A Phenomenological and Numerical Model for Scaling the Flow Aggressiveness in Cavitation Erosion

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France

LEGI

DGA

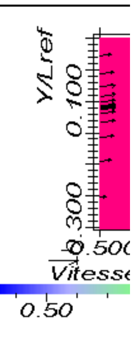
EDF
Electricité

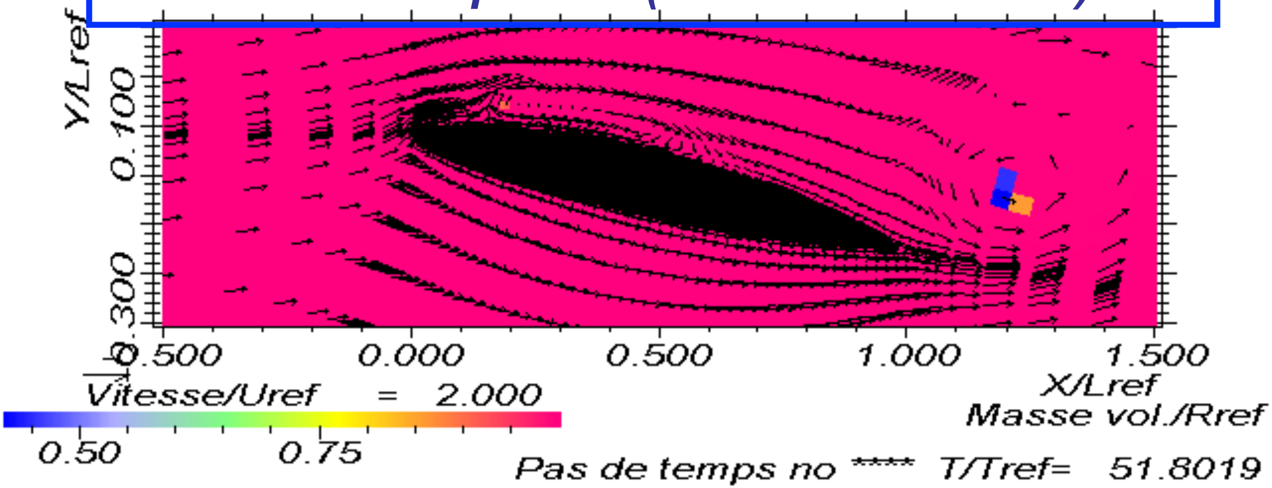
I. Targets

- evaluation of cavitation aggressiveness
- characterization
- prediction model

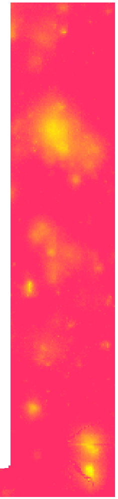
} *experimental and numerical studies*

incubation period (without mass loss)





pitting tests



II.a - Physical Scenario

Mechanism : Pressure Wave

[Fujikawa and Akamatsu, 80 ; Tomita and Shima, 89]

[Avellan and Farhat, 89 ; Fortes-Patella, 94]

⇒ **amplitude ~ 1GPa**

⇒ **celerity: 1500 m/s – 2000 m/s**

⇒ **duration: 10 ns up to 1 μs**

⇒ **indentation size: R ~ 100 μm ; h ~ 1 to 10 μm**

⇒ **collapses of vapour structures:**

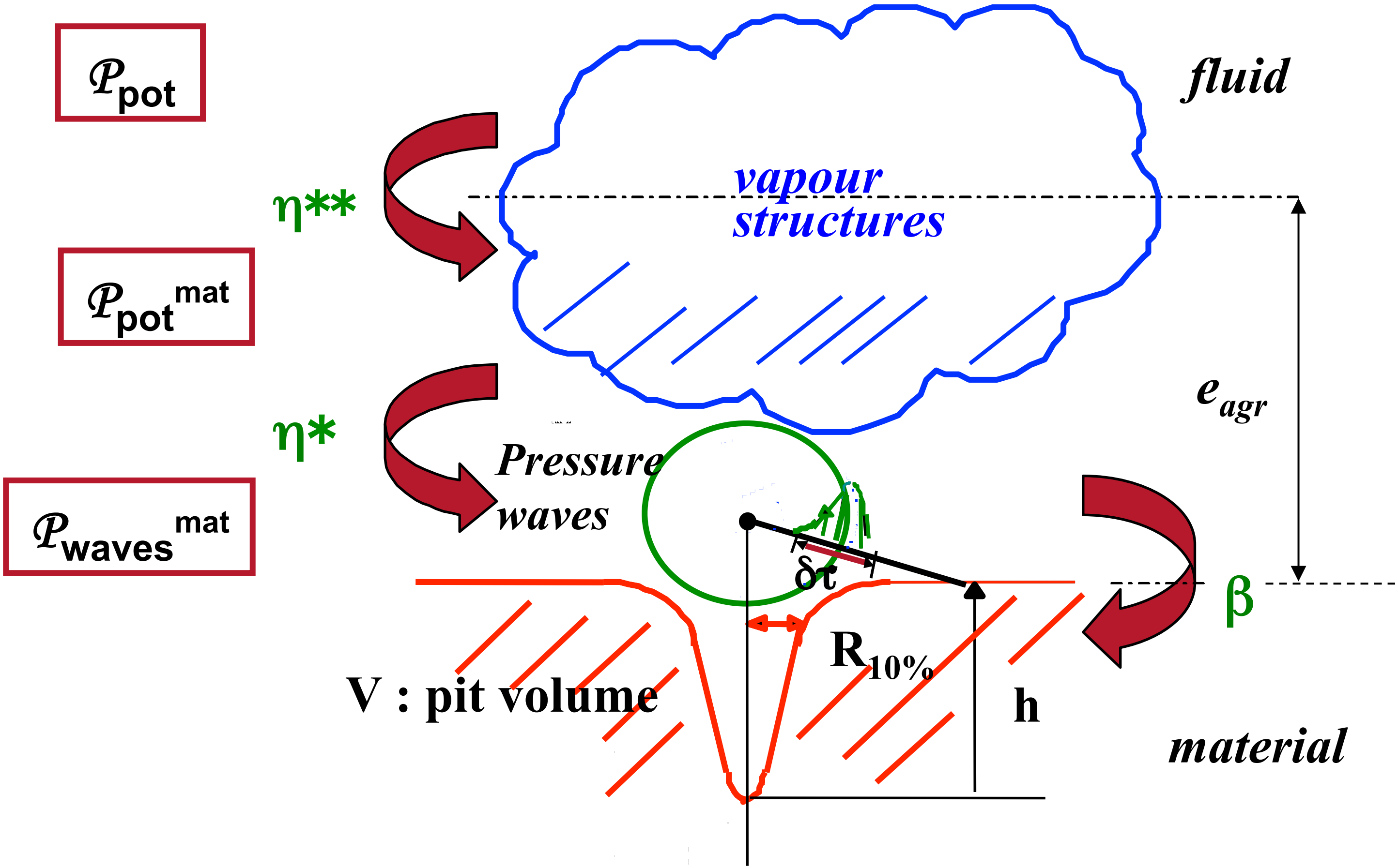
- **spherical bubbles**
- **vortex**

} ***[Vogel et al., 89 ; Ward et al., 90]***

- **microjet** ***[Phillip et al., 95]***

II.b – Physical Scenario

Energy Balance

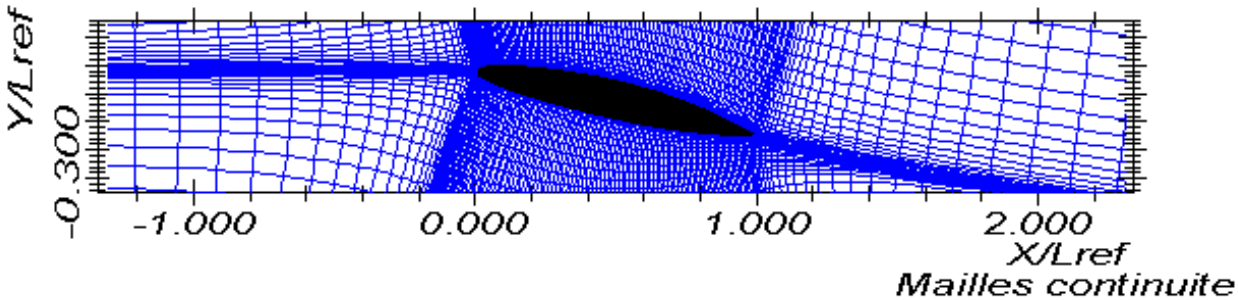


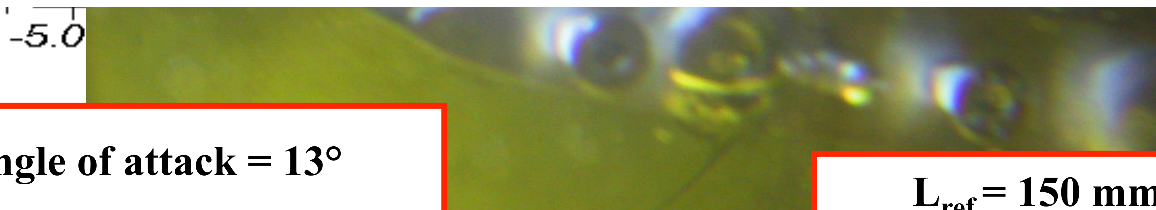
III.a - Flow Aggressiveness

- **numerical calculation of unsteady cavitating flows : « IZ »**

  (developed with the support of the French Space Agency CNES)

