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GUIDELINES FOR PERFORMING CAVITATION TESTS

PROTOCOLE D'ESSAIS DE CAVITATION

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SUMMARY

For Francis turbines, outlet cavitation is a major critical phenomenon in determining the prototype setting level. To predict the full-scale cavitation characteristics, it is technically interesting to provide reliable model cavitation tests. This can be done by a similar cavitation development on the model and on the prototype.

In this paper, previous results obtained during systematic cavitation tests using nuclei injection and counting techniques are recalled. An alternative procedure to nuclei injection is then investigated with a high gas content in the water. The unique feature of the IMHEF test facility to perform cavitation tests either with a closed loop (low dissolved air content) or with an open loop (high dissolved air content), whatever the nuclei content, means that the difference between the influences of the dissolved gas content and of the cavitation nuclei content can be studied, independently.

Moreover, the determination of the water active nuclei content leads to predicting the cavitation inception, provided the pressure distribution in the runner can be estimated.

Based on the results of all our investigations guidelines for performing cavitation tests on Francis model are suggested.

RESUME

Pour les turbines Francis, la cavitation de sortie est un phénomène majeur dans la détermination du niveau d'implantation du prototype. Pour prédire les caractéristiques en cavitation du prototype, il est nécessaire de présenter à l'exploitant des résultats d'essais de cavitation fiables. On obtient de telles valeurs par des développements de cavitation similaires entre modèle et prototype. Dans ce papier, on rappelle les résultats obtenus précédemment durant des essais systématiques de cavitation avec injection et comptage de germes. Une procédure alternative à l'injection de germes est examinée, en travaillant avec de l'eau à haute teneur en air dissous. La différence entre la teneur en air dissous et la teneur en germes actifs est étudiée d'une manière indépendante, grâce à la possibilité offerte par les plateformes d'essais de l'IMHEF de travailler en cavitation soit en circuit ouvert, soit en circuit fermé.

De plus, la détermination de la teneur en germes actifs de l'eau permet de prédire le début de cavitation, pour autant que l'on puisse estimer la pression minimale dans la roue.

Enfin, sur la base des résultats de toutes nos études, une nouvelle procédure d'essais de cavitation des modèles de turbines Francis est envisagée.

1. INTRODUCTION

During cavitation tests on hydraulic machine models, it is necessary to know the role played by the test head and the nuclei content of the water on the hydraulic characteristics. Their influence has been written about in many publications. The IMHEF studies have already pointed out the development of the model cavitation characteristic as a function of the two above-mentioned parameters [1], [2]. The main problem is transposing the results obtained with a model turbine to the full-scale machine. So it is necessary to find a reliable cavitation characteristic on a model independent of the water quality and the test head.
Systematic cavitation tests on several Francis turbine models have revealed that there is a threshold for the test head and for the nuclei concentration beyond which the model performance is no longer affected by these parameters. This important curve is called the saturation characteristic of the machine [4]. Solving the Rayleigh-Plesset equation makes it possible to study the behaviour of a single bubble in the runner flow field,[3]. This can explain the saturation effect, and shows that if the saturation characteristic is reached on the model, it leads to saturation in the prototype [5]. This saturation characteristic is obtained by increasing either the test head or the water nuclei content. However, investigations made using high specific speed Francis turbines have shown the important Froude effect on cavitation development, and then on the whole performance of the machine, [5].
In this paper the previous results obtained during systematic cavitation tests with nuclei injection and counting techniques are recalled. An alternative procedure to nuclei injection is then investigated with a high gas content in the water. The unique feature of the IMHEF test facility allowing it to perform cavitation tests either with a closed loop (low dissolved air content) or with an open loop (high dissolved air content), whatever the nuclei content, means that the difference between the influences of the dissolved gas content and of the cavitation nuclei content is studied in an independent way. As the cavitation characteristic of a model depends very much on the water quality, the question arises whether these open loop tests correspond to the same conditions as those performed with nuclei injection.
Moreover, the determination of the water active nuclei content leads to predicting the cavitation inception, provided the pressure distribution in the runner is known.

