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FRANCIS CAVITATION TESTS WITH NUCLEI INJECTION : A NEW TEST PROCEDURE

ESSAIS DE CAVITATION AVEC INJECTION DE GERMES DANS LES TURBINES FRANCIS : UNE NOUVELLE PROCEDURE D'ESSAIS

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Summary

Experimental studies have shown that outlet cavitation of a Francis turbine is influenced by the active nuclei content of the test loop water, up to a limit curve called the saturation characteristic. To determine the importance of this influence in operating conditions, tests are performed for a $\nu = 0.38$ Francis model, for many operating points.
Moreover, based on the resolution of the Rayleigh-Plesset equation, it can be shown that, even with a low nuclei content of the plant water, the cavitation characteristic of the full-scale machine should correspond to the saturation curve determined on the model. To verify the condition on this minimum amount of nuclei, *in-situ* measurements are performed.

Résumé

Les études expérimentales ont montré que la cavitation de sortie d'une turbine Francis est fortement influencée par la teneur en germes actifs de l'eau d'essai, jusqu'à une limite, appelée courbe de saturation. Afin de déterminer l'importance de cette influence dans le domaine d'exploitation d'une turbine, des essais sont effectués sur un modèle de turbine Francis de vitesse spécifique $\nu = 0.38$, pour de nombreux points de fonctionnement.
D'autre part, sur la base de la résolution de l'équation de Rayleigh-Plesset, on peut démonter qu'il suffit d'une faible teneur en germes de l'eau prototype pour être en similitude de saturation. Afin de vérifier cette condition de teneur minimale, une campagne de mesures de germes *in-situ* est effectuée.

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1. INTRODUCTION

In order to provide reliable cavitation tests on Francis models, IMHEF has carried out many studies on the influence of the test head and the cavitation nuclei content on the model operation [1,2]. As a major result, it was found that increasing the test head or the nuclei content leads to a saturation of their influences, this limit σ-efficiency curve being called the saturation characteristic [3,4,5]. But, to guarantee similar cavitation developments on model and prototype, it is suitable to perform the cavitation tests as closely as possible to the Froude similarity operating condition, to ensure similar pressure distributions and similar performances [6,7]. It is then necessary to inject nuclei to reach the saturation characteristic curve.

To determine the importance of these nuclei content influences in operating condition, cavitation tests were performed for a ν = 0.38 Francis model, for many operating points. The result of this investigation shows that a large range of the operating domain can be influenced by the nuclei content.

Moreover, solving the Rayleigh-Plesset equation makes it possible to study the behavior of a single bubble in the runner flow field. It can explain the saturation effect, and show that if saturation is reached on the model, it should lead to saturation in the full-scale machine, as the saturation effect is governed by a limitation of the volume available to the bubble growth. As an important result, a minimum nuclei content in the full-scale water must be reached to ensure a saturation cavitation characteristic.

Then, a test campaign is performed to determine the *in-situ* nuclei distributions for several water qualities. As a major result, it is shown that *in-situ* nuclei distributions are large enough to correspond to a saturation cavitation characteristic.

In conclusion, it is essential to define the saturation curve during Francis model cavitation tests, to be in similarity with the full-scale machine.

Based on these investigations, a new procedure for Francis model cavitation tests is suggested, which leads to a precise determination of the saturation characteristic.

2. PRESENT STATE OF KNOWLEDGE

2.1 Cavitation saturation characteristic

During cavitation tests on a Francis turbine, the influence of the water nuclei content and the test head is well known. Figure 1 shows these influences, and, more particularly a typical threshold beyond which the performances are no longer affected either by the test head or the nuclei content. All the curves collapse to a single curve, called the cavitation saturation characteristic.

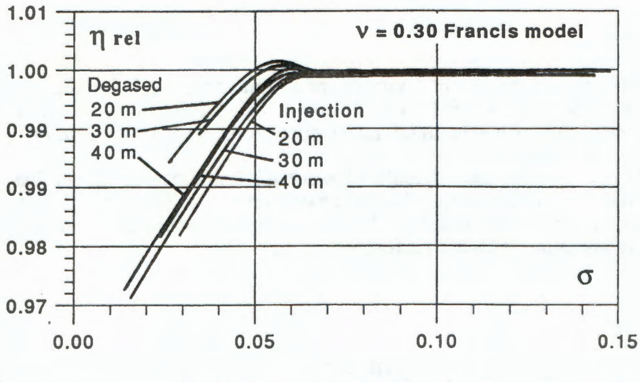

Figure 1 : Cavitation characteristic performance curves for a ν = 0.30 (nq = 47) Francis model.

