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SIMILARITY OF CAVITATION INCEPTION IN FRANCIS TURBINES

SIMILITUDE DE L'APPARITION DE CAVITATION DANS LES TURBINES FRANCIS

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SUMMARY

Cavitation tests using models are essential to determine the full-scale machine cavitation behaviour. As erosion prediction is still very empirical, in practice a "safe" machine shows no visible cavitation on a model at sigma plant. However, this way of defining the setting level can lead to errors due, among other things, to the nuclei transit time in the runner low pressure zone. It is shown in this paper that the absence of visible cavitation on a model does not correspond to absence of cavitation on the full-scale machine. Pressure distribution plays an essential role.
Moreover, it is shown that not respecting Froude similarity can also lead to a false determination of the full-scale machine setting level, as this similarity is the only one which guarantees similar pressure distributions between model and prototype.
As a correlation between cavitation and water quality is essential to give a physical explanation to the results, measurements of the water nuclei distribution must be made.

RESUME

Les essais en cavitation des modèles de turbines hydrauliques sont nécessaires pour la détermination du comportement en cavitation. Comme la prédiction de l'érosion est encore très empirique, la pratique veut que l'on qualifie de machine "sûre", une machine dans laquelle aucun développement de cavitation n'est visible sur modèle, au sigma d'implantation. Or, cette manière de procéder peut conduire à des erreurs importantes dues, entre autres, au temps de transit des noyaux de cavitation dans la zone de basse pression de l'aubage. Le fait de ne pas voir de cavitation sur le modèle, ne signifie pas pour autant qu'il n'y en a pas sur le prototype. La distribution de pression dans la roue joue ainsi un rôle fondamental.
De plus, le fait de ne pas respecter la similitude de Froude peut également conduire à des erreurs, puisque seule cette similitude permet de garantir des répartitions de pression homologues entre modèle et prototype.
L'explication physique des développements de cavitation ne pouvant être faite qu'en connaissant la qualité de l'eau, il est essentiel de mesurer la distribution de germes de l'eau d'essai.

1. INTRODUCTION

In hydraulic machinery cavitation erosion is one of the main limiting features which prevents engineers from designing machines with higher specific power. The setting level of a power plant is selected with a view to minimizing the cavitation erosion risk. Accurate determination of the setting level is very important in relation to high unit capacity and civil engineering costs. Usually the cavitation tests are done using models, and the sigma influence on the performance characteristics of the machine is measured. As a hydraulic performance criterion, this cavitation characteristic is important for :

1. The efficiency drop, with a typical sigma value, $\sigma_{standard}$. IMHEF have made a large contribution to solving this problem [1], [2], [3], [4].

2. The inception cavitation, with a typical sigma value, σ_b.

This problem of cavitation inception is a major one as in most cases the machine setting level is determined from σ_b by model testing. This is because erosion prediction is still very empirical and therefore visible cavitation can safely be avoided at sigma plant, σ_p. Up to now this characteristic value has been found by visual observation of the runner. This way of defining the σ_b value depends on the observer and on the size of the bubbles at the runner outlet. Depending on their size, the bubbles will be or will not be visible to the observer [5].
On the other hand we can not quantify the erosion rate or danger of such an inception cavitation development, but one well known fact is that cavitation erosion is found under the region where outlet cavitation takes place. This means that even if we can not really predict erosion from the inception cavitation development, it is necessary to take this major problem into account. Moreover, the bigger the bubbles are, the greater the erosion risk could be.
If no cavitation is detected by model testing, does it mean that no cavitation will occur in the prototype ? The answer is no. Moreover, in such a case, if bubbles appear in the full-scale machine, they will certainly collapse on the blades, and the erosion danger will be higher. This means that absence of cavitation in the model corresponds only to the conclusion that no bubbles can be seen in the model". If bubbles appear in the prototype, it would be better to have longer cavitation developments, corresponding to bubbles collapsing after the blade, with less erosion risk.Thus, the influence of the pressure distribution along the blade, and the transposition of these results to the full-scale case, are studied.