2. PRESENT STATE OF KNOWLEDGE

2.1 Cavitation saturation characteristic

When performing cavitation tests on a Francis turbine model, the influence of the water nuclei content and the test head is well known. There is a threshold beyond which the performances are no longer affected either by the test head or the nuclei content. Figure 1 shows the case corresponding to a $\nu = 0.30$ specific speed Francis turbine, (nq = 47). Close to the best efficiency operating point, this model presents bubble cavitation at the runner outlet and is very sensitive to the water nuclei content and the test head. However, as can be seen in Figure 1, by increasing the test head or the nuclei content, all the curves collapse to a single curve, called the cavitation saturation characteristic.

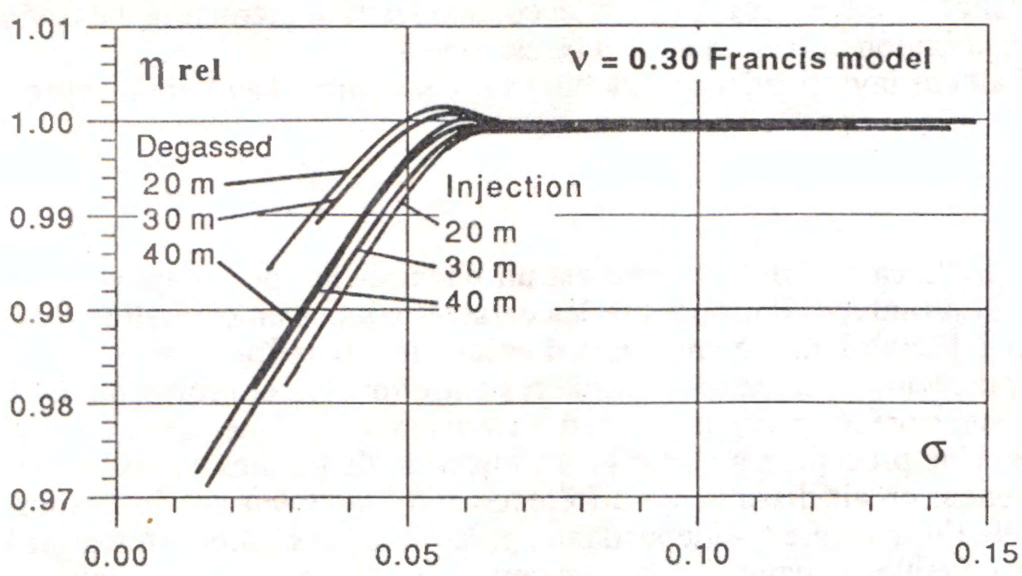

Figure 1 : Cavitation characteristic performance curves for a $\nu = 0.30$ Francis model

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2.2 Importance of Froude similarity

To reach the cavitation saturation characteristic, it is necessary to inject nuclei or to increase the test head. By increasing the head, the model sometimes diverges greatly from the Froude similarity with the prototype and the distortions in the cavitation development are unacceptable. Figure 2 shows the modification of the pressure distribution along the shroud streamline due to a head increase.

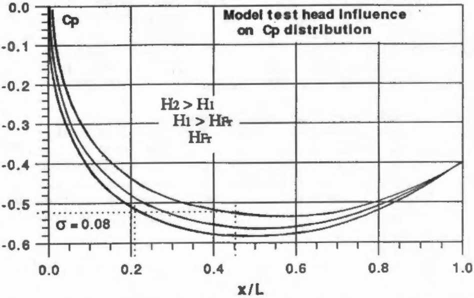


Figure 2 : Influence of the test head on the pressure distribution in the runner

The relative positions of the p_v isobar, corresponding to a sigma value of 0.08 in the above figure, are 20% of the chord length for the Froude head, H_{Fr}, and only 45% for the highest head, H_2, which means that cavitation develops at 45% of the chord length on the model, but starts at 20% of the chord length on the prototype.

By following a similar analysis for all the streamlines in the runner, the same results are found for the extension of the pressure zone under p_v along the trailing edge from the runner shroud to its hub. For a high head, the vertical extension along the trailing edge is smaller. The whole cavitation development is then reduced and machine performance is less affected.

The relative efficiency characteristic curves of a $\nu = 0.60$ (nq = 94.) Francis turbine are given in Figure 3 for a test head close to the Froude one (6 m), and a higher one (15 m), with degassed water and with nuclei injection leading to the saturation characteristics. Two different saturation curves corresponding to a different cavitation development can be observed for these two heads .