2.2 Froude influence

The saturation effect is directly driven by a limitation of the volume available to the bubble growth, in the region where the flow pressure is lower than the vapor pressure. The saturation characteristic can be obtained by increasing either the test head or the water nuclei content. However, by increasing the test head, the model sometimes diverges greatly from the Froude similarity with the prototype, which leads to unacceptable distortions in the cavitation developments. This effect can be explained by expressing the pressure distribution in the runner (Figure 2).

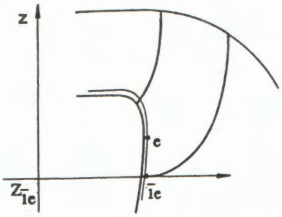

Figure 2 : Streamline in a Francis runner

The Bernoulli equation written between the point e and Ie, see Figure 2, along a streamline in the rotating frame of reference is expressed as follows:

$$\frac{p_e}{\rho} + gZ_e + \frac{W_e^2}{2} - \frac{U_e^2}{2} = \frac{p_{Ie}}{\rho} + gZ_{Ie} + \frac{W_{Ie}^2}{2} - \frac{U_{Ie}^2}{2} + E_{r_{e+Ie}} \qquad (1)$$

According to the velocity triangle we have the following geometrical relation:

$$W_e^2 - U_e^2 = \frac{Cm_e^2}{\sin^2\beta} - U_e^2 \qquad (2)$$

The local pressure coefficient c_{pe} is defined:

$$c_{pe} = \frac{p_e - p_{Ie}}{\rho E} \qquad (3)$$

and can be expressed by substituting (2) in (1)

$$c_{pe} = \frac{1}{\sin^2\beta_{Ie}} \frac{Cm_{Ie}^2}{2E} - \frac{1}{\sin^2\beta_e} \frac{Cm_e^2}{2E} - \left[\frac{U_{Ie}^2}{2E} - \frac{U_e^2}{2E}\right] + \frac{gR_{Ie}^2}{E}\left[\frac{Z_{Ie}}{R_{Ie}} - \frac{Z_e}{R_{Ie}}\right] + \frac{E_{r_{e+Ie}}}{E} \qquad (4)$$

If we introduce the flow coefficient φ_{Ie} and the energy coefficient ψ_{Ie}, (4) becames:

$$c_{pe} = \left[\frac{1}{\sin^2\beta_{Ie}} - \frac{1}{\sin^2\beta_{Ie}} \frac{Cm_e^2}{Cm_{Ie}^2}\right] \frac{\varphi_{Ie}^2}{\psi_{Ie}} - \frac{1}{\psi_{Ie}}\left[1 - \frac{R_e^2}{R_{Ie}^2}\right] + \frac{g\,R_{Ie}}{E}\left[\frac{Z_{Ie}}{R_{Ie}} - \frac{Z_e}{R_{Ie}}\right] + \frac{\psi_{r_{e+Ie}}}{\psi_{Ie}} \qquad (5)$$

The two first terms depends only on geometry, and on φ_{Ie} and ψ_{Ie}, which as the basic similarity coefficient are identical on model and prototype.

The third term will be equal on model on prototype only if the Froude similarity is respected.

The last term depends partially on friction losses and therefore on Reynolds number, but its influence is rather small.

Then, the local cavitation coefficient, with reference to the $\bar{1}e$ point, can be defined as:

$$\sigma_c = \frac{p_{\bar{1}e} - p_v}{\rho E} \tag{6}$$

which, with $p_e = p_v$, gives the general relation $c_{Pe} = - \sigma_c$.