- **2D approach : hydrofoil geometry**





tatic press

rm f
ity

Angle of attack = 13°

U_{ref} = 9.4 m/s T_{ref} = 16 ms

$\sigma_{upstream}$ = 1.85

L_{ref} = 150 mm

of the wall

ental study (BEC – DGA)

III.b – Physical Modelling: Barotropic Approach

RANS equations :

- mass :

$$\partial\rho/\partial t + \text{div}\,\rho U = 0$$

- momentum :

$$\rho\, dU/dt = -\nabla P + \nabla\tau$$

• <u>Finite volume method</u> :

curvilinear orthogonal staggered meshes

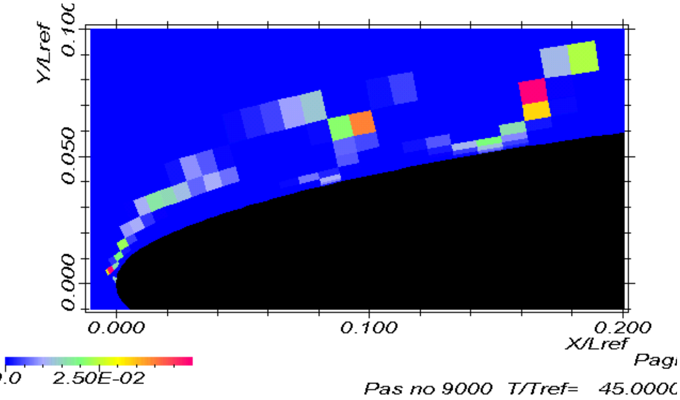
• implicit method :

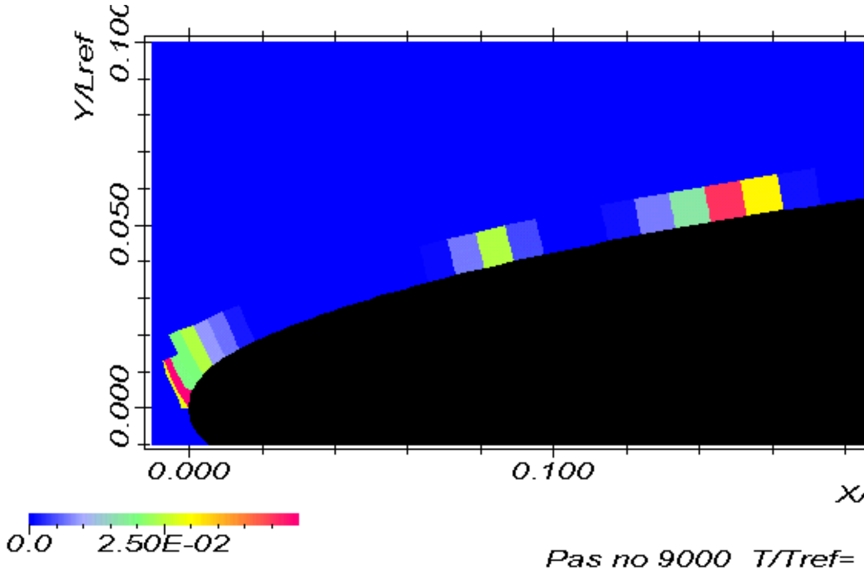
SIMPLE algorithm

<u>Turbulence model</u> : modified k-ε

(Cμ reduced when $0 < \alpha < 1$)

III.c - Flow Aggressiveness Potential Power $\mathcal{P}_{pot}^{mat}$





nitial study: **large mesh, few events (statistic representation)**

esults:

- **more aggressive zone at the cavity closure**
- **$P_{pot}^{mat}/\Delta S \propto V^3$**
- **non relevant influence of σ (erosion zone displacemen**

IV.a – Pressure Wave Power $\mathcal{P}_{waves}^{mat}$

[Challier et al., 2000 ; Fortes-Patella et al., 1999]

ubble dynamics: Keller's Model *[Prosperetti and Lezzi, 86]*

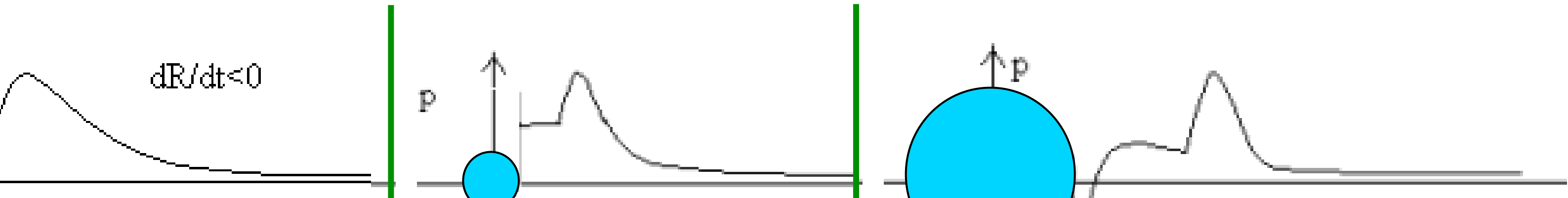
fluid compressibility *- viscous effects* *- surface tens*

- adiabatic non-condensable gas *- thermal effects are not taken into accou*

ressure Wave:

- **Tait equation** *[Cole, 48]*
- **1srt velocity potential approximation** *[Fujikawa and Akamatsu, 80]*

simulation code: P_{∞}, P_{g0}, R_0 $\Rightarrow$ $P(r,t)$, δt, $R(t)$, E_{wave}



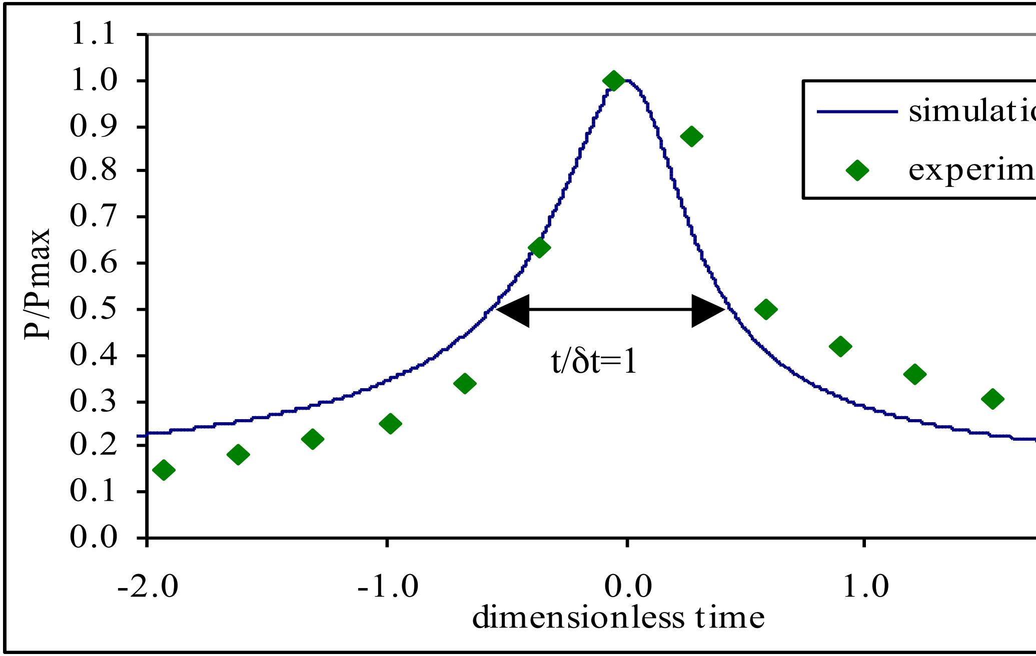
IV.b – Pressure Wave Simulation

n Dimensional Pressure Signal

stic Energy Approach:

$$_{de} \approx \frac{4\varsigma\pi P_{max}{}^2 r^2}{\rho C_\infty}\delta t$$

P ~ 1/r



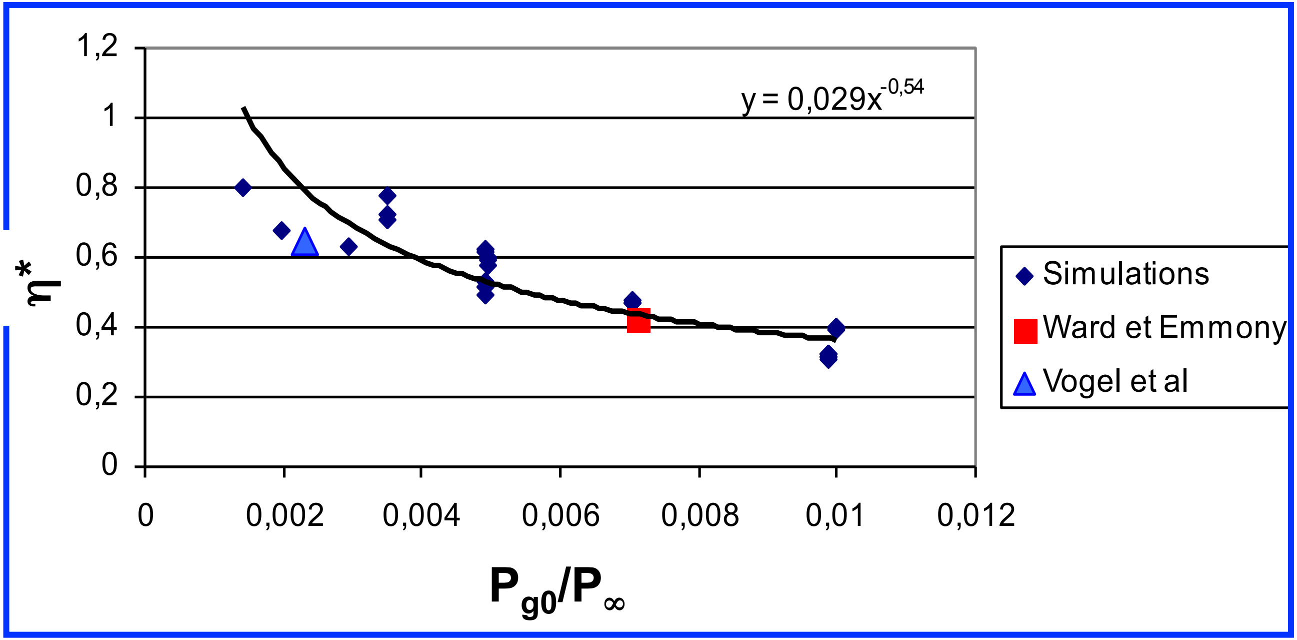
Time distribution of the pressure signal at a given radius "r".

δt: wave passage time.

[Isselin et al., 1998] : **pressure signal measured by a PVDF**

IV.c – Collapse Efficiency η^*

$$\eta^* = \frac{E_{wave}}{E_{pot}} = \frac{P_{waves}^{mat}}{P_{pot}^{mat}}$$



$P_{g0} \propto$ air contents *[Kato et al., 1996]*

lid" Code [Reboud, 1987]

licit, 2D Cylindrical Axisymmetric
Numerical Code

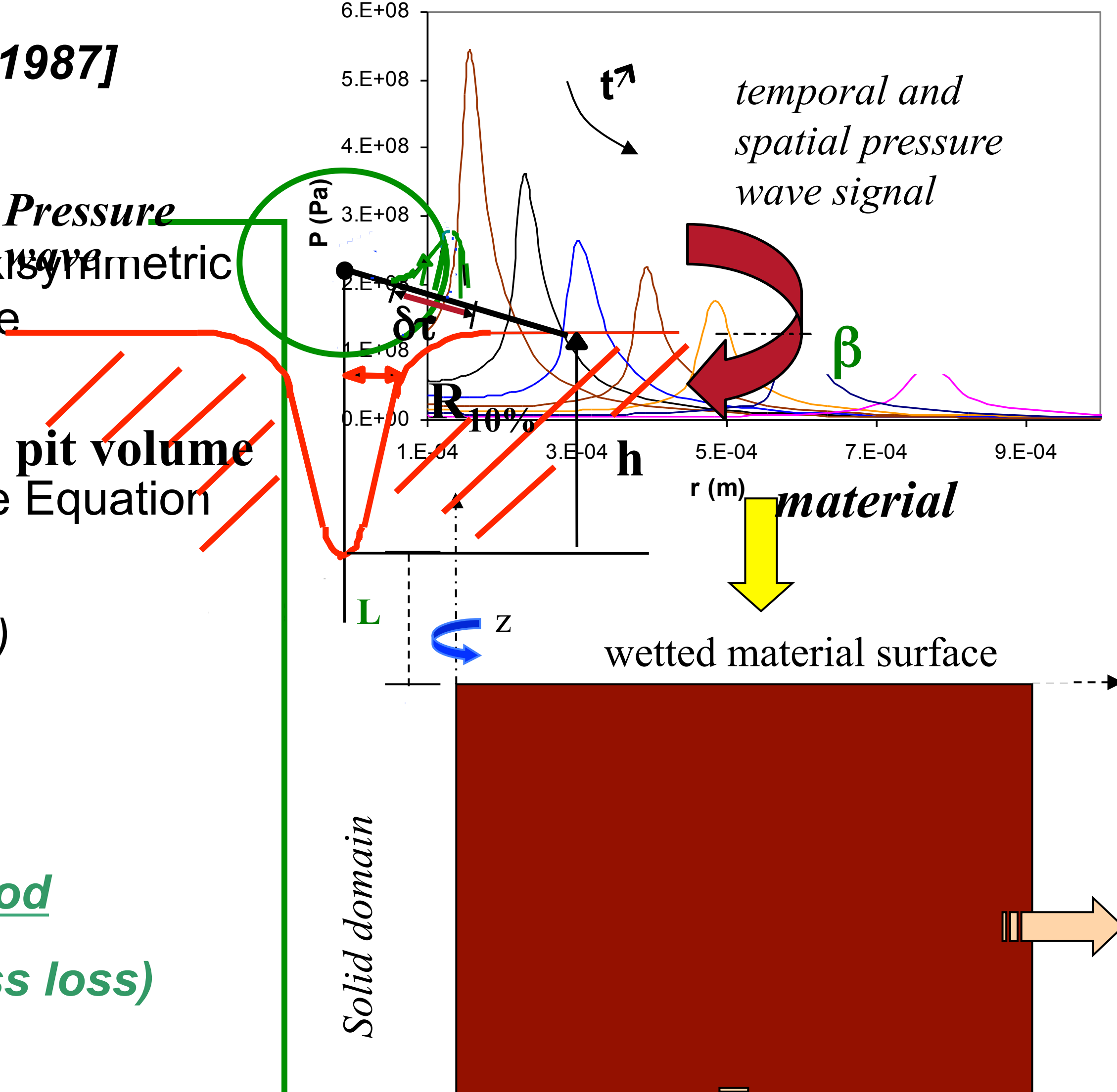
ntinuum Mechanics

astoplastic Constitutive Equation

E, ν, S_0, $C_L(E,\rho)$

(strain hardening)

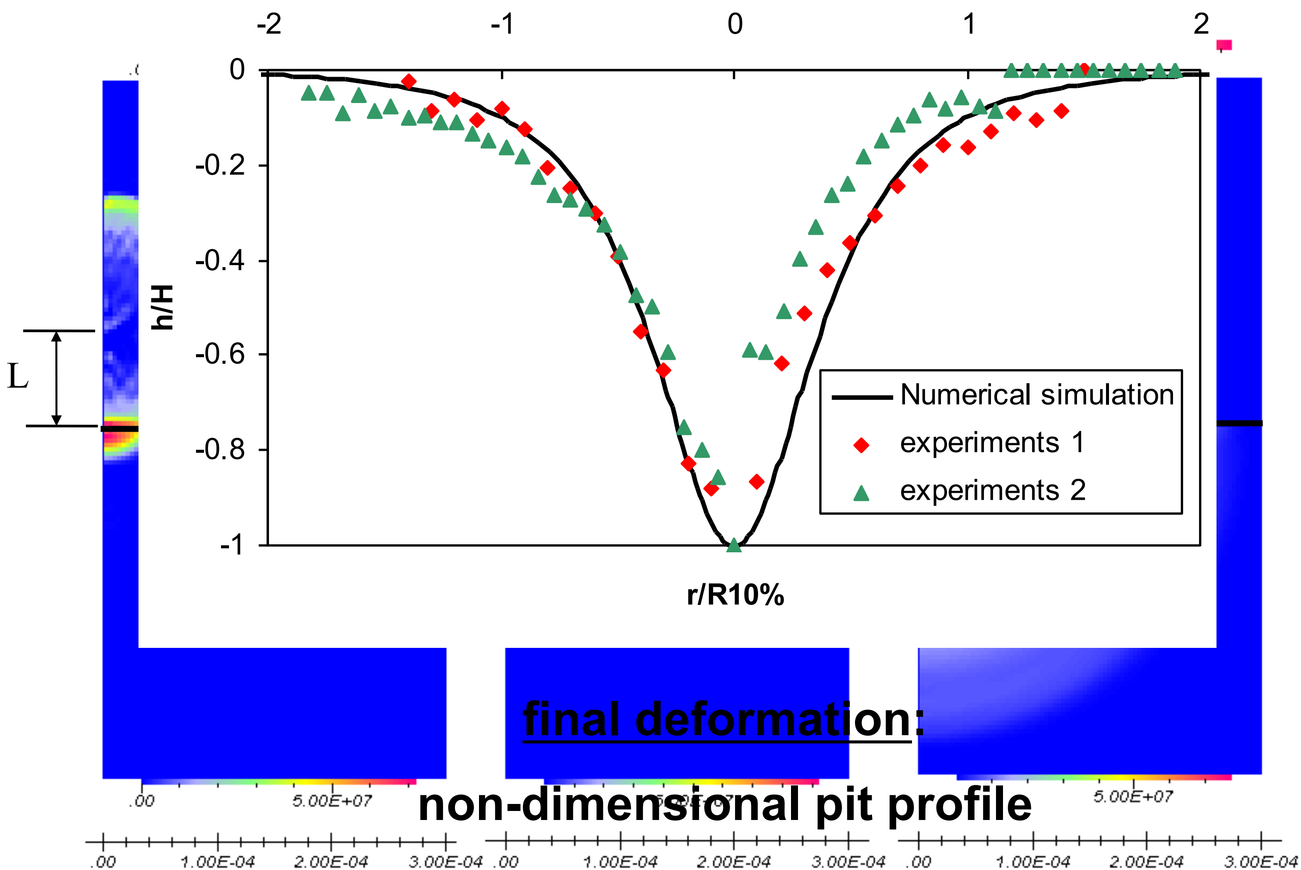
ite-Elements Method



Incubation period

(no fracture, no mass loss)