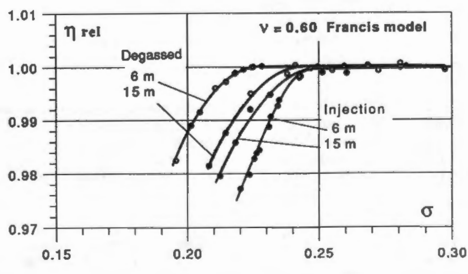


Figure 3 : Cavitation characteristic performance curves for a ν = 0.60 Francis model

Moreover, the saturation characteristic is reached on the model with a lower nuclei content for the Froude head than for the higher head, as the bubble transit time is longer and bubble growth is more important.
As the model tests must predict the full-scale behaviour, it is necessary to perform them in a similarity flow condition. This means that they must be performed as closely as possible to the Froude head and by injecting cavitation nuclei in the water to reach the saturation characteristic. However, the limited head range of the test facilities prevents us from following this similarity rule. For instance, the Froude head corresponding to a high specific speed Francis turbine can lead to a test head as low as 1m, which is obviously impossible to achieve. In that case this cavitation test must be carried out for different test heads in order to check the influence of the Froude similarity. In order to minimize this effect the cavitation number should refer as closely as possible to the altitude where the cavitation takes place.

2.3 Saturation characteristic on a full-scale turbine

Solving the Rayleigh-Plesset equation makes it possible to study the behaviour of a single bubble in the runner flow field, [3]. It can explain the saturation effect, and show that if saturation is reached on the model, it will lead to saturation in the full-scale machine [5]. The saturation effect is governed by a limitation of the volume available to the bubble growth in the region where the flow pressure is lower than the vapour pressure. This region can be defined as the cavitation volume. Then, the condition of a constant ratio of the cavitation total volume on the model and the prototype, can be written as follows :

$$\frac{N_m}{N_p} = \left(\frac{L_p}{L_m}\right)^3 \left(\frac{E_m}{E_p}\right)^{3/2} \qquad \text{Equation 1}$$

With respect to the Froude similarity,

$$\frac{N_m}{N_p} = \left(\frac{L_p}{L_m}\right)^{3/2} = \left(\frac{1}{\lambda_L}\right)^{3/2}$$

By assuming that the nuclei content follows an inverse n-power law, and the active radius limit, R_i being scaled by the specific hydraulic energy, the following expression of the above equation is obtained :

$$1 \leq \left(\frac{1}{\lambda_L}\right)^3 \left(\frac{E_p}{E_m}\right)^{n-3/2} \quad \text{or} \quad 1 \leq \left(\frac{1}{\lambda_L}\right)^3 \left(\frac{1}{\lambda_E}\right)^{n-3/2} \qquad \text{Equation 2}$$

This relation must be verified in order to have the saturation effect in the prototype if the saturation effect occurs using the model. Typically, the following orders of magnitude for the geometrical scale, λ_L, and the specific energy scale, λ_E, are found :

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

$$\lambda_E = \frac{E_m}{E_p} \qquad \text{with, typically : } \lambda_E = 1 \text{ to } \frac{1}{5}$$

The corresponding nuclei content ratio between laboratory water and plant water, is :

$$\frac{N_m}{N_p} = 90 \text{ to } 8000$$

Since a nuclei content of less than $2.0 \cdot 10^6$ nuclei/m^3 is generally enough to reach saturation in a model, it means that a content of $0.03 \cdot 10^6$ nuclei/m^3 leads to saturation in the prototype, which should be the case for plant water. These numerical values obviously prove that saturation in the model leads to saturation in the prototype. If it is assumed that the prototype operates under a saturation condition, the model cavitation tests must be performed to obtain the corresponding saturation performance curve.

3. EXPERIMENTAL STUDY

3.1 Test procedure

Since the usual way to perform cavitation tests is first to perform a degassing of the test rig in order to avoid bubbles in the pressure lines and to have a good quality flow visualization, IMHEF investigates the opportunity to overcome the injection of nuclei by doing tests with fresh water. The unique feature of the IMHEF test facility allowing it to perform cavitation tests either with a closed loop (low dissolved air content) or with an open loop (high dissolved air content), whatever the nuclei content, means that the influence of these two parameters, the dissolved gas content and the cavitation nuclei content is studied independently. As the cavitation characteristic of a model greatly depends on the water quality, it can be asked if these open loop tests correspond to the same condition as those performed with nuclei injection.