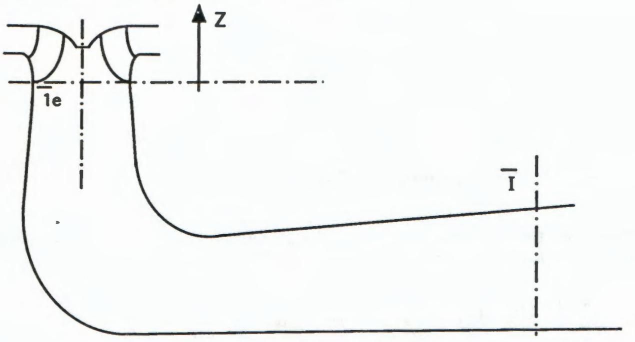

Figure 3 : Pressure reference in a Francis turbine

Now regarding the machine Thoma number (IEC Code), with reference to the $\bar{1}e$ point, we have :

$$\sigma = \frac{\frac{p_{\bar{I}} - p_v}{\rho} + \frac{C_{\bar{I}}^2}{2} - g\,(Z_{\bar{1}e} - Z_{\bar{I}})}{E} \tag{7}$$

The relation between the local cavitation coefficient and the machine Thoma number can be written as follows :

$$\sigma_c = \sigma - \frac{C_{\bar{1}e}^2}{2E} + \frac{E_{rd}}{E} \tag{8}$$

Then, the cavitation coefficient at the e location, σ_c becomes :

$$\sigma_e = \sigma_c - \frac{g\,R_{\bar{1}e}}{E}\left[\frac{Z_e}{R_{\bar{1}e}} - \frac{Z_{\bar{1}e}}{R_{\bar{1}e}}\right] \tag{9}$$

For the same operating points (φ,ψ) and σ values, the above equation (9) will remain valid for both model and prototype :

$$\sigma_{cM} = \sigma_{cP} \tag{10}$$

But, the cavitation coefficients at the same relative location will be different between model and prototype, as long as the Froude similitude is not respected.

The numerical example below shows the large influence of Froude similarity on Thoma number σ.

$R_{\bar{1}ep} = 2{,}5$ m ; $E_P = 500$ J/kg using Froude similarity, with R_{Ie_M} = 0,2 m leads to E_M = 40 J/kg which is obviously too low for testing.

The usual specific energy for such a test is in the order of E_M = 200 J/kg

The Figure 4 giving the σ value against the relative level $\frac{Z}{R_{Ie}}$ in the machine with σ = 0,1 at reference level Ie shows clearly that σ_M is almost constant and σ_P decrease strongly with the level.

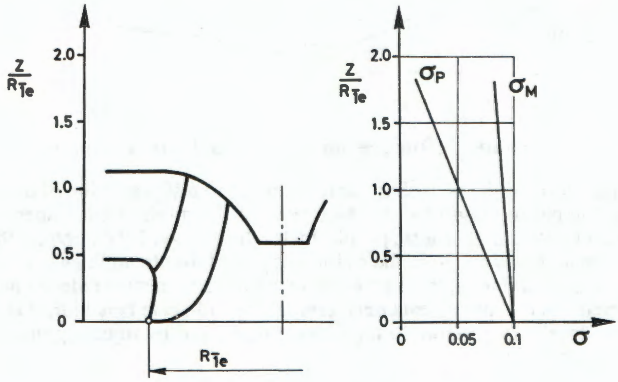

Figure 4 : Comparison of σ-values for model and prototype

With reference to the to the Ie point, equation (9) can be written as follows :

$$\sigma_e = \sigma_c - \frac{g\,Z_e}{R_{Ie}} \cdot \frac{R_{Ie}}{E} \quad (11)$$

Then, according to equation (5), by extending the same analysis to the whole pressure field in the runner, we can compare the pressure coefficient corresponding to two different specific hydraulic energy E_1 and E_2. For the same operating point φ, ψ we have

$$c_P(E_1) - c_P(E_2) = \left[\frac{g\,R_{Ie}}{E_1} - \frac{g\,R_{Ie}}{E_2}\right]\left[\frac{Z_{Ie} - Z_e}{R_{Ie}}\right] \quad (12)$$

Which means that, for a specific hydraulic energy E_2 higher than E_1, the pressure coefficients are similar at the Ie point , but for the other locations, we have $Z_{Ie} < Z_e$ and then:

$$c_P(E_1) - c_P(E_2) < 0 \text{ since} \quad (13)$$

This effect is illustrated in Figure 5, by comparing calculated pressure coefficient distributions between a full-scale ν = 0.30 Francis turbine and its model.

