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Computational modeling: valuable tool or math exercise?

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Computational modeling: valuable tool or math exercise?

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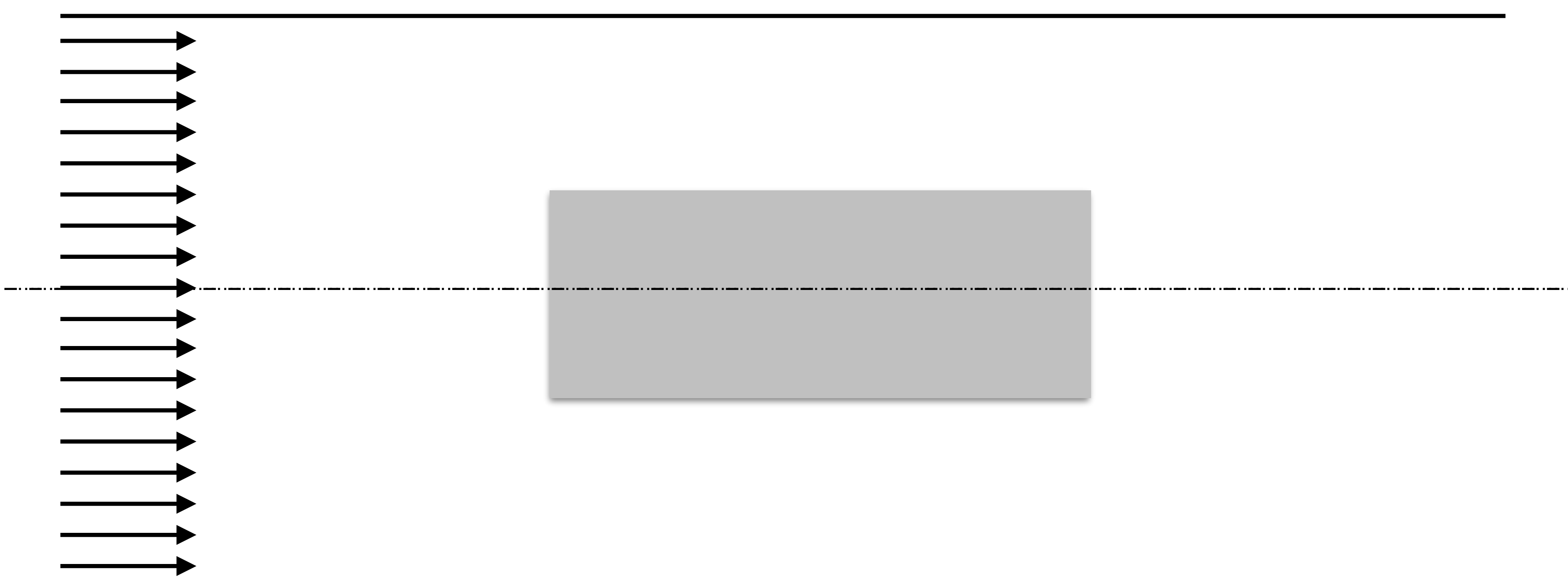
- *“When numerical simulations are presented nobody believes in the results but the one who did the calculations”*

- *“When experimental data are presented everybody believes in the results but the one who did the measurements”*

- *case 1: optimization of an axisymmetric body*
- *case 2: calibration of cavitation modeling*
- *case 3: optimization of air filter*

