CF-8M	1.16
GCu Al 10 Ni	1714	B 148	C 95500	1.22
GX 5 Cr Ni 13.4	SEW 410	A 743	CF-10 Mc	1.25
GCu Al 11 Ni	1714	-	-	1.31
GX 5 Cr Ni Mo 16.5	SEW 410	-	-	1.33

Table 2 Comparison of resistance against cavitation erosion for various materials expressed in the critical peripheral speed ratio.

Impeller inlet velocity distribution can be significantly irregular, unstable and also involve local whirls. Clearly cavitation erosion is influenced by this velocity distribution and a factor α_1 has been established to correct the erosion free criterion for inlet velocity distribution for the following cases:

an inlet elbow with or without vanes, for example as in a vertical in-line overhung impeller pump;
a pump inlet with or without guide vanes, for example a double suction pump;
an open sump with or without special anti-swirl provisions.

In case of straight end suction inlet it is assumed that $\alpha_1 = 1$.

Impeller type

Impeller type is characterised by the pump's specific speed and also by its construction, i.e. shrouded, unshrouded, etc. Pumps with unshrouded impellers can experience cavitation in the gap between the impeller blade tips and the adjacent casing. Erosion of the blade tips increases the gap resulting in performance deterioration. A correction factor α_2 considers impeller type.

Impeller inlet geometry

Impeller design, particularly that of its inlet, determines its cavitation behaviour. As the test NPSH(R) is used as the reference level, a correction factor for impeller inlet geometry is not necessary. The influence of impeller inlet design on the relationship between NPSH for a 1% head drop and other criteria is neglected although it could be concluded from detailed tests that this influence does depend on the detailed impeller design. The method proposed, however, is intended to be general and therefore a consistent relationship is used between the various cavitation criteria and flow given in figure 5. In this figure recirculation flow Q_{rec} is indicated. This flow is significantly influenced by impeller inlet geometry and is discussed further in chapter 5.

Impeller size can affect cavitation behaviour as well as shape, particularly where very small impellers are considered, for example with diameters less than 200 mm. A correction factor for impeller size on the criterion for acceptable cavitation is not included but is currently under discussion.

4.2 Operating conditions

Duty point versus design conditions

Whilst in practice the interaction of impeller and pump casing influences the pump best efficiency point, for the purposes of this exercise we assume that the best cavitation point coincides with the pump best efficiency flow. The best cavitation point being defined as the flow at which incipient visual cavitation is minimum, e.g. shock free inlet conditions.

At off-design conditions the various cavitation criteria show differing characteristics. A further correction factor α_3 is given in figure 6 for the determination of erosion free NPSH at off-design conditions. If a range of operating flows is considered, the extreme conditions should be related to the operation time.

4.3 Fluid characteristics

The reference liquid for this analysis is clean water at 20°C as defined in the standard VDMA 24423 for valve testing. Cavitation susceptibility of a fluid depends on its thermodynamic characteristics and the amount of dissolved gas, pollution, etc. The influence of water temperature on cavitation erosion is well known (see refs. 9 and 17); for other liquids, however, data are scarce. Correction factor α_4 given in figure 7 considers liquid characteristics and is related to density and speed of sound in the liquid.

4.4 Summary of the criteria for determining acceptable cavitation

All aspects which influence the amount of cavitation and the possibilities for damage have been considered and lead to the following procedure for determining $NPSHR_{e.f.}$:

1. Determine the 1% head drop NPSH for the required operating duty from previous tests.

2. Determine the correction factors:

   α_1 (pump inlet shape), α_2 (impeller type), α_3 (off design condition), α_4 (fluid characteristics and temperature).

3. Determine the threshold speed U_{cr} for the materials selected (table 2).

4. Calculate the impeller eye peripheral speed U_1.

5. Calculate:

   $$(U_1/U_{cr})_{corr} = \alpha_1.\alpha_2.\alpha_3.\alpha_4.U_1/U_{cr}$$

6. From figure 4 the ratio $NPSHR_{e.f.}/NPSH_{1\%}$ can be obtained and lead to the $NPSHR_{e.f.}$ for the conditions under consideration.

A further refinement of this method is possible to take account of pump life. As indicated previously, the procedure is based on a life of 40 000 hours continuous operation. This criterion depends on the pump application which could lead to a further correction. This correction is not, however, included.