2. INFLUENCE OF THE PRESSURE DISTRIBUTION

A parametric study is made on the dynamic evolution of a bubble, from the Rayleigh-Plesset equation [2], and an important result was found : the maximum size of a cavitation nucleus is scaled by the chord length of the blade, L, and by the specific hydraulic energy, E :

$$R_{max} = A \cdot \frac{L}{\sqrt{E}} + R_o$$

Where A is a proportional factor and R_o is the initial size of the nucleus, which can be neglected for small nuclei without causing large errors,

and, $\frac{L}{\sqrt{E}}$ represents the bubble transit time.
The cavitation nuclei will explode only when the pressure value decreases under the p_v value. The longer the streamline length with a pressure value under the vapour pressure is, the bigger the bubble size. Then the following relation can be written :

$$R_{max} \approx \frac{L_{p<p_v}}{\sqrt{E}}$$

Where $L_{p<p_v}$ represents the approximate bubble growth length below p_v.

If the pressure distribution along the runner has a long low pressure zone, corresponding to profile 1 (Figure 1), to obtain the maximum possible torque, the bubble growth transit time will be long and the activated nuclei will become large. In such a situation the risk of cavitation erosion will be higher.

To illustrate these results, investigations are made on two pressure distributions with the Rayleigh-Plesset bubble dynamic model. Figure 1 shows both pressure distributions. The first, named profile 1, has a constant minimum pressure and the second one, profile 2, corresponds to a typical pressure distribution. Both cases are characterized by the same minimum pressure value and the same total length. The pressure coefficient Cp is defined as :

$$Cp = \frac{p - p_o}{\rho E}$$

where p is the absolute pressure value
p_o is the absolute pressure at the blade outlet (same reference as for sigma definition)
E is the specific hydraulic energy

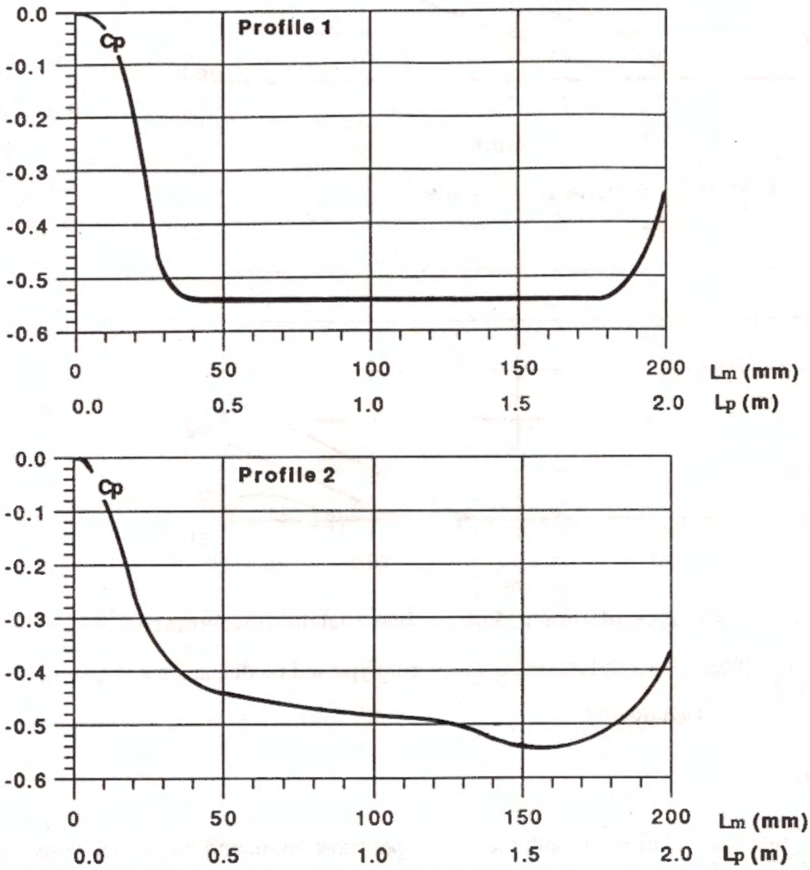

Figure 1 : Pressure distributions along a streamline close to the shroud

As a typical result, Figure 2 shows the size development of a 5 μ radius nucleus by decreasing the sigma value for both pressure distributions. Such 5 μ radius nuclei are typically found in test water.