The Erancis turbine tested has a specific speed of $\nu = 0.35$ (nq = 55.). Close to the best efficiency operating point this model presents outlet cavitation and is very sensitive to the water nuclei content. Two operating points are tested. The first one corresponds to the best efficiency operating point, and the second to a 20% higher flow.
The cavitation tests were performed for the two above-mentioned operating points, 3 different heads (30 m ; 15 m ; 6.5 m) and different water qualities : non-degassed water (open circuit), degassed water, 3 different nuclei injections. The test head corresponding to Froude similarity with the prototype was in this case 6.5 m. The hydraulic characteristics are measured in accordance with the standard IEC test procedure. The nuclei and dissolved air contents are measured simultaneously and the nuclei injection is performed continuously.

3.2 Nuclei instrumentation

To define the $\eta - \sigma$ saturation characteristic it is necessary to inject nuclei. The injectors are based on a rapid saturated water expansion through a diaphragm. A special nuclei seeding device is used which can work continuously. The modular design of the injectors allows the number of individual injectors to be varied in order to produce the required amount of nuclei to each model test, (Figure 4).

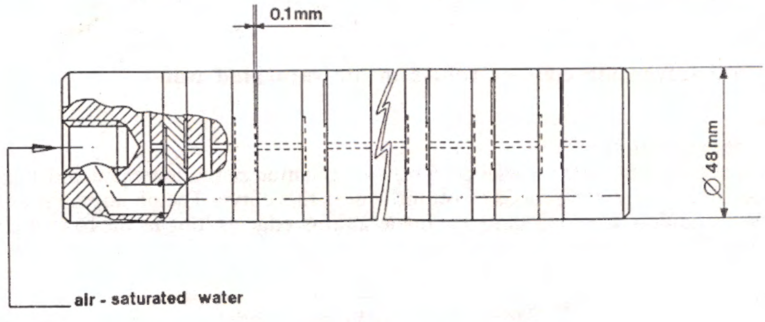


Figure 4 : Cavitation Nuclei Injectors (IMHEF)

The cavitation nuclei counter presented in reference [5] has been designed to overcome the limited possibilities for counting nuclei during low head tests (Figure 5). In this counter, the flow is accelerated through a restricted section bounded by a central conical body and a cone diffuser in order to promote the explosive growth of the nuclei. This counter is calibrated by analyzing real time information given by the signal from the piezo-ceramic, which detects the exploding bubbles, the number of counted bubbles (through the electronic part) and simultaneous high-speed photographs of the exploding bubbles. All the measurements showed good reliability of this counting technique.

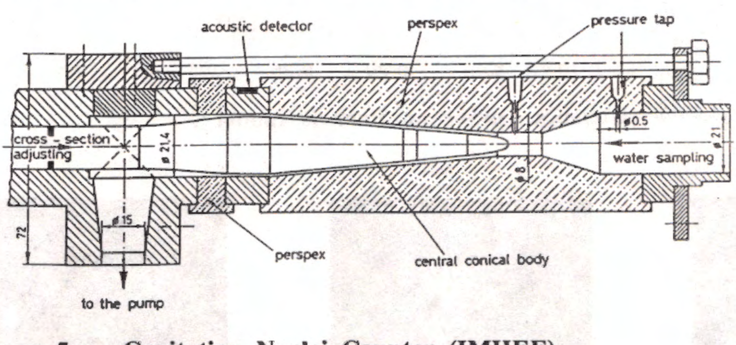


Figure 5 : Cavitation Nuclei Counter (IMHEF)

3.3 Dissolved air instrumentation

The dissolved air content is measured with two amperometric systems (Beckman and Orbisphere), based on a reduction-oxydation reaction which generates an electric current between two electrodes .
Both systems are calibrated either as proposed by the manufacturer, by measuring the value corresponding to water saturated air and comparing it with value tables from the constructor, or using a proprietary direct gas dissolved content measuring system developed by Voith. The principle of the latter

system is based on the measurement of the net volume of gas released by considerably decreasing the pressure in a closed vessel. The physical air saturated water curve provided by the two amperometric systems and the values measured with the Voith system are reported in Figure 6. Comparisons of the two methods show that they agree well.