5 IMPROVEMENT OF CAVITATION PERFORMANCE

Three aspects of cavitation performance optimisation are important:

a. a well chosen pump hydraulic design in which the delay of cavitation inception is maximised;

b. a well chosen pump mechanical design to minimise cavitation effects on the life of seals and bearings;

c. the correct selection of materials to avoid damage due to cavitation erosion, abrasive erosion and corrosion.

In this section only the first aspect will be discussed and this completes the optimisation method presented in reference 5.

The hydraulic design of the pump includes the pump inlet passage, the impeller and the diffuser or volute. All these elements influence the pump cavitation performance.

5.1 Impeller design

The hydraulic design of a pump impeller has the biggest influence on pump cavitation performance. A delay of cavitation inception can be achieved by careful calculation of the flow conditions around the impeller inlet and an accurate matching of the blade geometry to the flow. Reference 5 demonstrates that close attention to detail in impeller design can result in improved cavitation performance.

In reference 5 a formula for the optimum impeller eye diameter was derived. Assuming zero pre-rotation in the inlet flow the eye diameter can be calculated with the formula:

$$D_{1\,opt} = 1,533 \left(\frac{Q.C_r}{\omega.q_1}\right)^{1/3} \left(\frac{1+k_2}{k_2}\right)^{1/6} \left(\frac{1}{1-\lambda^2}\right)^{1/2} \quad \text{--(2)}$$

where: Q = flow rate (m^3/s)
C_r = ratio of absolute velocity near the impeller inlet at the shroud and the mean velocity in the eye
ω = angular velocity (s^{-1})
q_1 = blockage factor
k_2 = blade cavitation factor (see formula 1)
λ = hub/shroud diameter ratio in the impeller eye (= D_h/D_1)

Two important considerations have not, however, been included in this flow pattern based optimisation process. Firstly that of cavitation erosion where the eye peripheral speed plays a dominant role, and secondly off-design conditions. One aspect of off-design conditions e.g. recirculation at part flow will be considered here.

Cavitation erosion

In chapter 4 the influence of the impeller eye peripheral speed on the cavitation erosion criterion has been discussed. When this speed exceeds the threshold speed U_{cr} for the material used the cavitation erosion criterion should be used, thus introducing another relationship for the impeller inlet eye diameter:

$$\frac{NPSH_{e.f.}}{NSPH_{1\%}} = f\left(\frac{U_1}{U_{cr}}\right)$$ according to figure 4 and table 2.

To illustrate the effect of the erosion criterion on the optimum eye diameter, two examples are given in figure 8.

The suction specific speed: $K_s = \dfrac{\omega\sqrt{Q}}{(g.NPSH)^{3/4}}$ has been calculated for two values of the blade cavitation factor k_2. The other parameters Q, C_r, ω and q_1 are considered to be constant whilst the diameter ratio λ has been neglected. (λ = 0 and k_2 = 0,15 and 0,1 based on a 1% head drop). If k_2 is decreased the maximum obtainable suction specific speed increases with increasing diameter. This applies for $U_1 < U_{cr}$. When $U_1 > U_{cr}$ the cavitation erosion criterion should be included as shown by the dotted characteristics in the figure. Depending upon the material selected (characterised by U_{cr}) an optimum inlet diameter is found in most cases to be intersection between the solid and dotted lines.

From these examples it can be concluded that for materials which have good resistance to cavitation erosion the optimum impeller inlet diameter is close to that calculated for the flow pattern. Furthermore, the blade cavitation factor remains the most important parameter in determining the maximum obtainable suction specific speed.

When optimising an impeller design for cavitation performance, attention should therefore be paid to minimising the blade cavitation coefficient. To allow the correct choice of optimisation criteria, material selection considerations should be made in an early phase of the impeller design.

Recirculation at part flow

Figure 9 clearly shows a peak in the NPSH curves for the initial (I) impeller design. This peak is the result of flow recirculation in the impeller eye. In this example it is conspicuous that the flow at which the peak occurs is very close to the pump best efficiency flow.

Various authors (see for example refs. 12 and 13) have discussed this phenomenon and have proposed calculation methods to establish the flow at which recirculation will have the greatest effect.