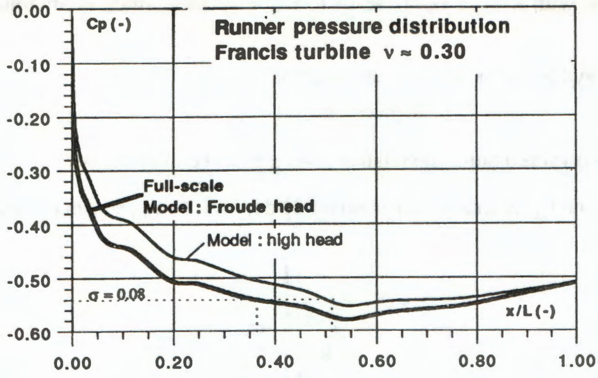

Figure 5 : Froude influence on a ν = 0.30 Francis model

The relative positions of the p_v isobar, corresponding to a sigma value of 0.08, for example, are 35 %, resp. 50 % of the chord length for the prototype or the model with respect to the Froude similarity, resp. the model with a higher test specific hydraulic energy. By extending this result to all the streamlines, the vertical extension along the trailing edge and the streamlines is smaller for a high test specific hydraulic energy, and then, the whole cavitation development is reduced and the machine performance less affected. As the model tests must predict the full-scale behavior, it is recommended to perform the tests as closely as possible to the Froude head, and by injecting nuclei to reach the cavitation saturation characteristic.

3. INFLUENCE OF THE NUCLEI ON A COMPLETE OPERATING DOMAIN

All the studies about nuclei influence on the Francis model performance were made close to the best efficiency point, as the cavitation developments correspond to outlet bubble cavitation. But, in operating conditions, the useful domain is wider than the particular point. Thus; it is important to examine the nuclei influence on a complete operating domain.

3.1 Test procedure

Tests are performed for a ν = 0.38 (nq = 60) Francis model. The results corresponding to the usual way to determine the cavitation - performance curve, using degassed water, are compared with the saturation characteristic obtained with nuclei injection. The test specific hydraulic energy is kept constant (294 J/kg) and the number of installed injectors increases from 2 to 17 modular elements, up to the saturation characteristic. In parallel, nuclei measurements are performed to determine precisely the corresponding nuclei distributions.

3.2 Results

Figure 6 represents the relative efficiency hillchart, with all the studied operating points, with the corresponding performance curves. The comparison is made between the results with degassed water and with nuclei injection, up to the cavitation saturation characteristic. By examining these curves, we can see that more than $^3/_4$ of the operating domain is influenced by the water nuclei content. In the case of the B point, the standard sigma value increases of more than 30%, between the results of degassed water and saturation. Moreover, only about 1 active nucleus per ccm is enough to reach the saturation characteristic.