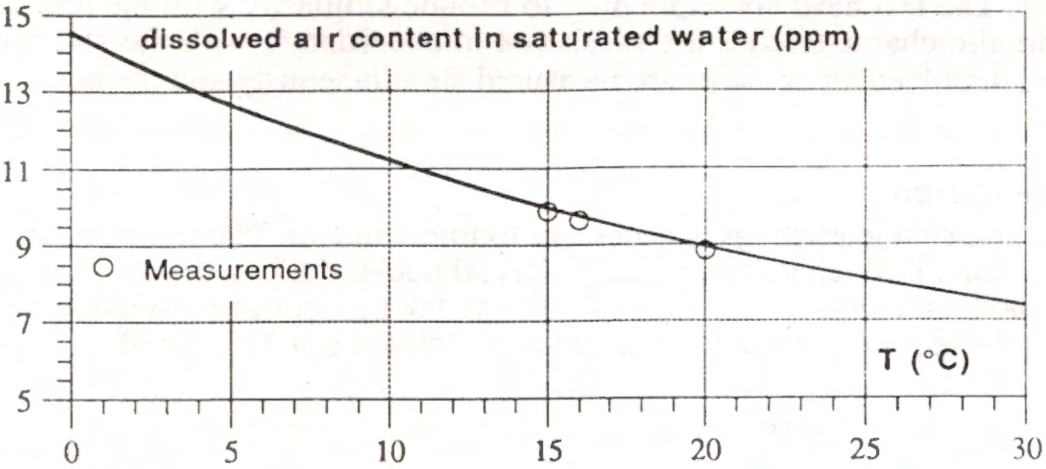


Figure 6 : dissolved air content values in air saturated water

4. RESULTS

4.1 Saturation characteristic

By increasing the test head and the water nuclei content, the cavitation saturation characteristic is found. However, as indicated in Figure 7, the Froude effect influences this curve. The photographs in Figure 8 show clearly how the cavitation develops along the blade trailing edge as long as the head is decreased up to the Froude one.

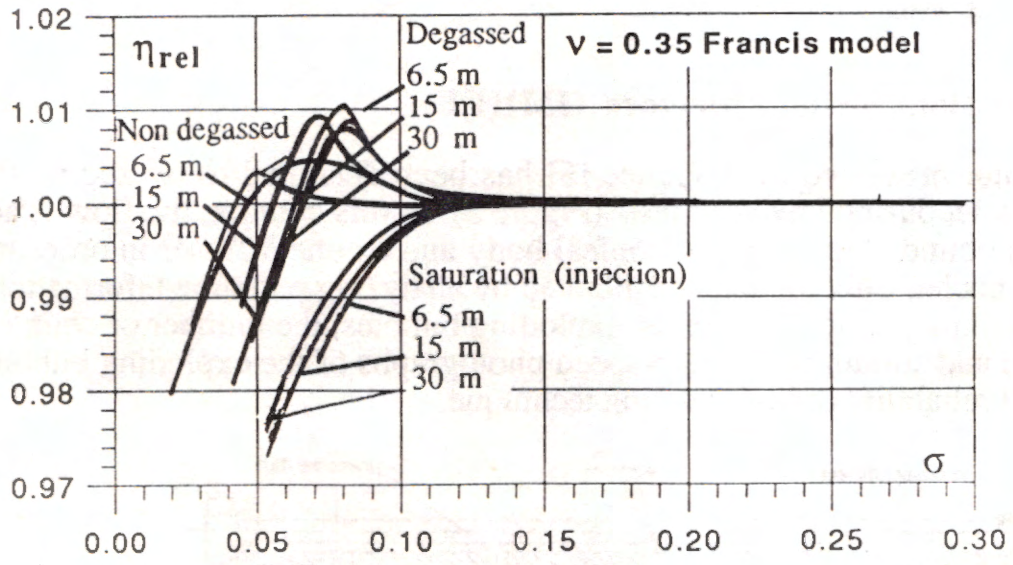
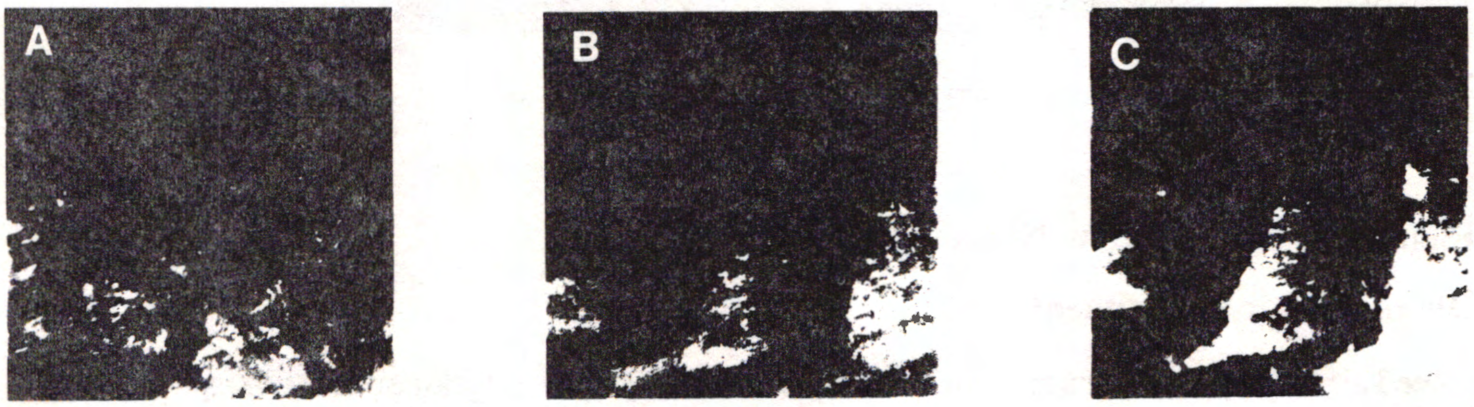