For a visual observation, a bubble with a radius smaller than 0.5 mm can not be seen with certainty. Then, by comparing bubbles of maximum size in both cases of the above example, the inception sigma values are σ4 for profile 2 and σ2 for profile 1. The relative difference between σ2 and σ4 corresponds to approximately 20 % of the machine inception σ value. Moreover, if the chord lengths are different between two models this effect can increase.

One thing must be pointed out : if visual observation does not detect inception cavitation, it does not mean that there is no cavitation. Indeed, the water nuclei can be activated and then explode but the transit time along the streamline can be too short to reach visual sizes. We have to consider the conclusion that there is no cavitation, and it is necessary to examine what will happen on the full-scale machine, since the transit time which governs the development of the bubble size can be very different in this case.

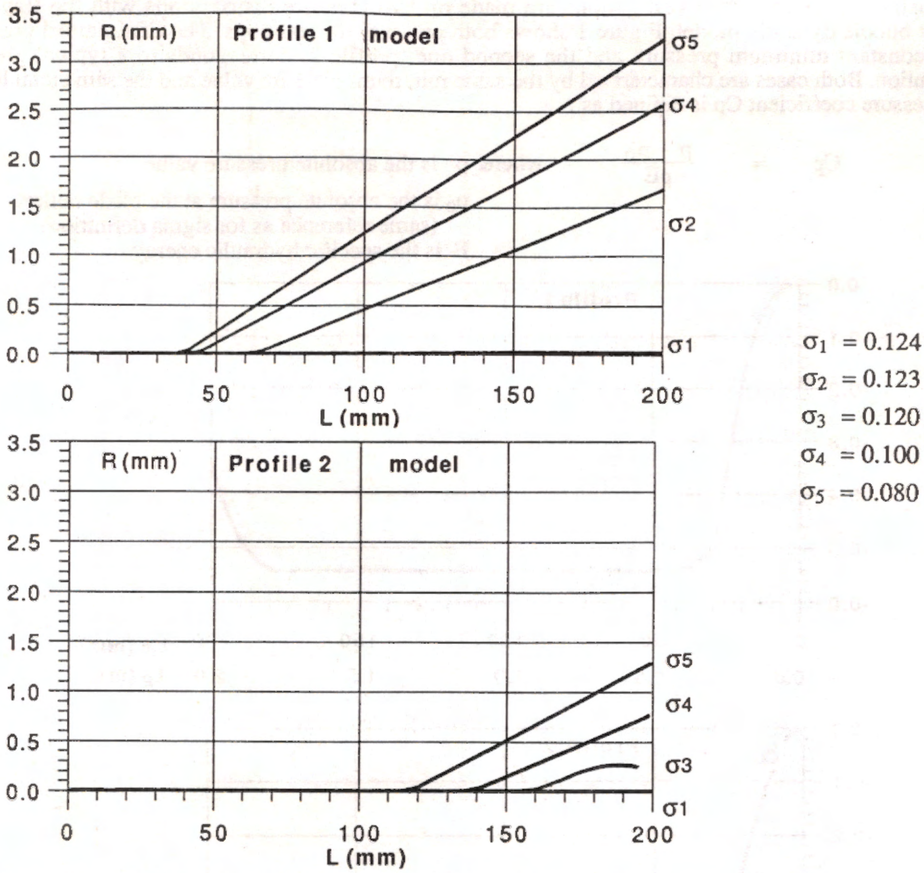

Figure 2 : Influence of σon a 5 μ radius nucleus development

Let us examine the typical values and scales between prototype and model, and try to quantify the bubble maximum size scale.
The maximum radius is scaled by :

$$R_{max} \approx \frac{L}{\sqrt{E}}$$

Then, by writing the same relation for both the prototype, subscript p, and the model, subscript m, the bubble size scale is obtained :

$$\frac{R_{max\,p}}{R_{max\,m}} = \frac{L_p}{L_m} \cdot \sqrt{\frac{E_m}{E_p}} \quad \text{or} \quad \frac{R_{max\,p}}{R_{max\,m}} = \frac{1}{\lambda_L} \cdot \sqrt{\lambda_E}$$