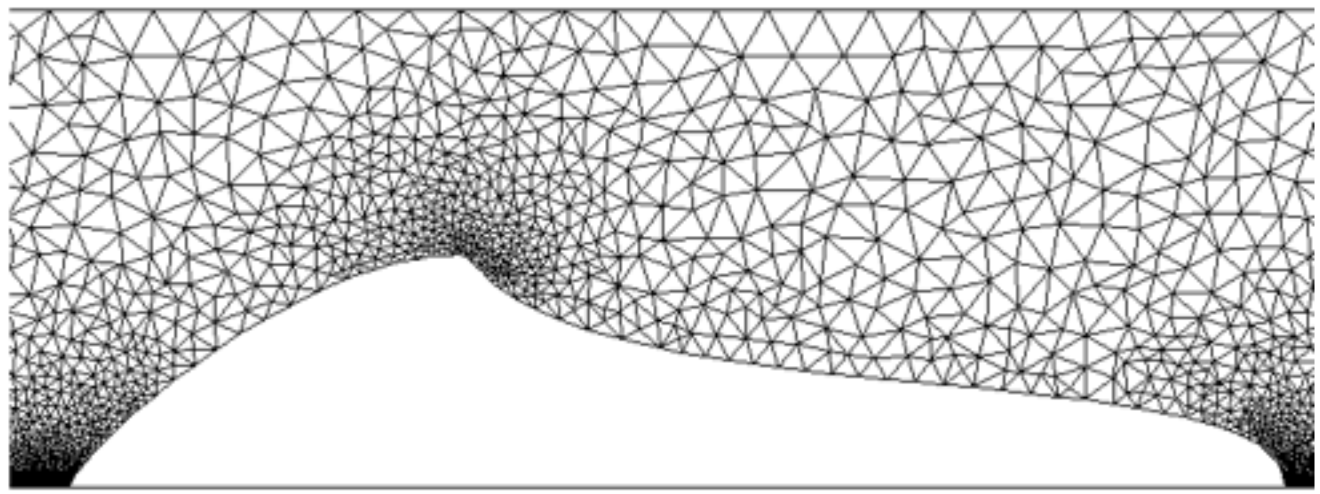
...example from the past

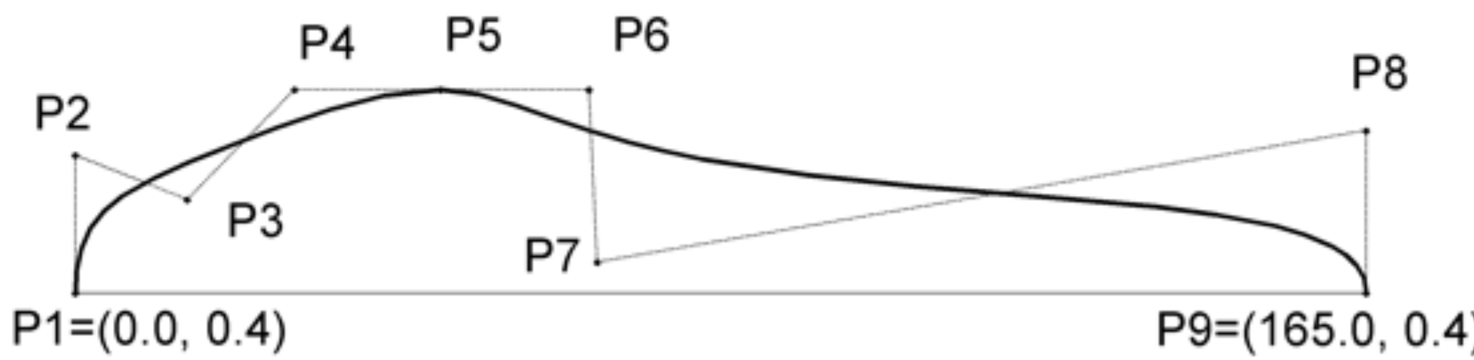
- find the shape with minimum drag at low Reynolds number with prescribed maximum size

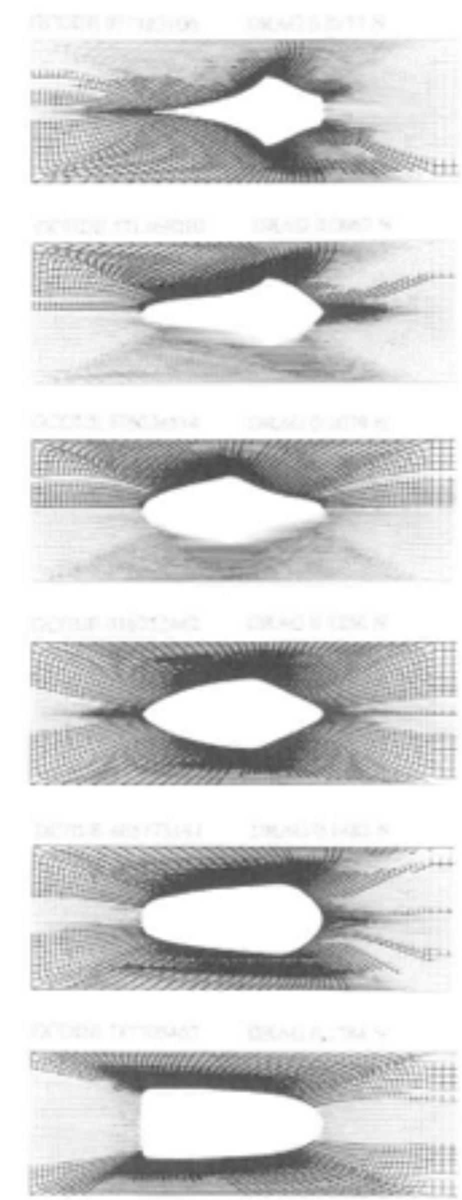


C.Poloni, G.Mosetti, Aerodynamic Shape Optimization by Genetic Algorithm, ISCFD Sendai, August 1993