Figure 7 : Relative efficiency curves on Francis model ν = 0.35



A : H = 6.5 m **B : H = 15 m** **C : H = 30 m**

Figure 8 : Cavitation developments at σ = 0.08 for different heads

In this case the influence of the nuclei injection is very important. For example, the extreme $\sigma_{standard}$ values, as defined in Figure 12, corresponding to a 6.5 m head with non-degassed water (open loop condition) and to the 6.5 m head saturation characteristic are 0.04 and 0.11 respectively. Such an uncertainty in the prototype machine setting level can lead to bad consequences.

4.2 OPEN-CIRCUIT RESULTS ANALYSIS

The performance curves with non-degassed water, degassed water and nuclei injection leading to saturation are compared to the corresponding nuclei distributions and dissolved air content. As can be observed in the efficiency curves for the cavitation-free operating condition, Figure 9, there is a big difference between the values corresponding to the three cases.

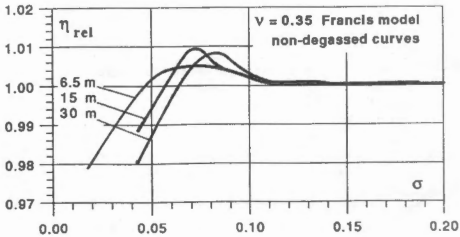


Figure 9 : Relative efficiency curves, non-degassed water (open circuit)

By considering all the results reported in Figure 7, these non-degassed curves are far from reaching the saturation characteristic. This can easily be explained by studying the nuclei distributions for the 3 test heads, Figure 11.The cavitation development is governed by the active nuclei content. Performing tests using non-degassed water, i.e. with a high dissolved air content, Figure 10, does not correspond to a high active nuclei content. Non-degassed water does not therefore generate large cavitation development.

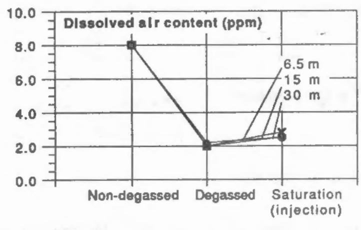


Figure 10 : Dissolved air content for different nuclei distributions

Performing cavitation tests using non-degassed water leads to large relative fluctuations in the measurements, and obtaining accurate results takes a long time. Moreover, the nuclei content corresponding to the non-degassed water case depends to a large extent on the whole time history of the liquid particles in the test rig, and this content is also likely to vary in time. In our opinion, it is more consistent to work with a low dissolved gas content, giving accurate measurements and a homogeneous monophasic flow, and by seeding nuclei up to the content corresponding to the saturation cavitation characteristic of the model.