***Pressure wave characteristics* : P ~ 0.6 GPa ; dt ~ 30 ns ; L ~ 0.1 m**



final deformation:

non-dimensional pit profile

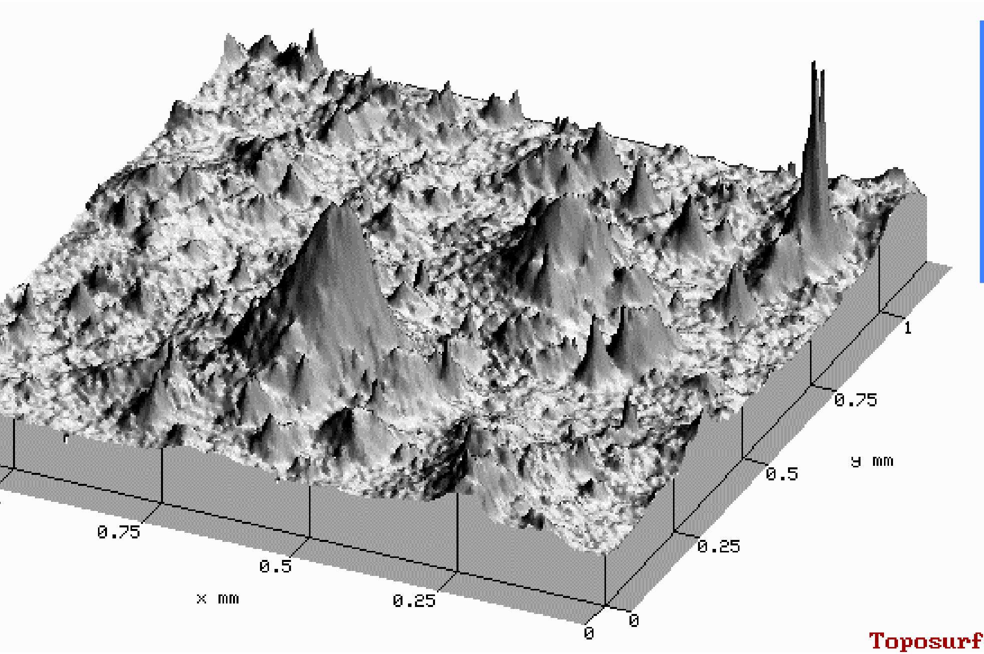
3D profilometer (EDF)

transient stress field in the material

Pressure f
in the wate

Cliq ~ 150

V.c – Fluid/Material Interaction: Energy Balance



$\beta_{aluminum} \sim 4\ (\pm\ 0.4)\ J/mm^3$

$\beta_{copper} \sim 20\ (\pm\ 3)\ J/mm^3$

$\beta_{SS} \sim 30\ (\pm\ 2)\ J/mm^3$

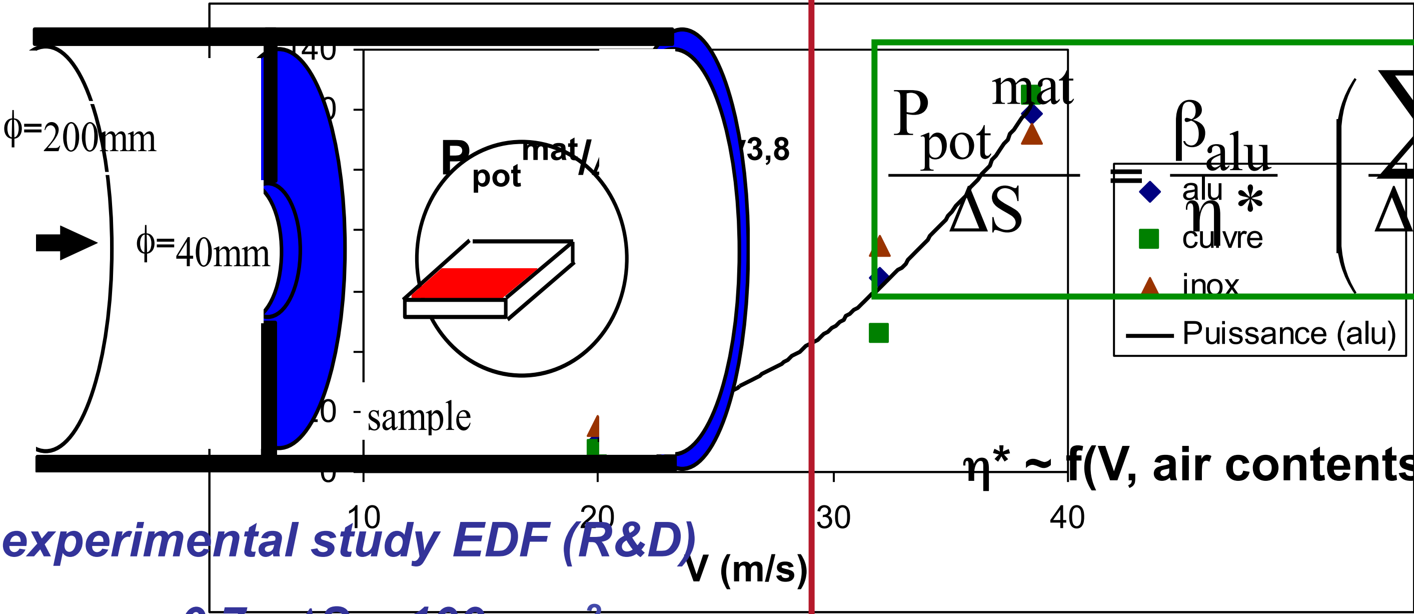
$$E_{wave} = \beta_{material}\ V_{p}$$

Local point of view

$$\frac{\dot{P}_{pot}^{mat}}{\Delta S} = \frac{P_{waves}^{mat}}{\Delta S\,\eta^*} = \frac{\beta_{material}}{\eta^*}\,\frac{\sum V_{pit}}{\Delta S\,\Delta t}$$

	Alu	Copper	S. S.
S_0 (MPa)	100	200	200-38 *strain hard*
E (GPa)	50	120	200
C_L (m/s)	5000	4700	5800
ν	0.3	0.33	0.3

VI – Application : Modulab



$$\frac{P_{pot}^{mat}}{\Delta S} = \frac{\beta_{alu}}{\eta_{alu}^{*}} \left(\frac{\sum V_{pit}}{\Delta S \;\; \Delta t} \right.$$

$\eta^* \sim f(V, \text{air contents})$

experimental study EDF (R&D)

σ = 0.7 ; ΔS = 100 mm²

samples: *aluminum*, *copper*, *SS 316L*

- $P_{pot}^{mat}/\Delta S$ ⇒ flow aggressiveness
- $P_{pot}^{mat}/\Delta S \propto V^3$ (numerical simulation)
- influence of flow velocity, geometric scale *[Lecoffre, 95]*, and materia

For a given cavitating flow

V, η^*, P_{pot}^{mat} } *cons*

Reference test:
20 m/s ≤ V ≤ 38.5 m/s

Damage:

VII – Final Comments

mprovements:

- **spherical bubbles collapses: simple model**
- **modelling of the influence of air contents**
- **evaluation of the vapour structures distance to the wall *(e_agr)***
- ***….***

Originality:

proposition and exploitation of a complete physical scenario:
cavitating flow ⇒ material

energetical approach: experimental and numerical study

numerical simulation of the pressure wave/material interaction

test methodology (EDF), analysis and treatment procedure [Choffat e

Complete prediction model based on simulations

Application to different geometries and materials

Tool for design, maintenance and monitoring

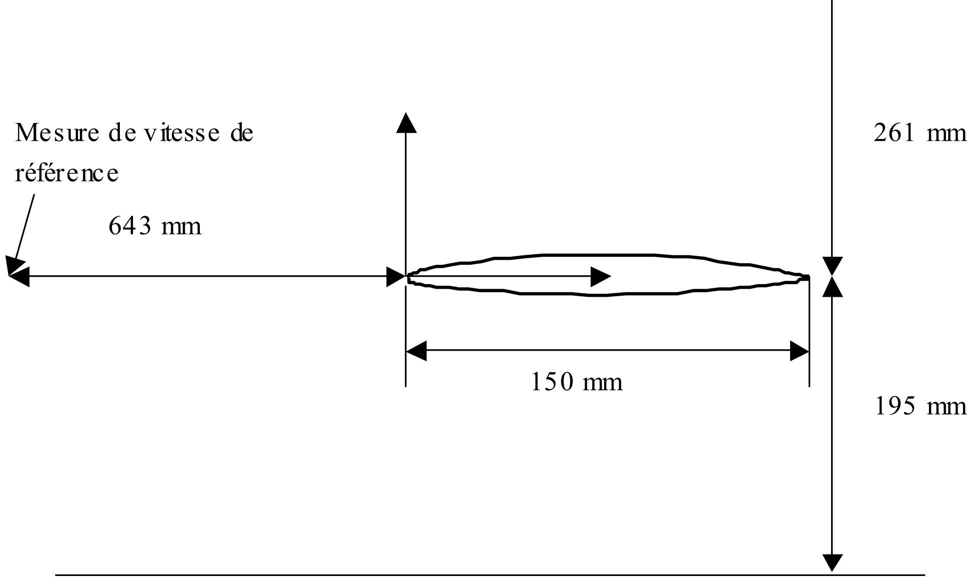
nodelling:

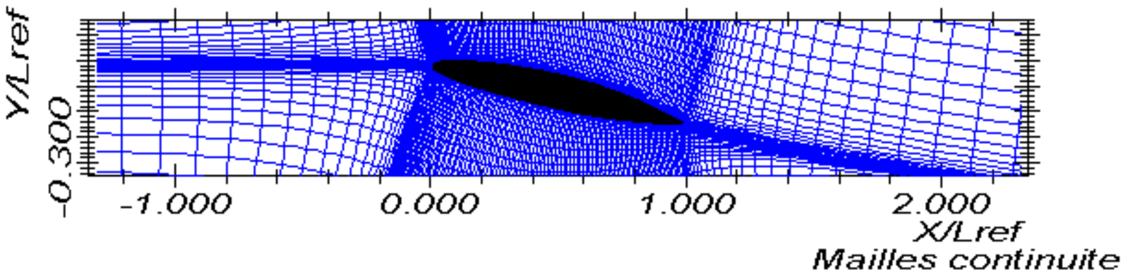
development of mass loss model

validation and improvement of proposed physical models

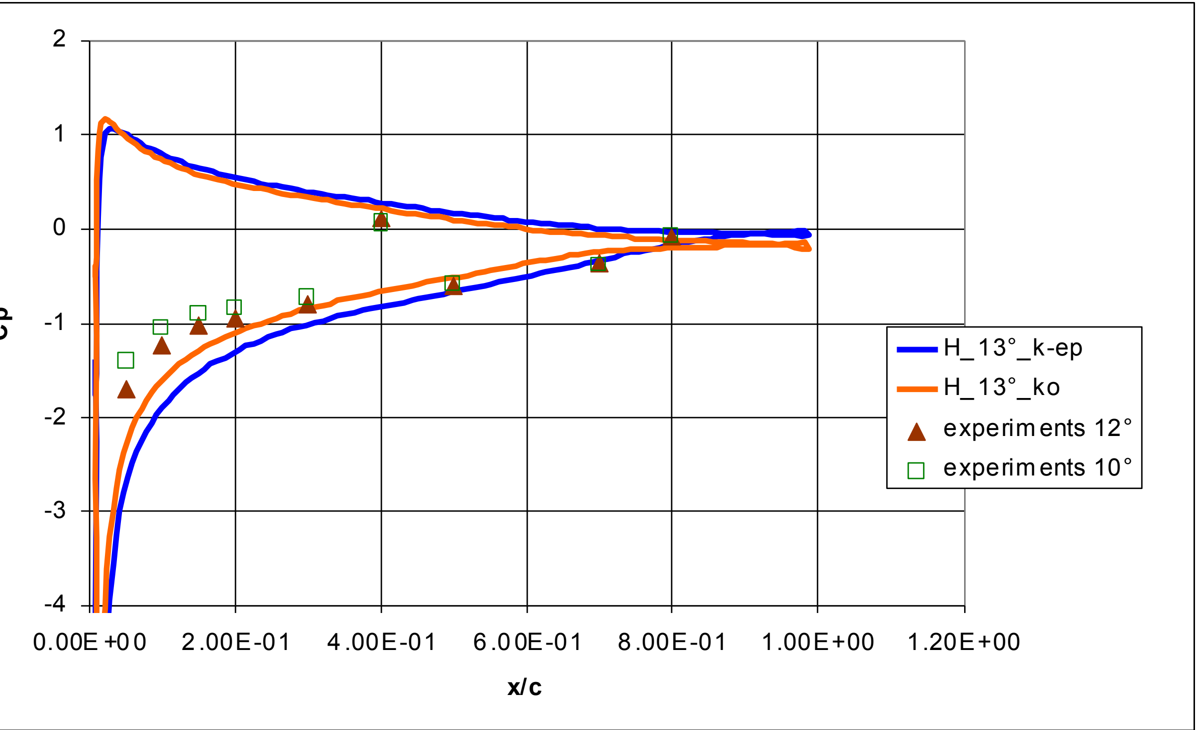
application : ship propellers, Diesel injectors, pumps

development of a 3D simulation code



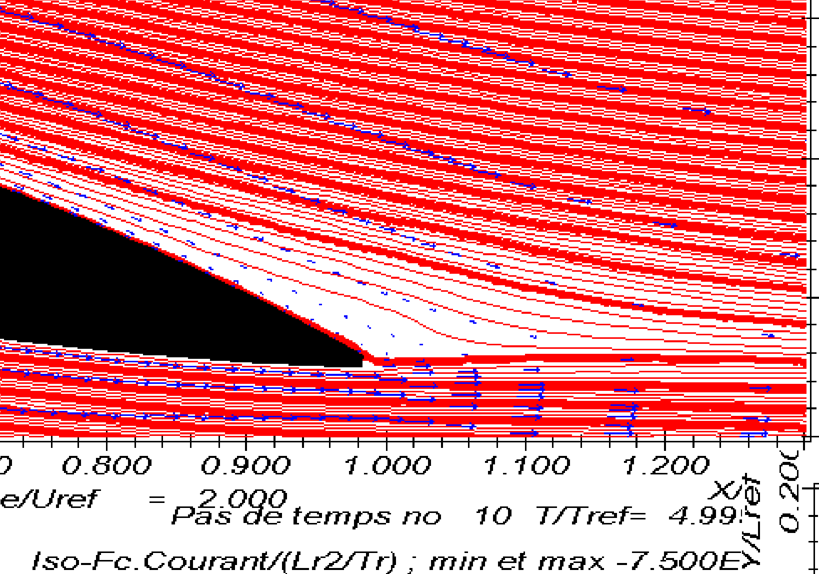


a) H Meshing: 180 x 73 nodes



$$C_p = \frac{P - P_{dow}}{\frac{1}{2}\rho U}$$

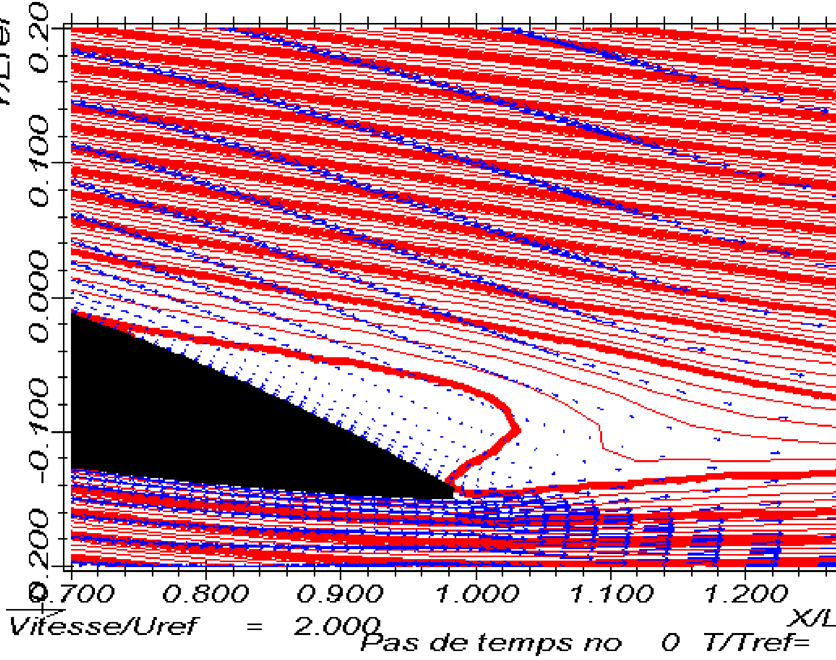
	13°_k-ε	13°_k-ω	12° exp	10° exp
lift	**0.57**	**0.47**	**0.42**	**0.38**
drag	**0.054**	**0.07**	**0.059**	**0.054**