Typically the following orders of magnitude are found, for the geometrical scale, λ_L, and the specific energy scale, λ_E :

$$\lambda_L = \frac{L_m}{L_p} \quad \text{with : } \lambda_L = \frac{1}{10} \text{ to } \frac{1}{20}$$

$$\lambda_E = \frac{E_m}{E_p} \quad \text{with : } \lambda_E = 1 \text{ to } \frac{1}{5}$$

And the following ratio between the full-scale and the model bubble sizes is obtained:

$$\frac{R_{max\,p}}{R_{max\,m}} \approx 5 \text{ to } 20$$

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This means that bubbles not detected by a visual observation on the model can become up to 20 times bigger on the full-scale machine, which can correspond to big bubbles. And, if the bubbles collapse on the blade surface, there is a high risk of erosion.

3. EXPERIMENTAL CAVITATION INCEPTION DETERMINATION

The cavitation development is a function of the water active nuclei content. The outlet cavitation inception will be fully dependent on the nuclei distribution, specially on the largest nuclei present in the test water [5] (Figure 3) :

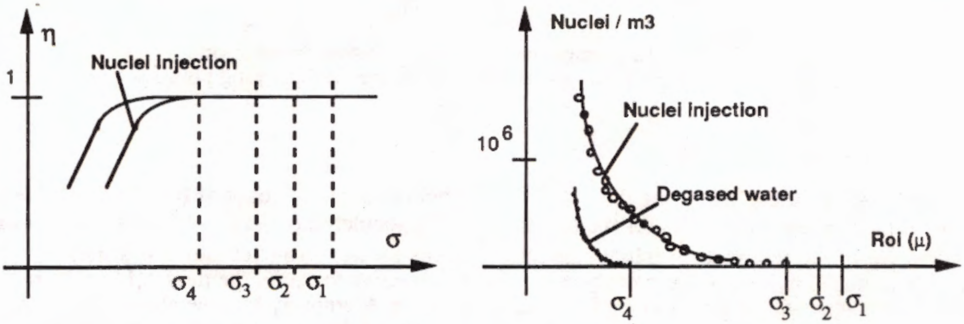

Figure 3 : Influence of the water nuclei distribution on the outlet cavitation inception

By decreasing the sigma value, as long as no nucleus is activated, no cavitation will occur (σ_1 and σ_2 in Figure 3), but as soon as one nucleus (corresponding to σ_3 in Figure 3, for the injection case and to σ_4 for the degassed water case), is activated, cavitation can develop.
The number of nuclei is not the main factor in determining the inception sigma value. The biggest nuclei will influence this characteristic value for a given pressure distribution. Increasing the number of large nuclei could somewhat increase the cavitating volume, but for such pressure values the runner zone likely to cavitate is very small, and then there is no need to inject a lot of nuclei as the available space will quickly be saturated. In the case of the v = 0.35 Francis model (nq = 55), the inception sigma value was found with less than $0.02.10^6$ nuclei/m^3, and even with more than $0.1.10^6$ nuclei/m^3 the inception cavitation development was not really greater.

4. PROTOTYPE BEHAVIOUR

Theoretically, in the full-scale machine, for pressure level equal to p_v, nuclei of infinite size would explode, at a critical pressure equal to p_v corresponding to an infinite radius :

$$R_{o\,cr} = \frac{3\Gamma-1}{3\Gamma} \cdot \frac{2 \cdot \gamma}{p_v - p_{cr}}$$

Such "infinite size nuclei" do not exist and even in such a case the explosion would be very small, according to the inertia of the nuclei and to the small pressure difference, $p_v - p_{cr}$. But large nuclei are usually found in the prototype water. It is then important to define the "large nuclei" behaviour and to find the corresponding test water condition for the model.
Study of the dynamic evolution of a bubble [6] has shown that the minimum size of an active cavitation nucleus is scaled by the specific hydraulic energy but not by the chord length :

$$R_{o\,i} \approx \frac{A}{E}$$

where $R_{o\,i}$ is the minimum active radius.