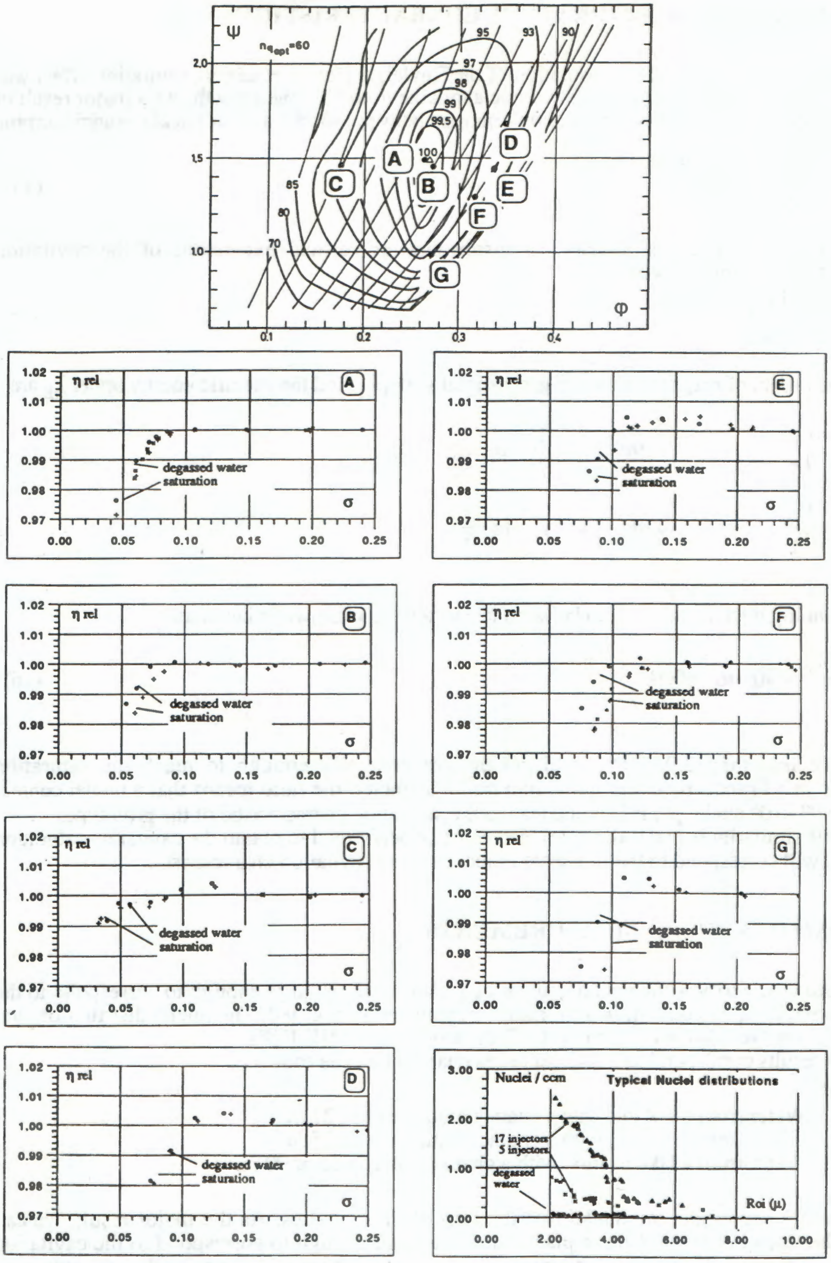

Figure 6 : Influence of the nuclei content on a ν = 0.38 Francis model.

4. SIMILARITY OF SATURATION CHARACTERISTIC

Based on the results of the resolution of the Rayleigh-Plesset equation, saturation effect was explained [4, 5, 8], by a limitation of the volume available to the bubble growth. As a major result of this study, the condition of similar cavitation volumes between model and full-scale Francis turbine can be written as :

$$\frac{N_m}{N_P} = \left(\frac{L_P}{L_m}\right)^3 \left(\frac{E_m}{E_P}\right)^{3/2} \qquad (14)$$

With respect to the Froude similarity, to ensure similar vertical extensions of the cavitation developments, this condition becomes :

$$\frac{N_m}{N_P} = \left(\frac{L_P}{L_m}\right)^{3/2} = \lambda_L^{-3/2} \qquad (15)$$

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

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

$$\lambda_L = \frac{E_m}{E_P} \qquad \text{with. } \lambda_E = 1 \text{ to } \frac{1}{5}$$

The corresponding nuclei content ratio between test water and plant water becomes :

$$\frac{N_m}{N_P} = 90 \text{ to } 8000. \qquad (16)$$

Since less than $2.0 \cdot 10^6$ nuclei per m^3 are generally enough to reach the saturation characteristic in a Francis model of a 400 mm outlet diameter, the ratio means that a nuclei content larger than $0.03 \cdot 10^6$ nuclei per m^3 should lead to the saturation characteristic of the prototype.

If this similarity is reached, model tests must be performed to obtain the cavitation saturation curve, which will correspond to the full-scale Francis turbine cavitation characteristic.

5. *IN-SITU* NUCLEI MEASUREMENTS

In order to verify if the nuclei content of a plant water is large enough to correspond to the minimum above-defined content, *in-situ* measurements are performed. The nuclei distributions are measured with the New Nuclei Counter (NNC) developped at IMHEF [8].

The results correspond to 3 different sites characterized as follows :

1. Water from the Alps, with a characteristic head of 21 m.
2. Water from the Alps, with a characteristic head of 85 m.
3. Water from a lake in Jura, with a characteristic head of 90 m.

Figure 7 represents the nuclei distributions of these 3 sites. As the major result, we ean notice that the nuclei content of these plant water are large enough to correspond to the cavitation saturation characteristic. In fact, these distributions are as large as the model one leading to saturation.