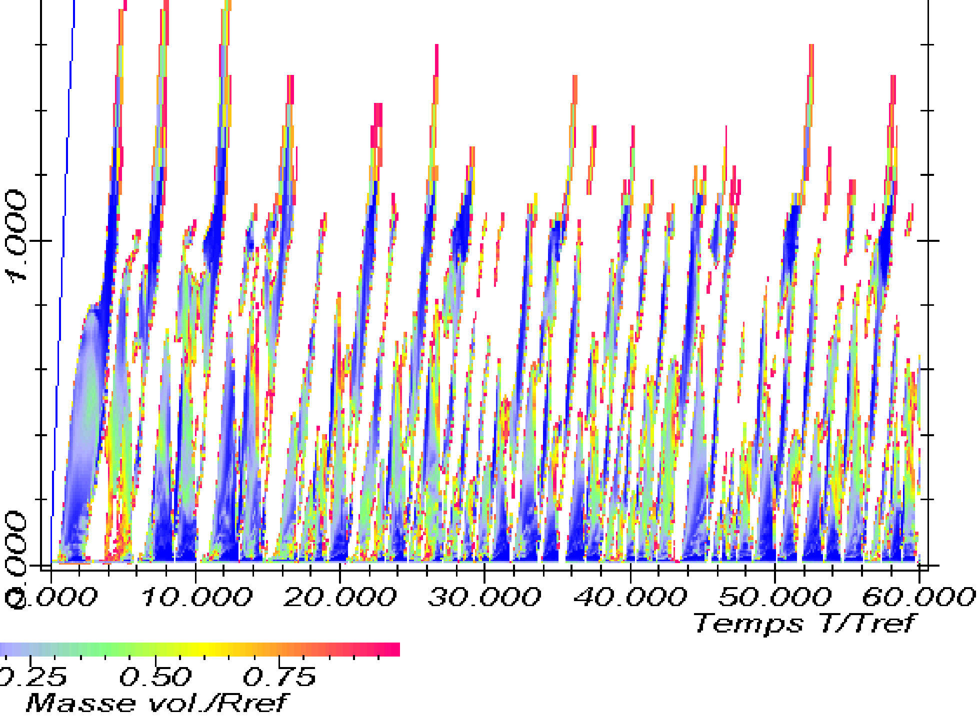


k-ε RNG model

⇒ **Streamlines at the trailing edge**

k-ω model



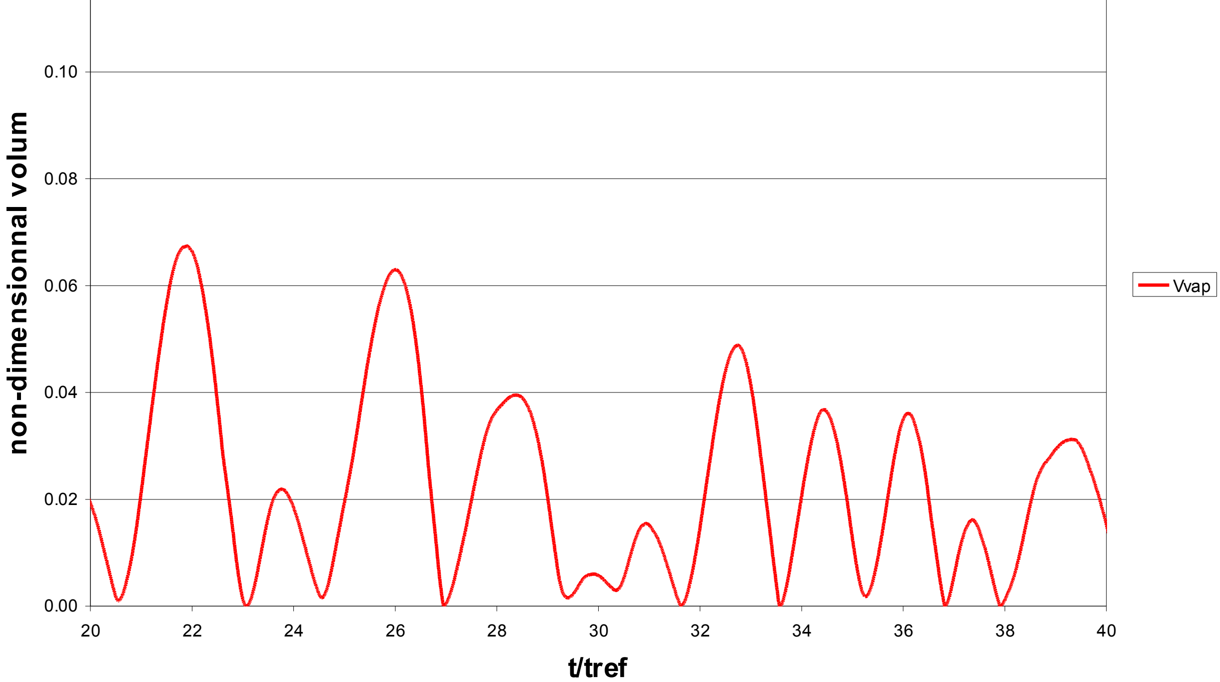


Time evolution of the cavity length.

he time is reported in abscissa, and the X position in the tunnel of avitation is graduated in ordinate.

he colors represent the density values: white for the pure liquid one nd from red to dark blue for the vapor one.

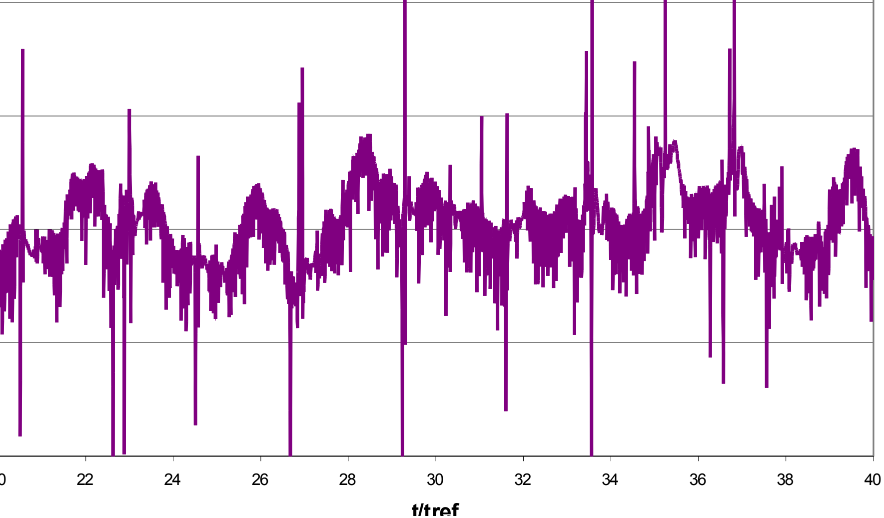
t a given point in time and position, the color indicates the inimum density in the corresponding cross section of the



Time evolution of the vapour volume

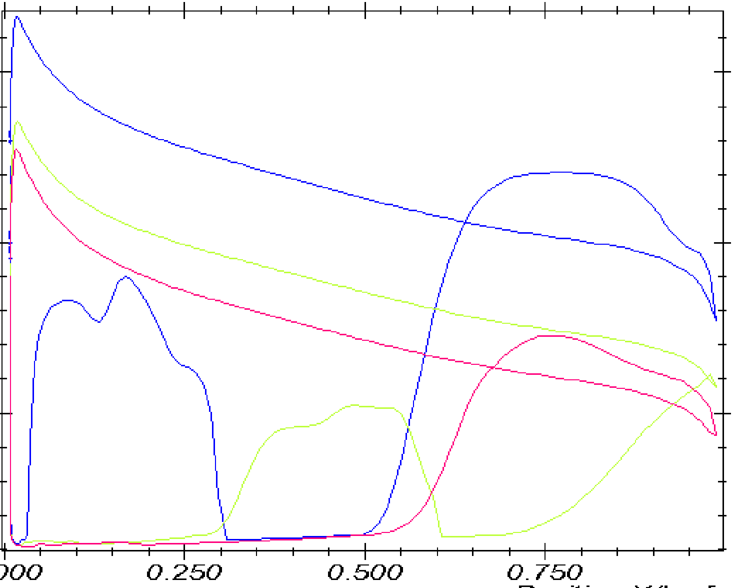
L_{cav} ~ 70 mm
f ~ 30 à 35 Hz

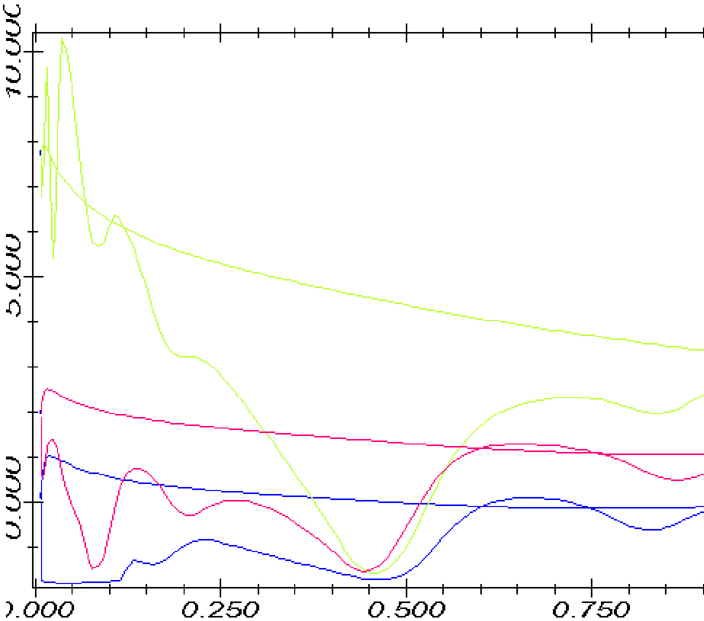
Strouhal = $f \cdot L_{cav} / U_{ref}$ ~ 0.2 to 0.25