Shape optimization of an axisymmetric body Re 500

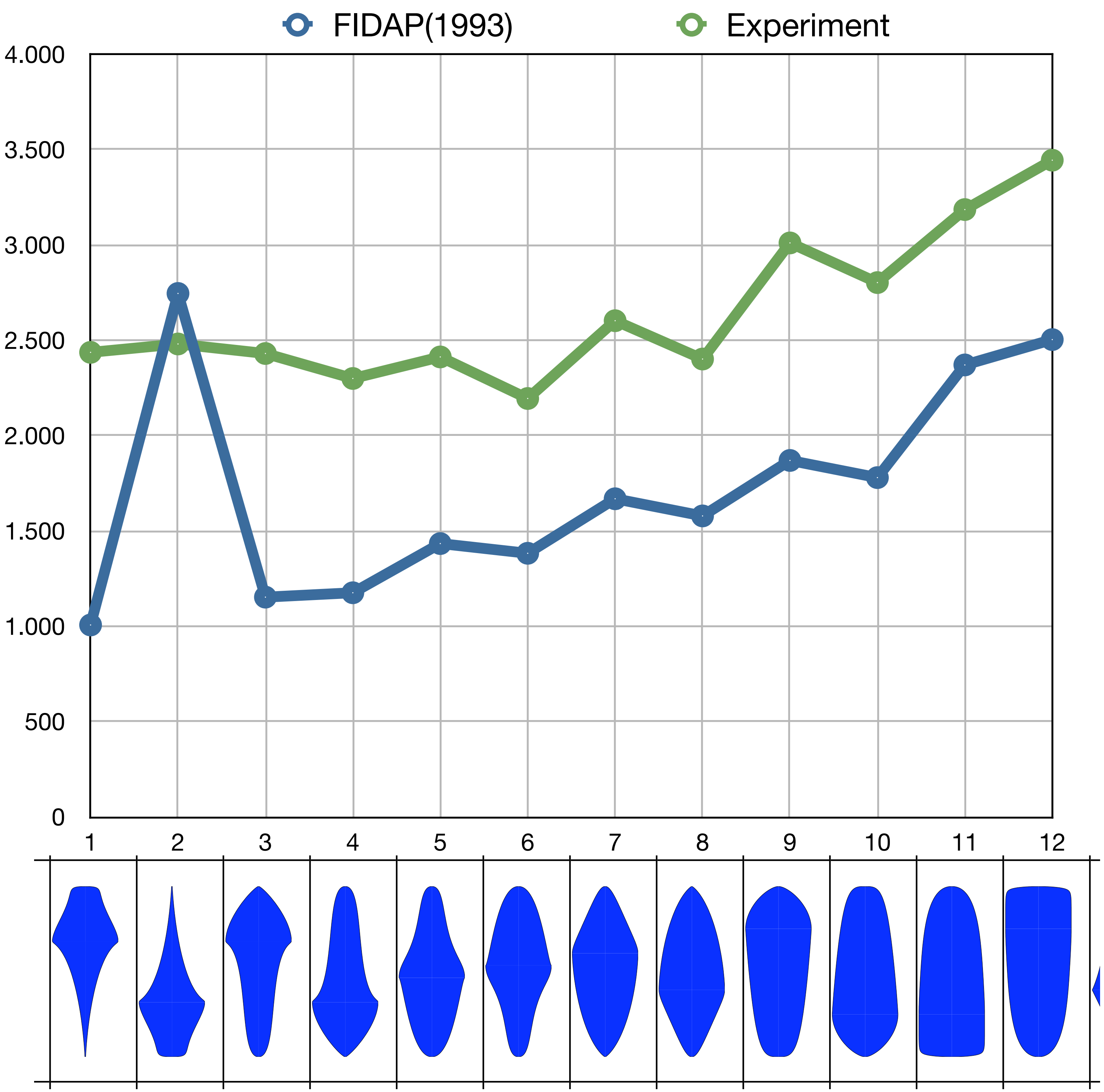




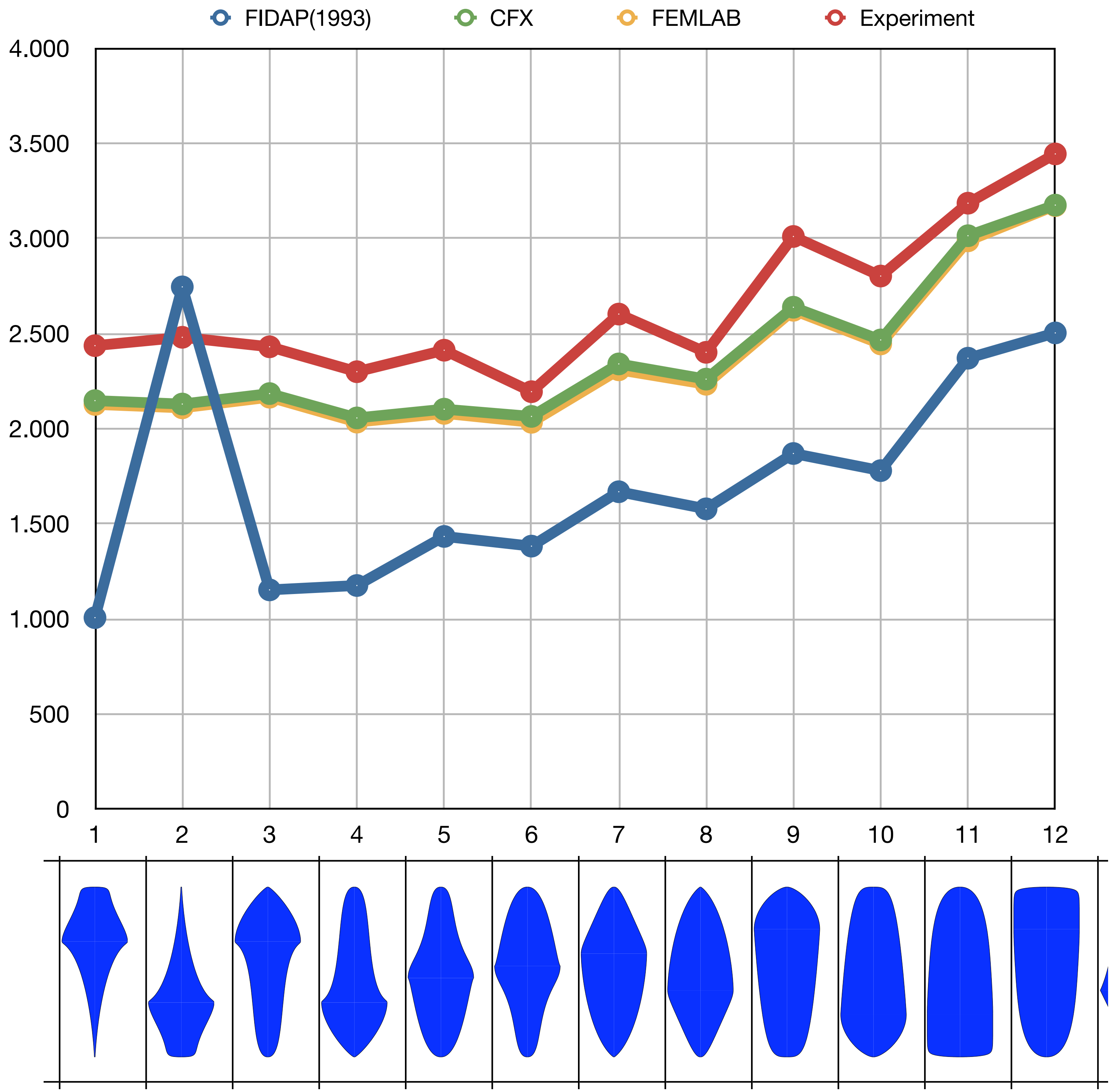