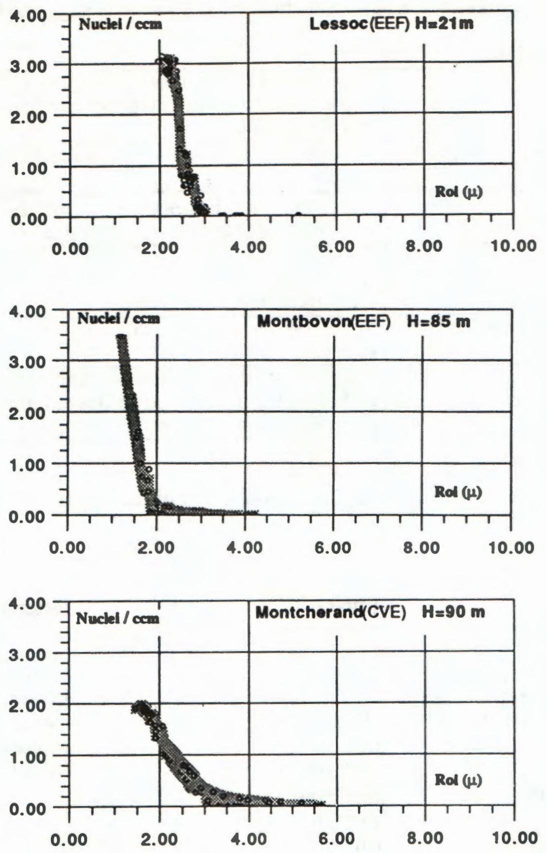

Figure 7 : *In-situ* nuclei distributions

6. PROPOSED TEST PROCEDURE

The cavitation test is one of the most important to determine the characteristic behavior 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. This can be achieved through similar cavitation developments in the model and the prototype. Thus, it is shown that the cavitation saturation curve defined in the model corresponds to the cavitation characteristic of the full-scale Francis turbine. To reach this saturation curve, either nuclei content or test energy increases can be provided. But when not respecting the Froude similarity, unacceptable distortions in the cavitation development will occur and the cavitation volumes between model and prototype won't be similar.

Moreover, based on a parametric study of the Rayleigh-Plesset equation, a nuclei content condition is defined to respect a similarity of the cavitation developments leading to saturation. *In-situ* measurements reveal that the nuclei content of a plant water is large enough to verify this condition. Then, the cavitation saturation curve obtained in a Francis model with nuclei injection and low test head, will correspond to the full-scale turbine cavitation behavior.

Based on the results of all investigations, a new cavitation test procedure is suggested :

Cavitation test conditions	
Degassed water	To minimize air bubble problems in the pressure lines, and to ensure a good quality of the flow visualization.
Test specific hydraulic energy E	As close as possible to the Froude head specific energy.
σ level reference	Using the σ definition given in the IEC code, with the reference level at the outlet edge.
Nuclei injection	To reach the model cavitation saturation curve, which corresponds to the cavitation characteristic of the full-scale Francis turbine.
Measurements of the active nuclei distribution	To control test water quality and cavitation inception value, σ_b .
Visual observations	Necessary to estimate the potential danger of pitting and to compare cavitation developments between different Francis runner, for example.

Table 1 : Test procedure for Francis turbines cavitation tests.

Notations

C	:	Velocity	(m/s)
Cm	:	Meridionnal velocity	(m/s)
E	:	Specific hydraulic energy	(J/kg)
E_{rd}	:	Specific hydraulic energy lost within draft tube	(J/kg)
H	:	Head	(m)
L	:	Chord length	(mm) or (m)
N	:	Nuclei content	(nuclei/m^3)
R	:	Nuclei radius	(mm) or (μ)
U	:	Peripheral velocity	(m/s)
W	:	Relative velocity	(m/s)
Z	:	Vertical position	(m)
cp	:	Pressure coefficient	(-)
p	:	Pressure	(N/m^2)
p_v	:	Vapor pressure	(N/m^2)
E_r	:	Losses	(J/kg)
Ω	:	Relative velocity	(m/s)
β	:	Blade angle	(-)
σ	:	Cavitation number	(-)
ν	:	Specific speed number	(-)
λ_L	:	Geometric scale	(-)
λ_E	:	Specific energy scale	(-)
η_{rel}	:	Relative efficiency	(-)
φ	:	Discharge coefficient	(-)
ψ	:	Energy coefficient	(-)
ρ	:	Density	(kg/m^3)

Subscripts

e	:	External, at the band
$\bar{1}e$	:	outlet of the runner (external)
Fr	:	Froude
o i	:	Minimum activated value
P	:	Prototype
M	:	Model
$\bar{1}$	:	Outlet edge of the runner blades
$\bar{I}$	:	Low pressure
$\bar{II}$	:	Outlet free level

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