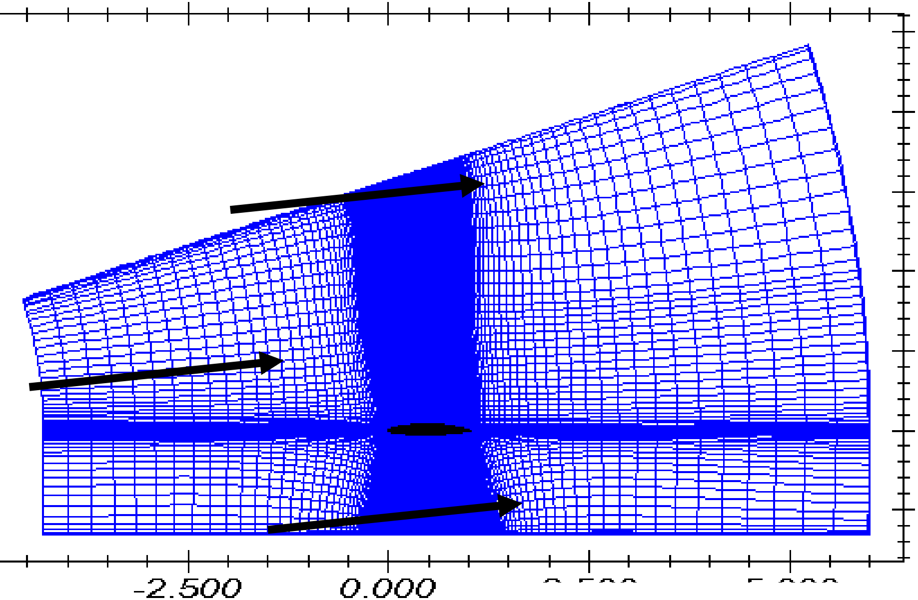
⇒ **time evolution of the lift coeffi**

mean lift coefficient = 0.47



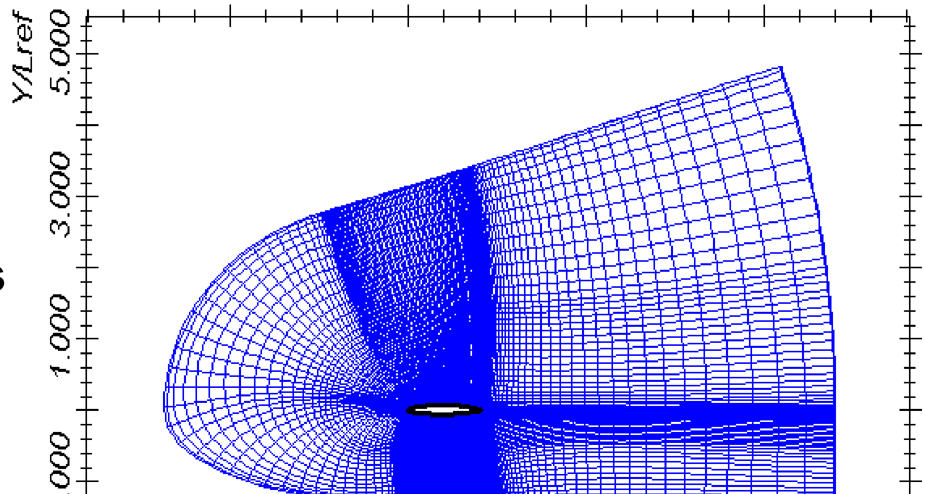


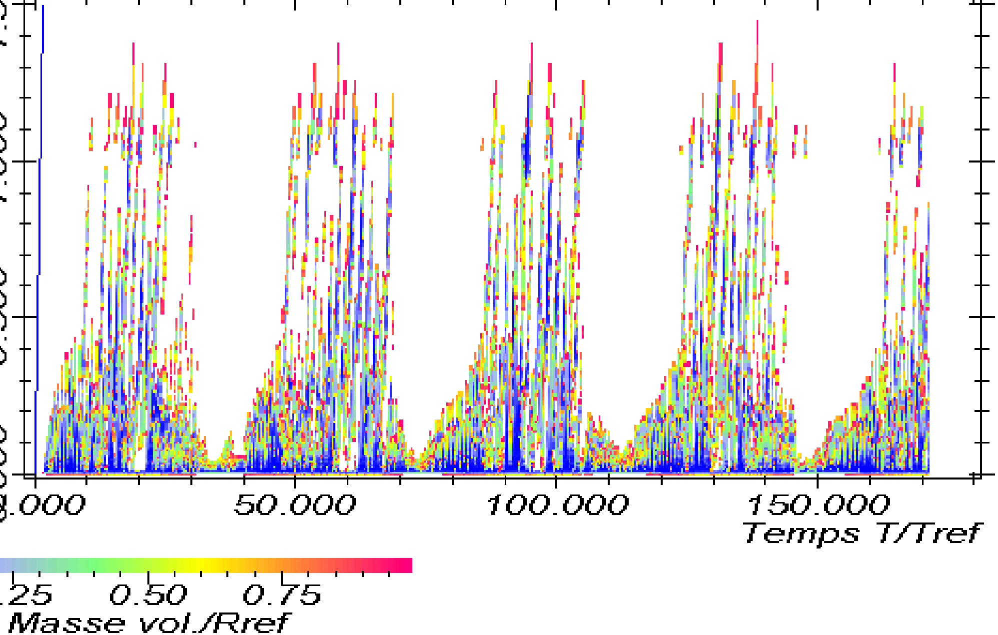
$\sigma_{upstream} \sim 1.9$
$U_{ref} = 9.4$ m/s $T_{ref} = 16$ ms
turbulence model : $\kappa - \varepsilon$ RNG
H meshing
oscillating frequency: 0.6 s