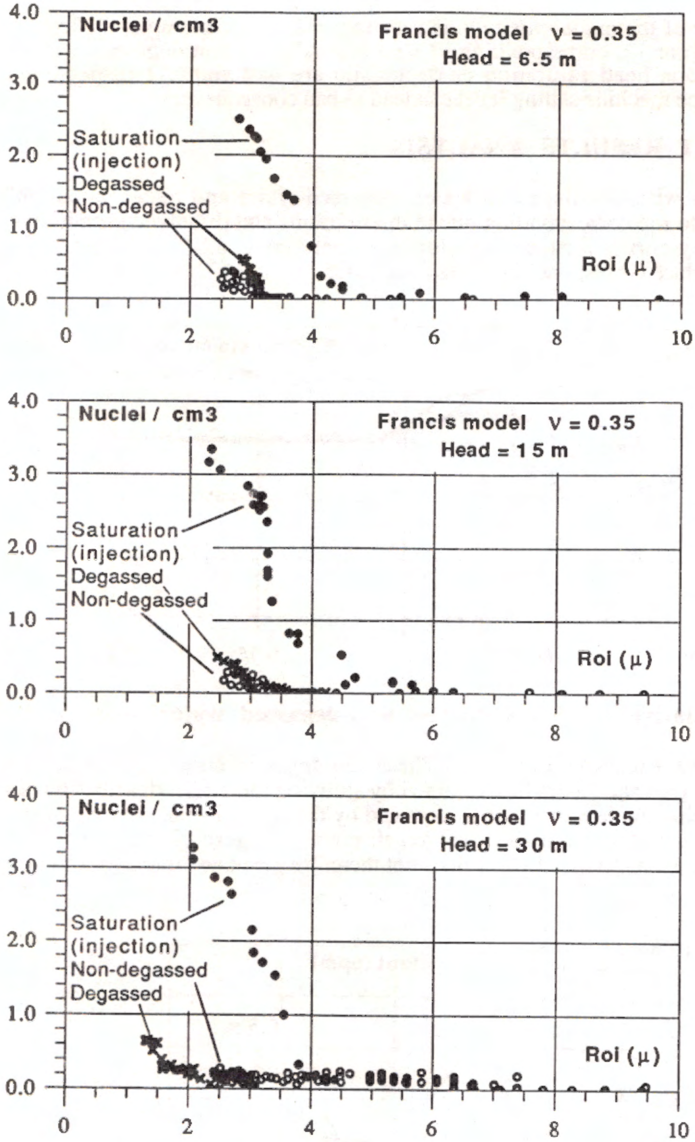


Figure 11 : Nuclei distributions.

4.3 Cavitation inception

As cavitation inception conditions are always investigated during the cavitation tests for the prototype setting evaluation of the σ-plant value, the influence of the nuclei content must be taken into account. The results of the influence of the water nuclei content on the onset of outlet cavitation are presented. Outlet cavitation inception depends entirely on the upper limit of the nuclei size distribution. The onset of cavitation is related to the occurrence of large critical pressure nuclei close to the vapour pressure. If the sigma value is decreased, as long as no nucleus is activated, no cavitation takes place (σ_1 and σ_2 in Figure 12). As soon as one nucleus, corresponding to σ_3 in Figure 12, is activated, cavitation can develop. This means that knowledge of the water nuclei distribution and pressure distribution in the runner makes it possible to predict precisely the cavitation inception. Even if the pressure distribution in the runner is not determined, it is essential to make a correlation between cavitation and water quality to understand the results and to give them a physical explanation.

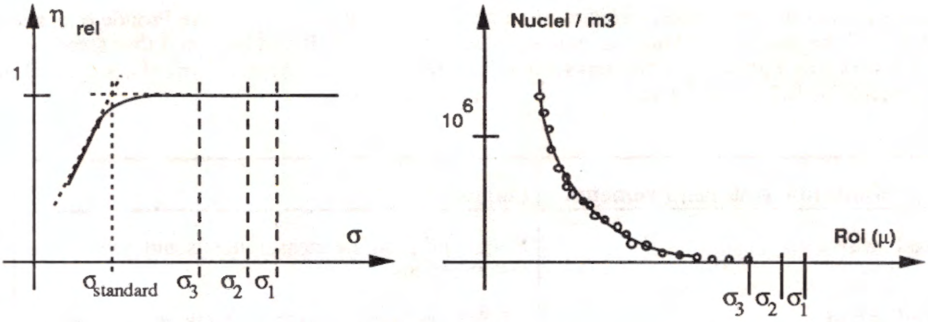


Figure 12 : Influence of the water nuclei distribution on the outlet cavitation inception

Prediction of the σ incipient value is made for this test from an estimation of the minimum pressure. Comparison with the standard method of detecting cavitation inception by observation leads to a good correlation between these two methods, see Figure 13.