If the minimum active nucleus on the model is $R_{oi\,m}$, for a model specific hydraulic energy, E_m, the corresponding values in the full-scale machine are $R_{oi\,p}$ and E_p. As the bubble maximum size after explosion is scaled by the chord length of the blade and by the square root of the hydraulic energy :

$$R_{max} \approx A \cdot \frac{L}{\sqrt{E}} + R_o$$

The following relation characterizes the size of the bubbles after explosion :

$$\frac{(R_{max\,m} - R_{o\,m}) \cdot \sqrt{E_m}}{L_m} = \frac{(R_{max\,p} - R_{o\,p}) \cdot \sqrt{E_p}}{L_p}$$

For cavitating nuclei their initial size, R_o, can be neglected without significant error.
Then, the maximum size scale between prototype and model for similar operating points, is :

$$\frac{R_{max\,p}}{R_{max\,m}} = \frac{1}{\lambda_L} \cdot \sqrt{\lambda_E}$$

As the evolution of a 5 μ nucleus along the 2 different model pressure distributions (profile 1, profile 2) is studied, let us examine the results for the prototype. For a geometric scale, λ_L of $^1/_{10}$, and a specific energy scale, λ_E of $^1/_5$, the nucleus initial size ratio is 1:5 as the active nuclei radius is scaled by $^1/_E$. Then, the initial nuclei radius for the prototype is 1 μ, corresponding to 5 μ for the model. It can be noted that such a 1μ nucleus will be found in the full-scale plant water. Moreover, with the above scale values, the maximum size ratio is 1:4.5. Figure 5 shows the development of the 1 μ in the full-scale machine.

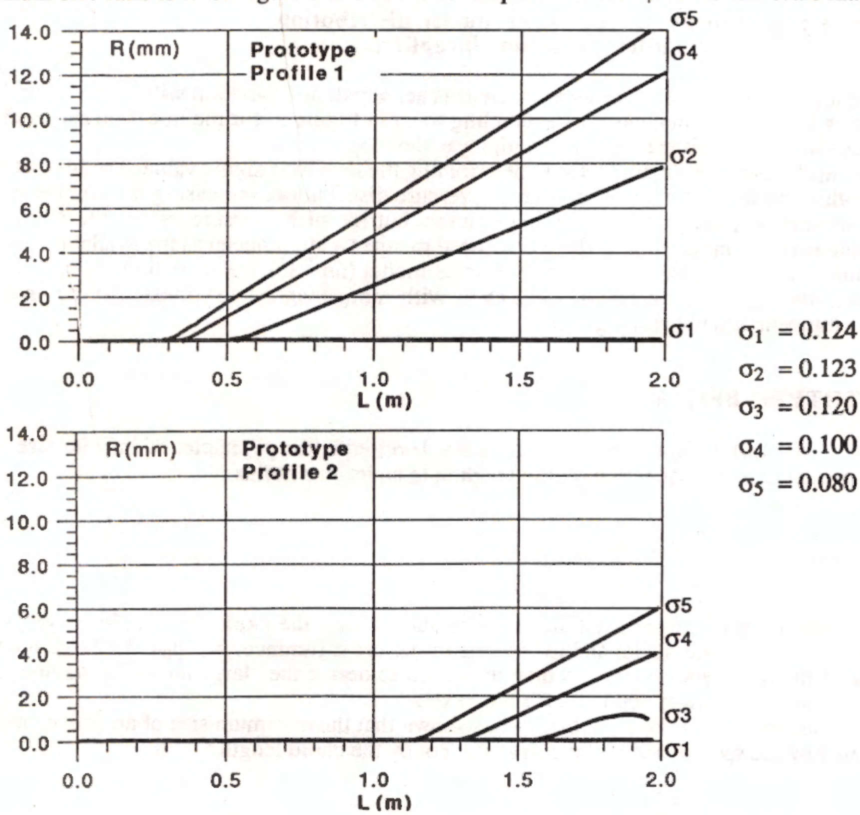

Figure 5 : 1 μ radius nucleus development for different σ values (full-scale)