a) H Meshing: 170 x 75 no

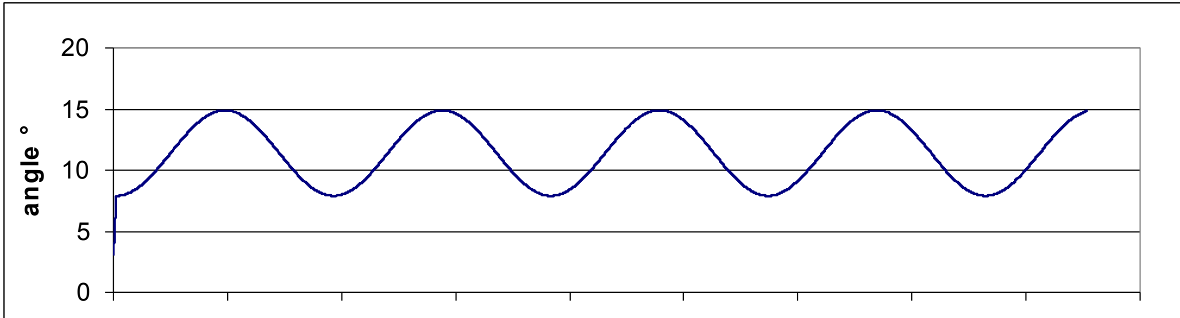
C Meshing: 270 x 44 nodes

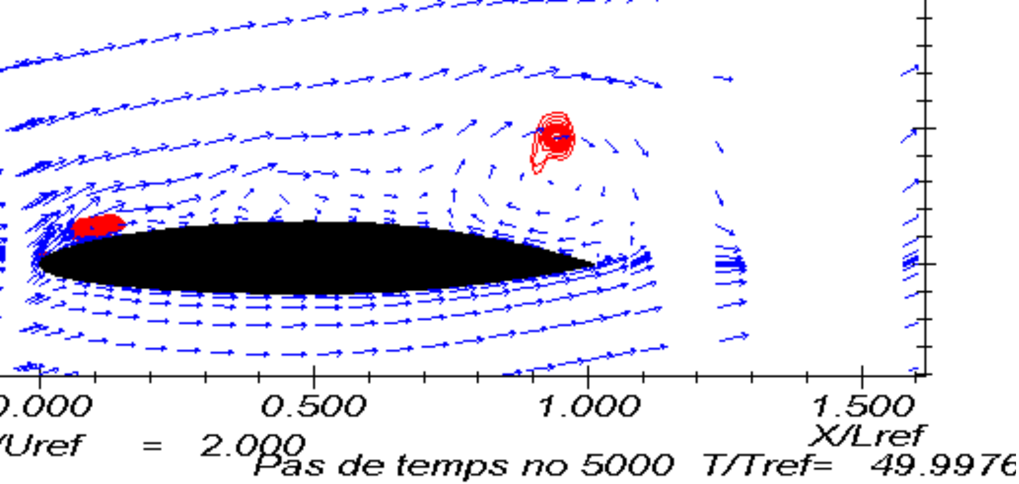




⇒cavitating unsteady behaviour

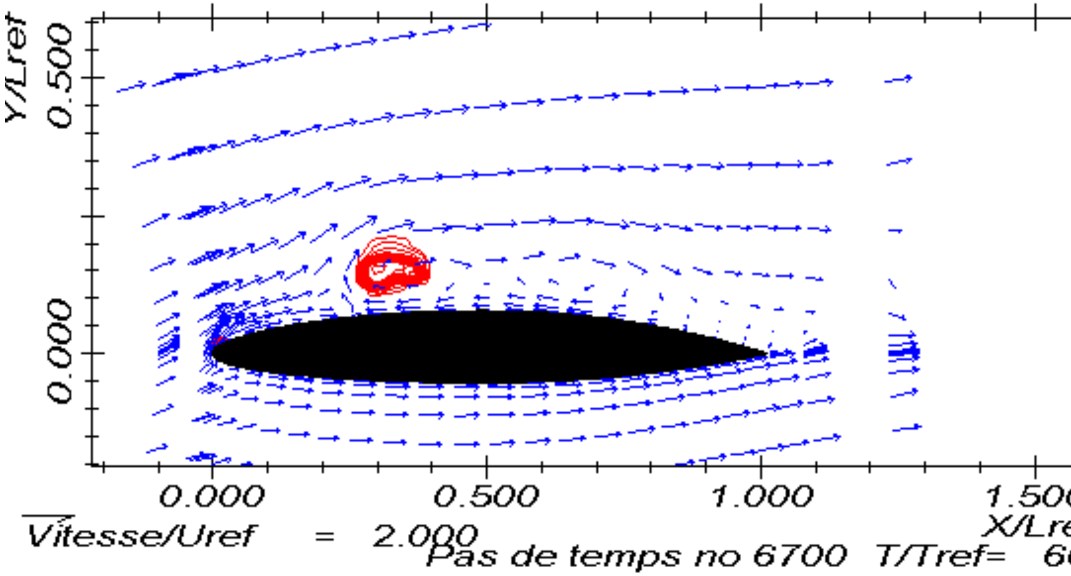
e variation of the angle of attack



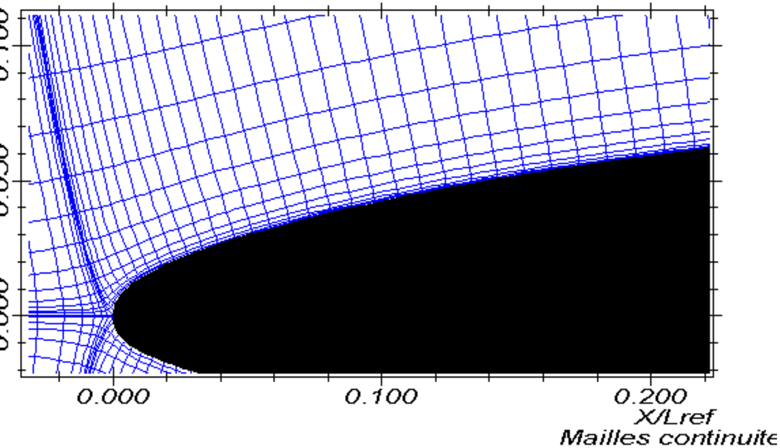


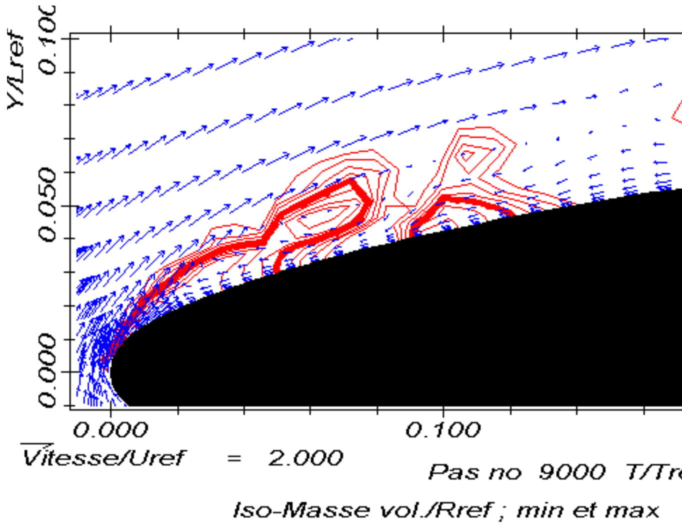
evolution of the
cavitation structures
between 40 and 50 Tref
weak angle of attack

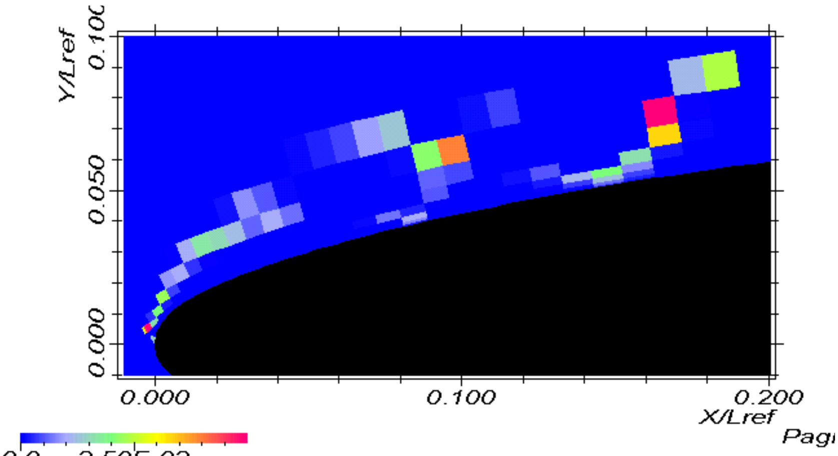
evolution of the
vitation structures
een 60 and 67 Tref
gh angle of attack



Flow Aggressiveness

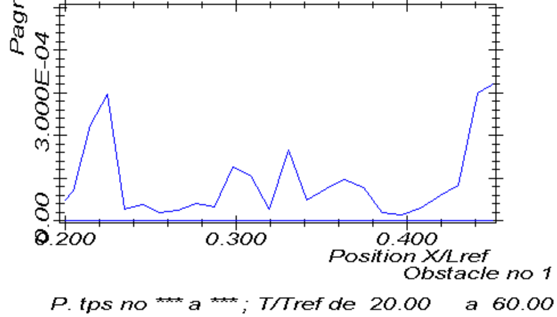


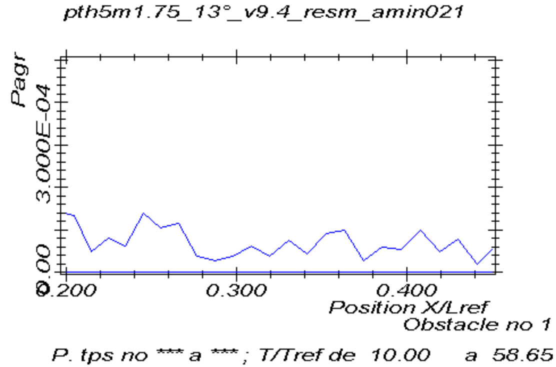


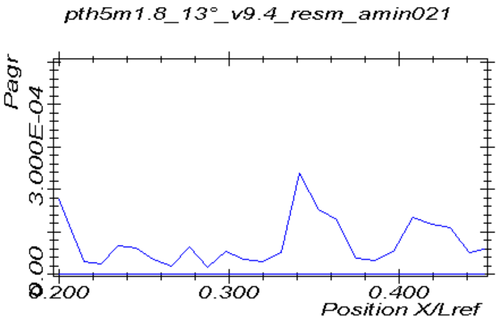


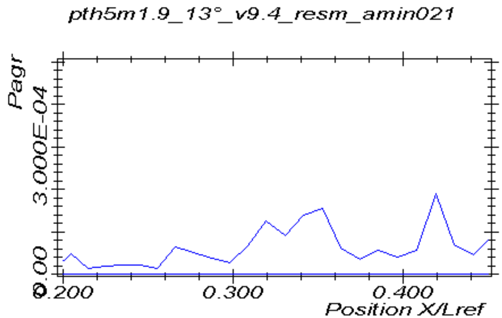
σ_{amont}	$e_{\_agr}/L_{ref}$
2.0	0.0011
1.9	0.0012
1.85	0.0014
1.75	0.00144

$_{ot}^{mat}/\Delta S \propto 0.5$ à $3\ 10^{-4}\ (0.5\ \rho\ V^3)$









ydrofoil in a channel , numerical simulation)

• $P_{pot}^{mat}/\Delta S \propto 2.10^{-5}\,(0.5\,\rho\,V^3)$

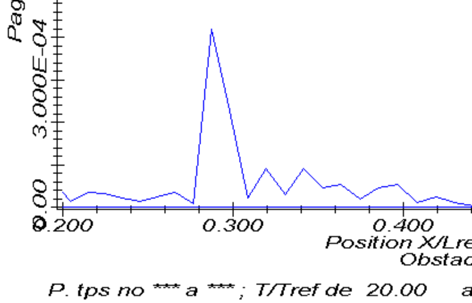
(hydrofoil « non-confined » , simulation)

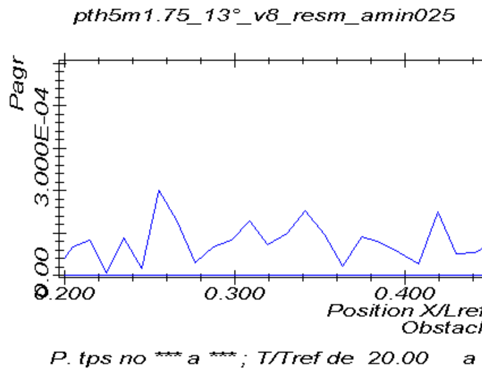
• $P_{pot}^{mat}/\Delta S \propto 4.10^{-4}\,(0.5\,\rho\,V^3)$

(hydrofoil with oscillating angle of attack)

• $P_{pot}^{mat}/\Delta S$ (MODULAB) $\propto 3.10^{-6}\,(0.5\,\rho\,V^3)$

(MODULAB , experimental results)





rofoil in a channel : 13°

constant

variable