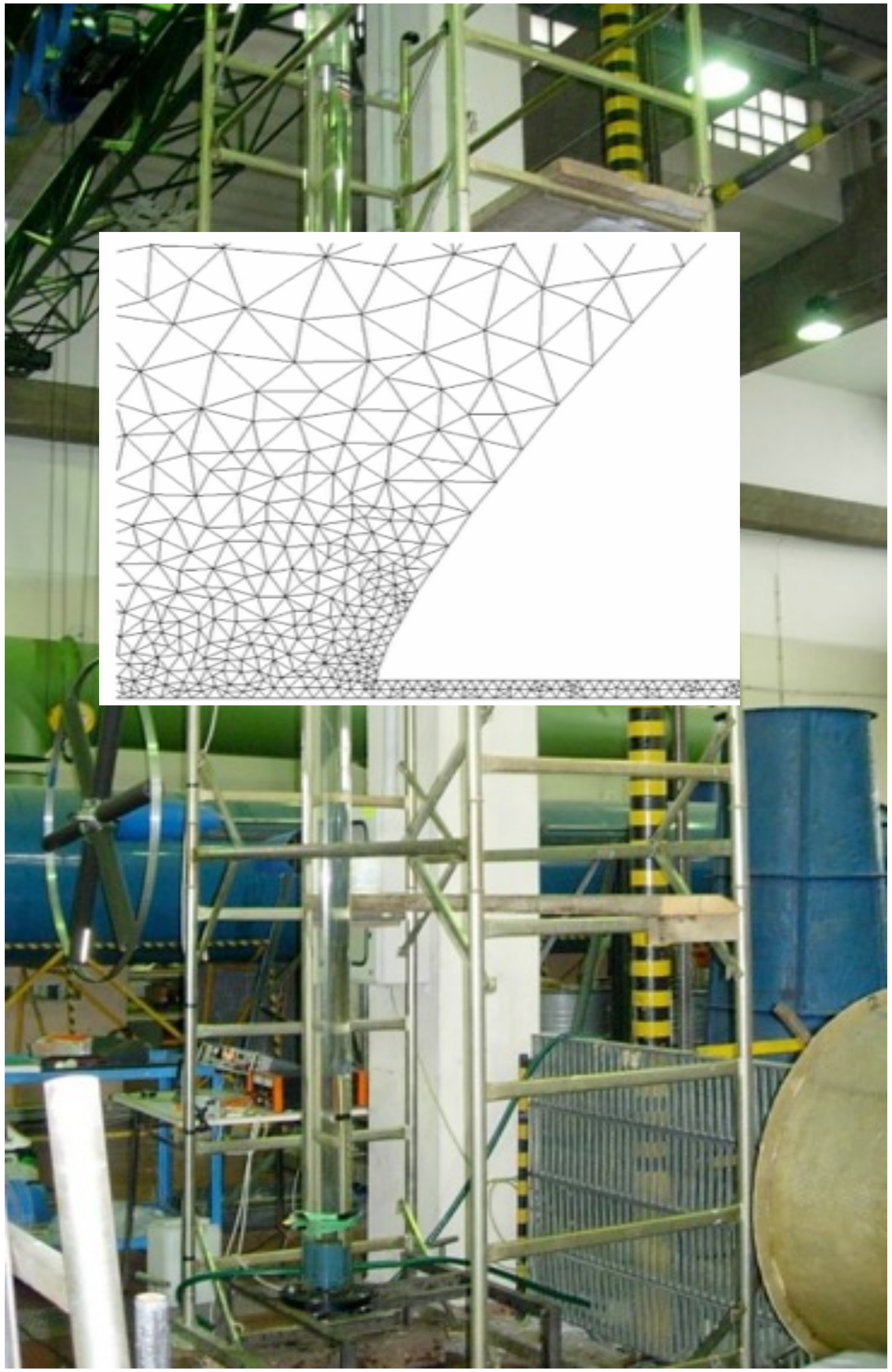
- C.Poloni, G.Mosetti, Aerodynamic Shape Optimization by Genetic Algorithm, ISCFD Sendai, August 1993