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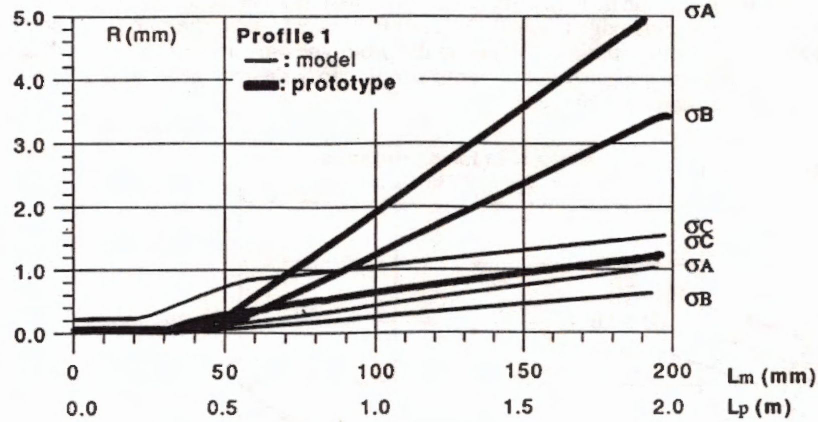
As soon as the pressure along a streamline in the runner decreases under vapour pressure, cavitation is likely to occur. It can then be said that the machine setting level should not be higher than this level, which corresponds to the vapour pressure value: However, this criterion is too conservative because even if the water contains large nuclei, they will not explode strongly enough to generate real cavitation. There is a level to be found so that the nuclei explosions are strong enough to create bubble cavitation. This level will be closer to the p_v pressure level when the transit time in a region where pressure is under the p_v value is longer (Figure 6).

For profile 2, sigma inception cavitation is lower than σA, but for profile 1 it is close to σC which, in this case, corresponds to a 15 % difference in sigma inception value.



model :

Ro_i (A) = 15 μ

Ro_i (B) = 30 μ

Ro_i (C) = 250 μ

Prototype :

Ro_i (A) = 3 μ

Ro_i (B) = 6 μ

Ro_i (C) = 50 μ

σ_A = 0.140

σ_B = 0.145

σ_C = 0.150

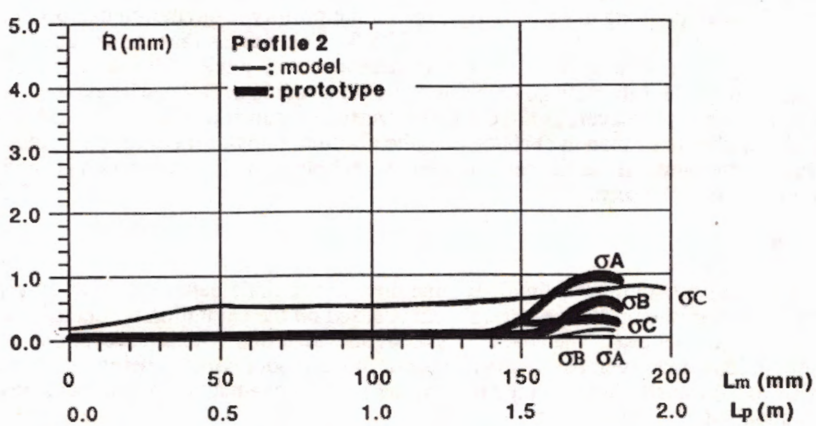


Figure 6 : Minimum active nuclei development for different sigma values

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5. FROUDE INFLUENCE

The test head changes the pressure distribution along the streamline which will influence the runner cavitation behaviour. Indeed, the only way to keep the real pressure distribution completely similar to the full-scale machine is to perform the cavitation tests respecting Froude similarity. If the head is higher than the Froude head, the modification of the pressure distribution can lead to wrong conclusions regarding cavitation inception determination. Figure 7 shows the pressure distributions for a $\nu \approx 0.30$ ($nq \approx 47$) runner corresponding to the Froude head (H_{Fr}) and to 2 higher heads (H_1, H_2).
The sigma reference level corresponds to the lowest part of the trailing edge (Te). At this point ($L_m = 200$) the pressure will be constant if the diffuser efficiency differences can be neglected.
If the Froude similarity is not respected, the difference between the model and prototype pressure coefficients will be greater insofar as the difference between the actual and the reference level is greater. Moreover, if the pressure at the trailing edge ($L_m = 200$) is not the lowest value, the minimum pressure level in the runner will be similar to the minimum value on the prototype only at the Froude head. In the example (Figure 7) the minimum pressure coefficients for the Froude test head and H_2, which corresponds to 40 m, show an important difference.