In reference 12 it is assumed that:

$$D_1/D_2 < 0,5:\; Q_{rec} = f(D_1, D_h, \beta_1)$$

$$D_1/D_2 > 0,5:\; Q_{rec} = f(D_1, D_h, \beta_1, D_2, b_2, \beta_2)$$

where: D_1 = impeller eye diameter
D_h = hub diameter in the eye
β_1 = blade inlet angle
D_2 = outlet diameter
b_2 = outlet width
β_2 = blade outlet angle

In reference 13 the authors state that recirculation occurs when the ratio of relative velocities at the impeller inlet and outlet do not exceed a given value. The value depends, however, on the blade loading along the streamlines as well as their relation to each other. Reduction of the recirculation effect can be obtained by reducing the impeller eye diameter or by changing the blade loading.

When considering both the erosion and recirculation at part flow which are influenced by impeller inlet geometry, attention is again drawn to reference 5; it is illustrated that the "forward sweep" concept of blade inlet geometry substantially improves cavitation performance as well as recirculation. The position of the blade leading edge, the shape of the blade profile and the blade loading at this position play a dominant role in achieving low blade cavitation factors($k_2 < 0{,}1$ for 1% head drop) and also a minimising effect on recirculation (see figure 9).

5.2 Pump inlet passage

The pump inlet passage establishes the flow pattern into the impeller eye. An even velocity distribution and the absence of local whirls are basic requirements in an inlet design specification.

In an end suction pump this is easily achieved with a cylindrical or slightly conically shaped inlet passage which can be provided with anti-swirl baffles. A between bearings pump requires more careful design consideration in order to achieve a smooth flow path for the 90^o direction change without setting up secondary flows. This similarly applies to overhung impeller pumps provided with a 90^o intake passage, for example a vertical inline pump.

The geometry of the inlet passage interacts with the impeller design in determining the flow recirculation at off-design conditions (see ref. 19). The basic hydraulic design of bends and suchlike inlet passages currently used by the authors' company have been model tested in the hydraulic laboratory. Flow separations and the intensity of local whirls have been minimised and the velocity distribution and flow direction at the impeller inlet position have been optimised. Many designs have been scaled up from these models and adapted to standardised suction flange diameters. Figure 10 shows a pattern for such a passage provided with guide vanes.

The effect of the inlet passage on pump cavitation performance is illustrated in figure 11 where the 3% head drop NPSH characteristics are given for two double suction horizontally split pumps provided with the same impeller. The improved inlet passage has a substantially lower loss coefficient k_1, the pump vibration level is better and the erosion rate is improved when compared with the original design. The improvement favoured the overall pump performance at design and off-design conditions. The flow recirculation effect was also lower. The example illustrates that the interaction between pump inlet passage and impeller geometry should be taken into account when calculating recirculation flows.

5.3 Diffuser/volute design

Although the diffuser or volute is situated after the impeller outlet, where liquid pressure has been increased by the impeller head, practice shows that cavitation can still occur at this position in a pump.

This phenomenon appears more readily at off-design flows and can be the cause of erosion damage or an increased noise level. Improvement can be obtained by selecting the correct clearance between the impeller outlet and diffuser inlet. An interaction with other hydraulic parts can also take place, for example, pressure fluctuation generated at the pump inlet can be transmitted to the outlet, thereby influencing the pump performance.

6 CONCLUSIVE REMARKS

Reference 16 proposes a relationship between pump failures and suction specific speed based on analysis of a large number of pumps. Failure probability is concluded to increase with higher suction specific speed. This conclusion has led to the establishment of a maximum acceptable suction specific speed for a pump to improve reliability.

This conclusion conflicts with the results achieved by the work presented in the present paper.

a. Suction specific speed characterises the hydraulic design quality with respect to cavitation performance. The relationship between available and required NPSH determines the effect of cavitation on pump reliability.

b. An erosion criterion should be used for impeller material selection. If the impeller speed exceeds the value for the material selected, the NPSH required for erosion free operation must be compared with the NPSH available. It is not sufficient to simply compare the NPSH pressure drop characteristic with NPSH available.

c. As indicated in chapter 5 excellent cavitation performance can be achieved in combination with the suppression of flow recirculation at off-design conditions if a superior hydraulic design is used, for example a correctly designed impeller having the "forward sweep" blade concept combined with a correctly shaped pump inlet passage.

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