1993 results

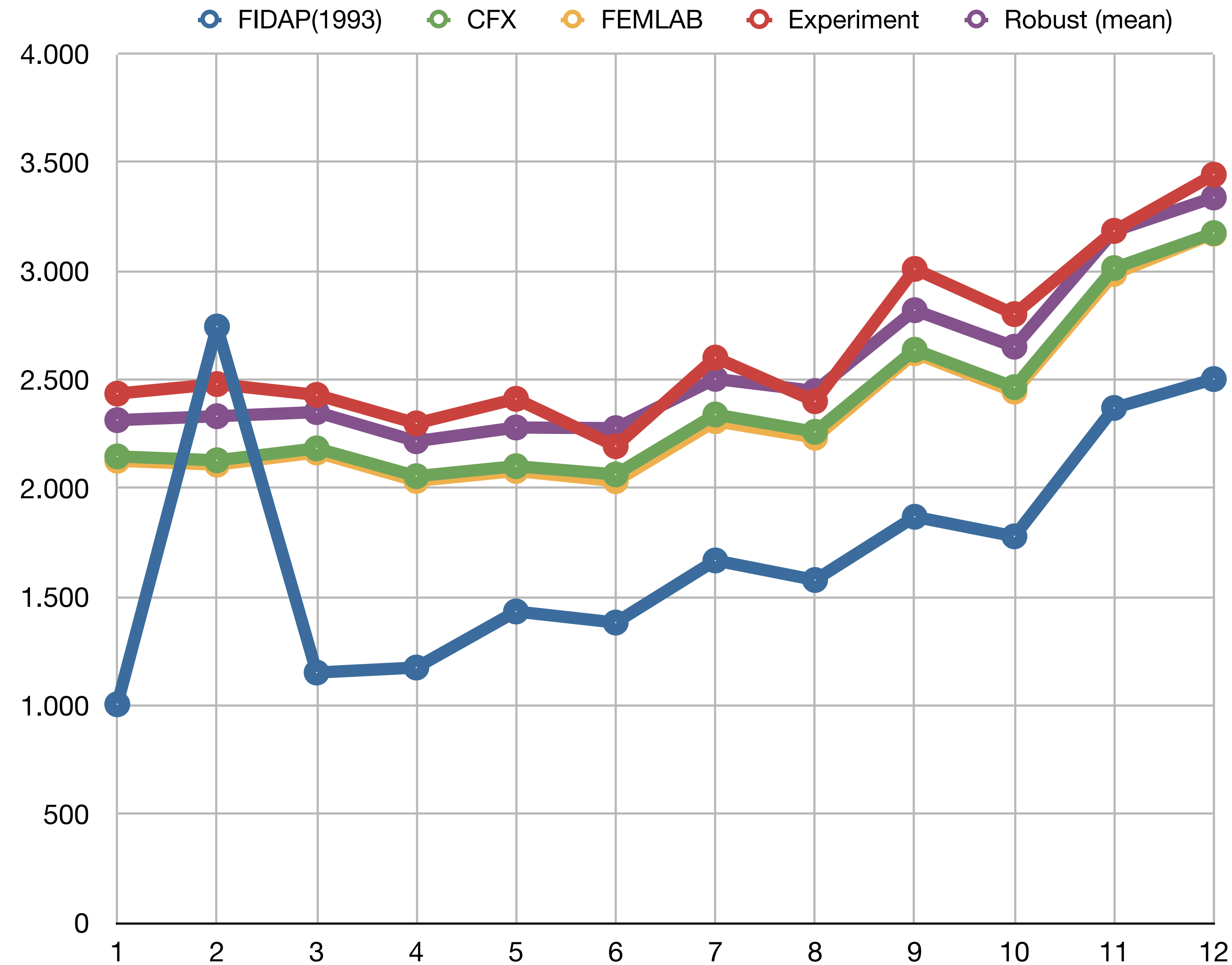


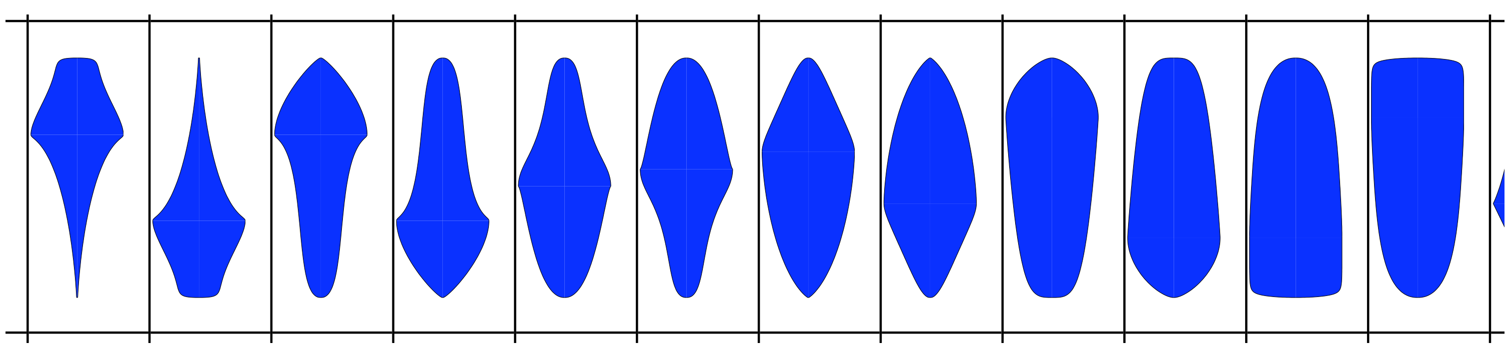
2006 results

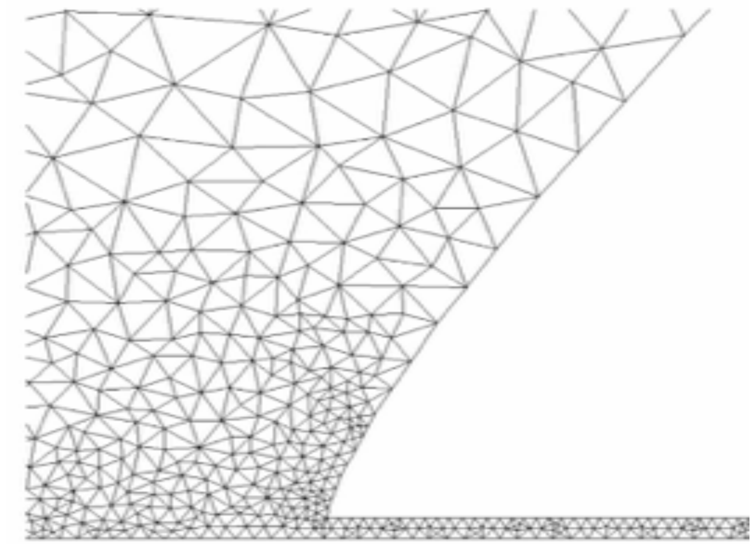


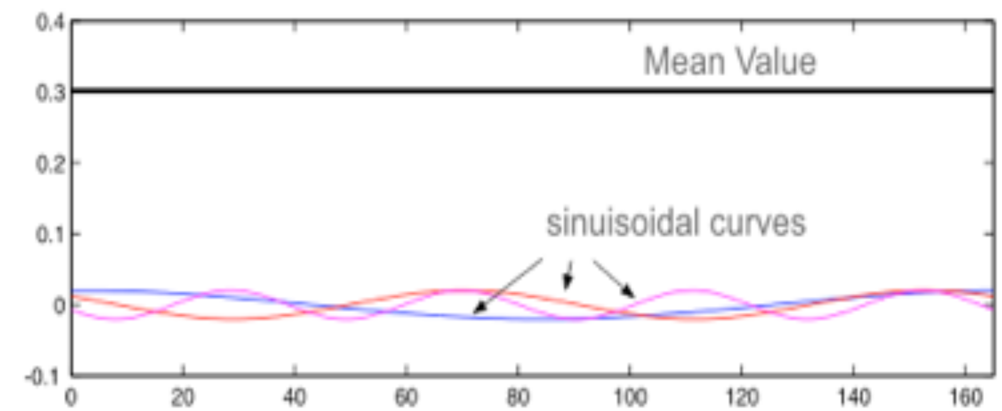


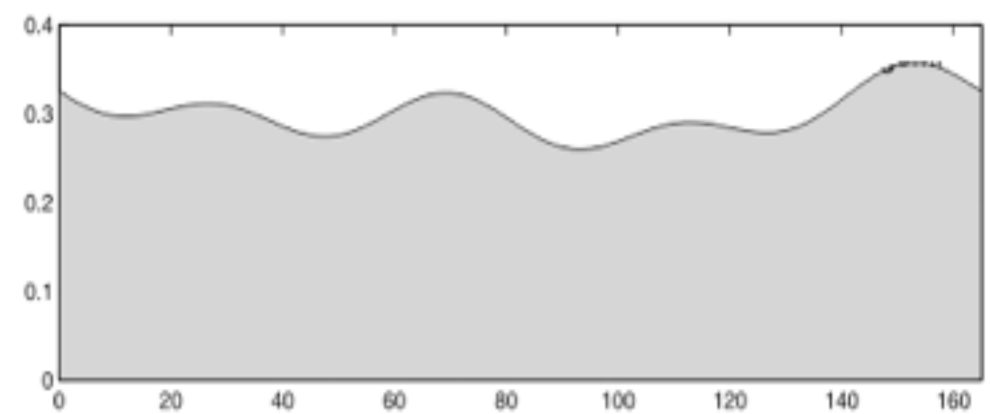
2006 results









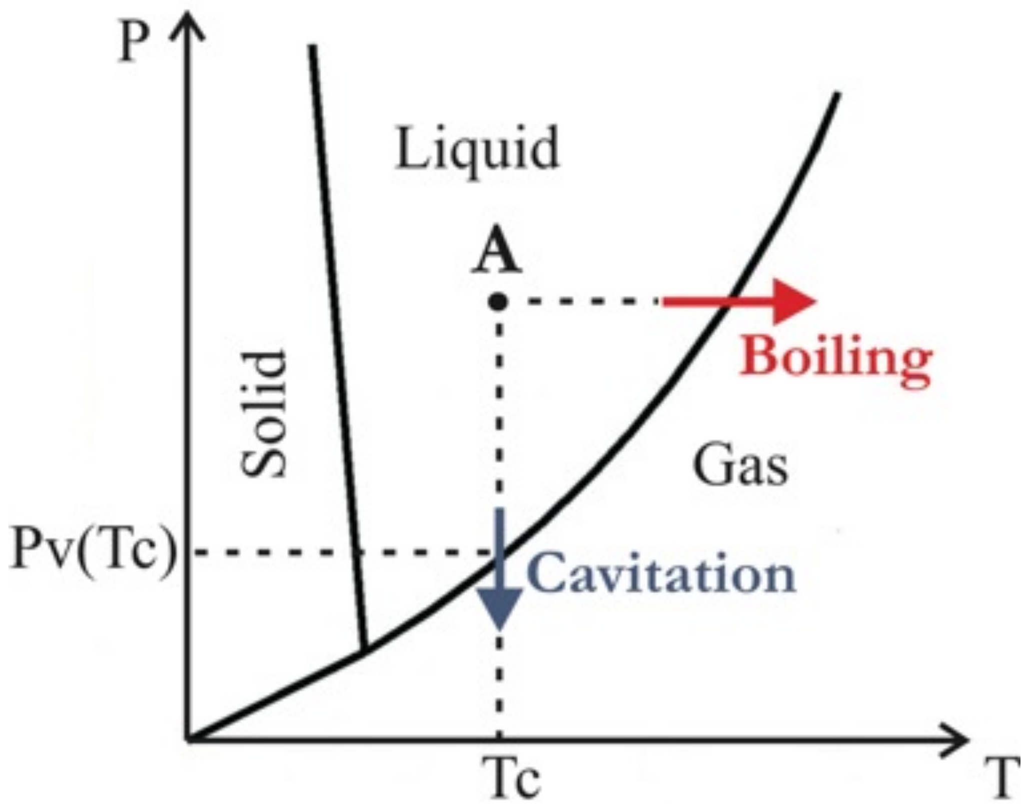


Build an accurate model

modelling cavitation in marin propellers

Mitja Morgut, Enrico Nobile, Ignacijo Bilušb, *Comparison of mass transfer models for the numerical prediction of sheet cavitation around a hydrofoil,* International Journal of Multiphase Flow Volume 37, Issue 6, July 2011, Pages 620–626

Definition of Cavitation



Cavitation can be outlined as:

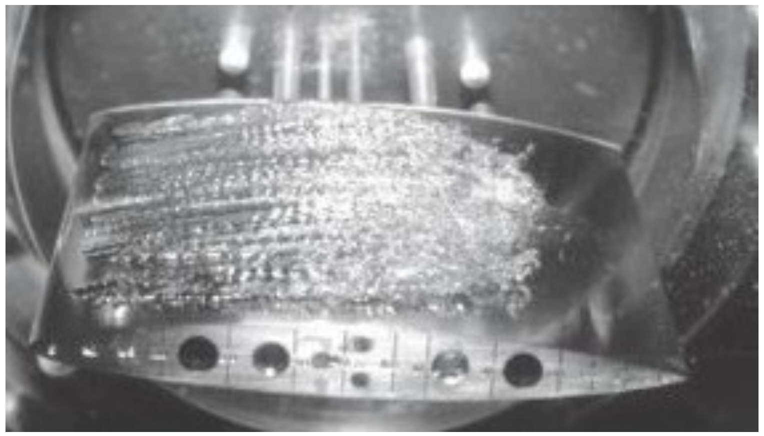
- the vaporization of a liquid when the static pressure decreases below its vapour pressure [1]
- the formation and activity of bubbles (or cavities) in a liquid [2]
- the breakdown of a liquid under very low pressures [3]

[1] Coutier-Delgosha, O., Reboud, J., Delannoy, Y., 2003. *Numerical simulation of unsteady behaviour of cavitating flows*. International Journal for Numerical Methods in Fluids 42, 527-548.

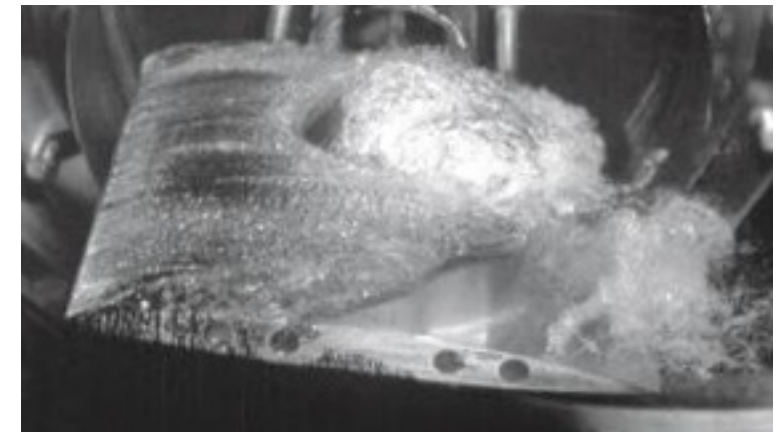
[2] Young, F., 1989. *Cavitation*. Imperial College Press, London

[3] Franc, J., Michel, J., 2004. *Fundamentals of Cavitation*. Kluwer Academic Publisher.