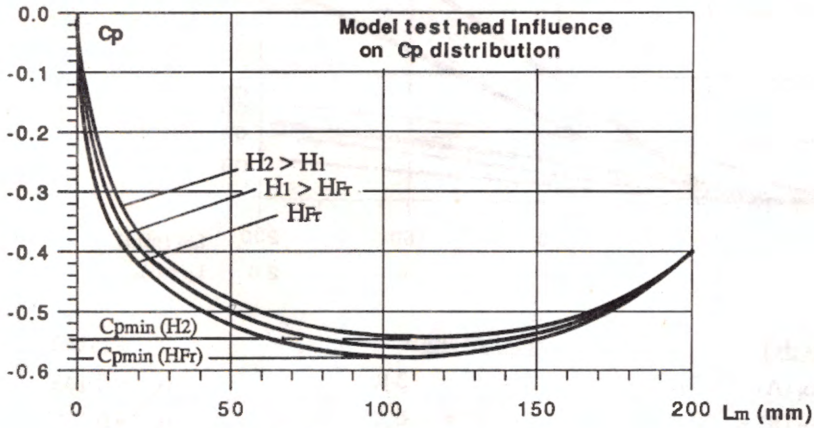

Figure 7 : Influence of the test head on the model pressure distribution

Performing cavitation tests using a high head can lead to the conclusion that there is no cavitation for a sigma value of about 0.09, corresponding to - $Cp_{min}(H_2)$, but on the prototype cavitation can occur for a sigma plant value of 0.12, which is a relative difference of 25 %. This means that in the case of the high test head (H_2) for a sigma plant value of 0.10, even if there are large nuclei with infinite radius, cavitation will not occur, but on the full-scale machine nuclei with a radius of 3.0 μ will explode, and these nuclei can be found in situ. Moreover, as the cavitation vertical extension is not respected if the tests are performed with a higher head than the Froude one, the absolute transit time through a pressure level lower than the vapour pressure will be shorter, and thus the bubble sizes smaller, which is another reason why cavitation inception is not seen.

6. CONCLUSIONS

The cavitation test is one of the most important to determine the characteristic behaviour in a full-scale machine. As the determination of the prototype setting level is based on the cavitation model tests, it is essential to perform accurate model tests. The characteristic sigma value of cavitation inception, σ_b, is obtained by visual observations. However, cavitation can occur in the model without being detected by visual observations. Due to the transit time along the runner, the bubbles can reach larger dimensions in the full-scale machine, and then generate erosion.
The pressure distribution along the profile is very important. The longer the transit time is through a region where the pressure is under the pv value, the deeper the machine setting level is. Indeed, bubbles have time to grow and to reach a size which generates visible cavitation, and which could then be dangerous when they collapse. These effects will be decreased the shorter the transit time is.
Moreover, performing inception cavitation tests without respecting Froude similarity can increase the risk of predicting a wrong full-scale setting level based on model inception cavitation, since respect of the whole pressure distribution is not guaranteed.

Cavitation inception determination should be performed with nuclei injection and with a test head as close as possible to the Froude similarity, to guarantee similar pressure distributions on both model and prototype (in order to keep the same relative minimum pressure values), and to obtain a long transit time in a model for a better cavitation inception visualization.
To understand the results, and to give them a physical explanation, it is essential to make a correlation between cavitation and water quality. Then, nuclei distributions must be measured to qualify the water.

NOTATIONS

R	:	Nuclei radius	(mm) or (μ)
L	:	Chord length	(mm) or (m)
E	:	Specific hydraulic energy	(m^2/s^2)
H	:	Head	(m)
Cp	:	Pressure coefficient	(-)
σ	:	Cavitation number	(-)
ν	:	Specific speed number	(-)
λ_L	:	Geometric scale	(-)
λ_E	:	Specific energy scale	(-)
N	:	Nuclei content	(nuclei/m^3)
A	:	Proportional factor	(mm/s)
Γ	:	Ratio of the gas specific heats	(-)
γ	:	Gas-liquid surface tension	(N/m)

Subscripts :

o	:	initial value
o i	:	minimum unstable initial value
m	:	model
p	:	prototype
Fr	:	Froude
max	:	maximum value
min	:	minimum value

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