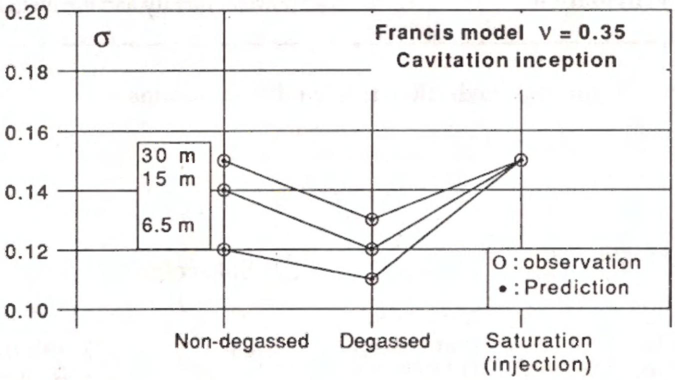


Figure 13 : Cavitation inception observation and prediction

5. CONCLUSIONS

For Francis turbines, outlet cavitation is an important phenomenon for determining the prototype setting level. To predict the full-scale cavitation characteristics, it is technically interesting to provide reliable model cavitation tests. This can be achieved through similar cavitation development in the model and the prototype.

The so-called model cavitation saturation characteristic is shown to correspond to the full-scale characteristic. It is then necessary to obtain this saturation characteristic during model tests. This can be achieved by increasing the "active" cavitation nuclei content, either by increasing the test head, by injecting nuclei into the water, or in another way by using non-degassed water.

Increase the head to activate more nuclei can cause unacceptable distortions in the cavitation development if the Froude similarity is not respected.

Investigation of a possible way to increase the nuclei content by performing cavitation tests with high dissolved gas content in the water shows that a high gas content does not mean high cavitation nuclei content, and does not lead to the required saturation characteristic. Moreover, this water condition leads to a two-phase flow which can affect the stability and the accuracy of the hydraulic parameter measurements.

It is of prime importance to measure the nuclei distribution to check the test rig water quality, as the active nuclei govern the whole cavitation development process. Moreover, these nuclei distributions allow accurate prediction of the outlet cavitation inception when the pressure distribution in the runner can be estimated.

Based on the results of all our investigations, guidelines for performing Francis model cavitation tests are suggested.

The best way to perform a cavitation test is to use a head as close as possible to the Froude one, and to inject nuclei until the cavitation saturation characteristic is reached. It can be noted that saturation is obtained for a very low water nuclei content such as $1.0 \cdot 10^6$ to $2.0 \cdot 10^6$ nuclei per m^3. These guidelines can be summarized as follows in Table 1.

Specific cavitation test requirements	Purpose
Degassed water	Easier and accurate measurements and good visualizations
Specified head	As close as possible to the Froude one and using the σ definition, given in the IEC code, which minimizes the Froude effect, when cavitation takes place at the runner outlet
Nuclei injection	To obtain the cavitation saturation characteristic which corresponds to the full-scale cavitation characteristic
Active nuclei size distribution measurement	To control the water quality and the incipient σ value

Table 1 : Francis turbine cavitation test guideline summary

NOTATIONS

R	:	Nuclei radius	(mm) or (μ)
L	:	Chord length	(mm) or (m)
E	:	Specific hydraulic energy	(J / kg)
H	:	Head	(m)
Cp	:	Pressure coefficient	(-)
σ	:	Cavitation number	(-)
ν	:	Specific speed number	(-)
λ_L	:	Geometric scale	(-)
λ_E	:	Specific energy scale	(-)
η_{rel}	:	Relative efficiency	(-)
N	:	Nuclei content	(nuclei/m^3)

Subscripts :

o i	:	Minimum unstable initial value
m	:	Model
p	:	Prototype
Fr	:	Froude

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