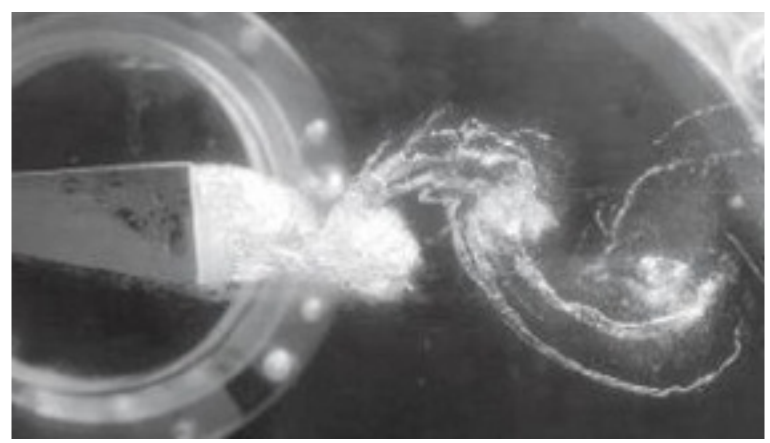
Examples of hydrodynamic cavitation

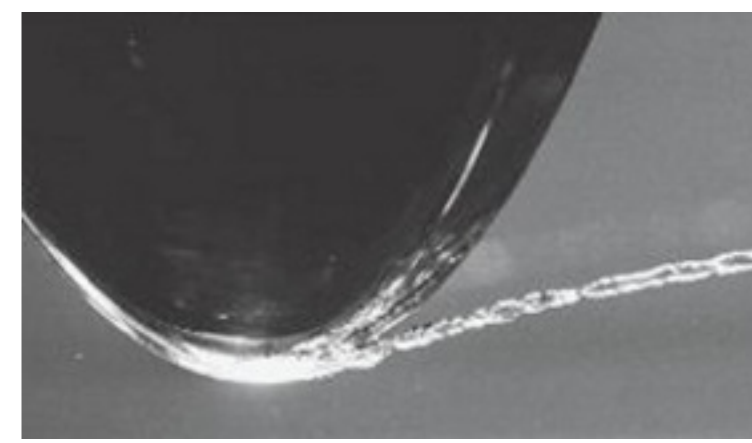

Partial Cavitation


Supercavitation


Cloud Cavitation


Bubble Cavitation


Vortex Cavitation


(Tip) Vortex Cavitation

Figures taken from: Fluid Dynamics of Cavitation and Cavitating Turbopumps. Edited by D'Agostino, L., and Salvetti, M.V., 2007

Examples of hydrodynamic cavitation

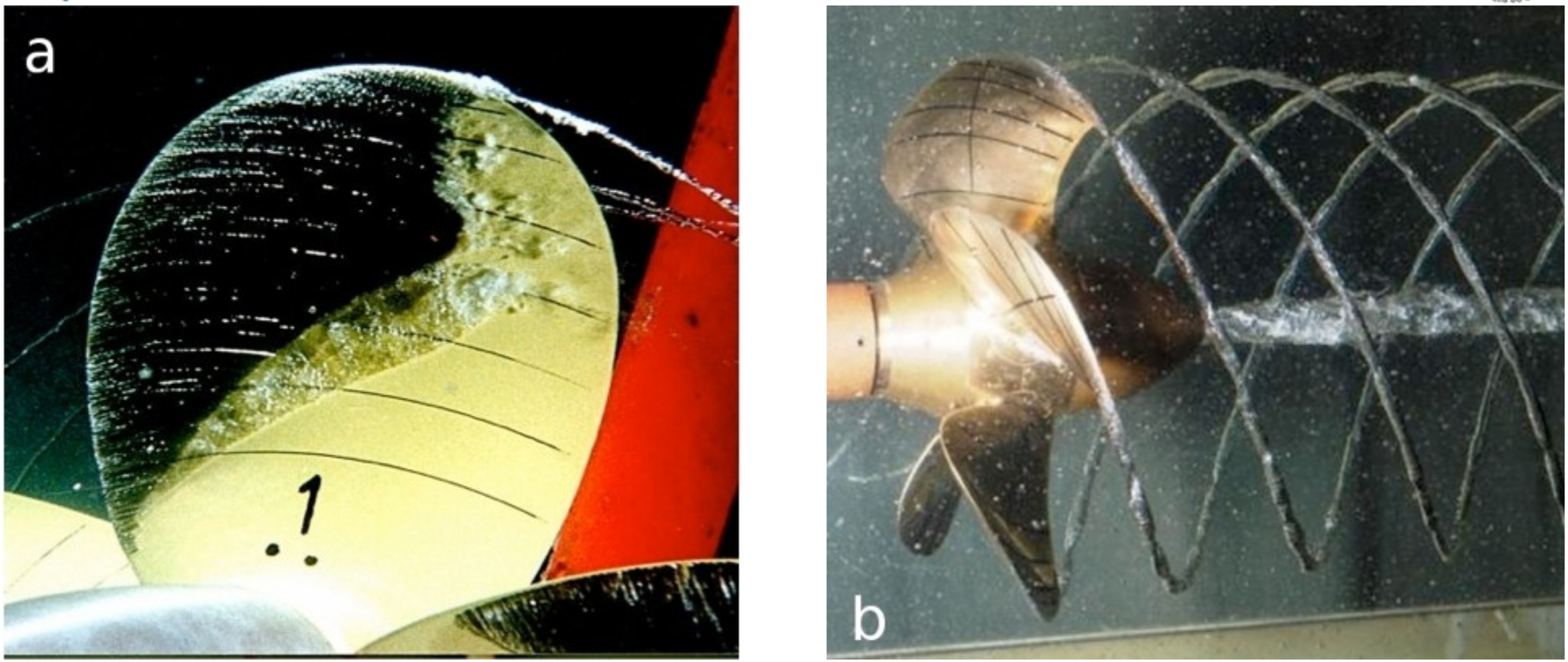


Figure (a) adapted from: Vaz, G.N.V.B. *Modelling of Sheet Cavitation on Hydrofoils and Marine Propellers using Boundary Element Methods*. PhD Thesis Universidade Tecnica de Lisboa, 2005.

Figure (b) adapted from: Heinke, H.-J. *Potsdam Propeller Test Case (PPTC), Cavitation Test with the Model Propeller VP1304*. SVA (Potsdam Model Basin), 2011.

Mathematical model

Governing Equations

Phases are considered incompressible and multiphase flow is assumed homogeneous

$$\begin{cases} \nabla \cdot \boldsymbol{U} = \dot{m}\left(\frac{1}{\rho_l} - \frac{1}{\rho_v}\right) \\ \frac{\partial(\rho \boldsymbol{U})}{\partial t} + \nabla \cdot (\rho \boldsymbol{U}\boldsymbol{U}) = -\nabla P - \nabla \cdot \tau + S_M \\ \frac{\partial \gamma}{\partial t} + \nabla \cdot (\gamma \boldsymbol{U}) = \frac{\dot{m}}{\rho_l} \end{cases}$$

$\gamma = water\ volume\ fraction$

$\rho = mixture\ density$

Mass Transfer Models ($\dot{m}$)

Zwart Model

$$\dot{m} = \begin{cases} -F_e \frac{3 r_{nuc}(1-\alpha)\rho_v}{R_B}\sqrt{\frac{2}{3}\frac{P_v - P}{\rho_l}} & if\ P < P_v \\ F_c \frac{3\alpha\rho_v}{R_B}\sqrt{\frac{2}{3}\frac{P - P_v}{\rho_l}} & if\ P > P_v \end{cases}$$

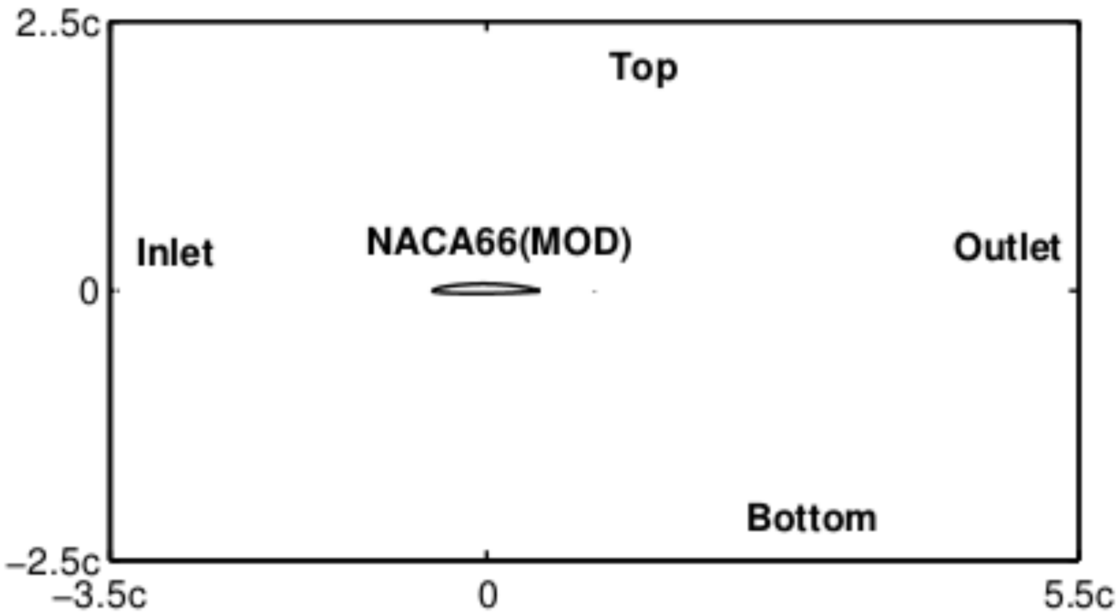
FCM (Full Cavitation Model)

$$\dot{m} = \begin{cases} -C_e \frac{\sqrt{k}}{T}\rho_l\rho_v\sqrt{\frac{2}{3}\frac{P_v - P}{\rho_l}}(1 - f_v) & if\ P < P_v \\ C_c \frac{\sqrt{k}}{T}\rho_l\rho_l\sqrt{\frac{2}{3}\frac{P - P_v}{\rho_l}} f_v & if\ P > P_v \end{cases}$$

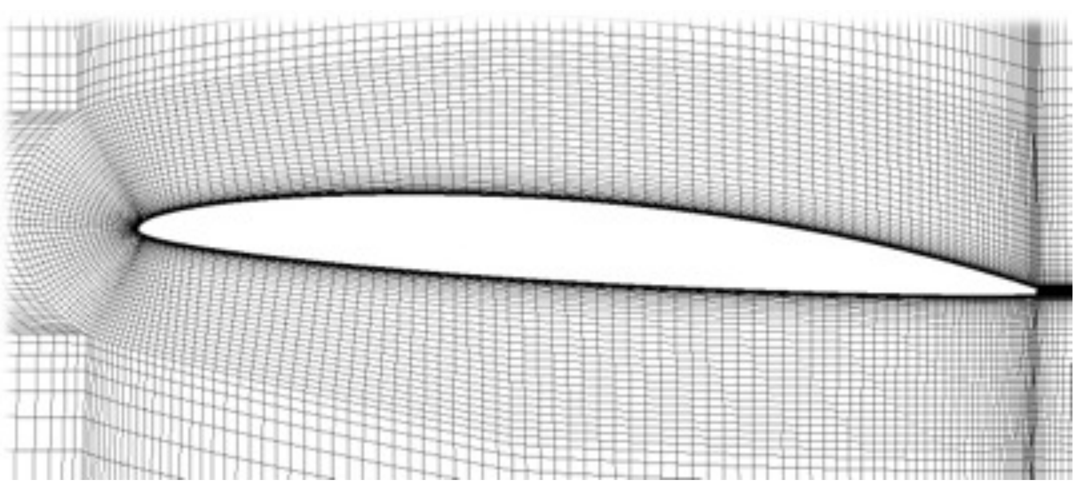
Kunz Model

$$\dot{m} = \dot{m}_+ + \dot{m}_- \quad \begin{cases} \dot{m}_+ = \frac{C_{prod}\rho_v\gamma^2(1-\gamma)}{t_\infty} \\ \dot{m}_- = \frac{C_{dest}\rho_v\gamma\min[0, P - P_v]}{(0.5\rho_l U_\infty^2)t_\infty} \end{cases}$$

Reference test case



Shape of the computational domain



Computational grid around the NACA66MOD hydrofoil

[4] Shen, Y.T., Dimotakis, P.E. *The influence of Surface Cavitation on Hydrodynamic Forces*. In Proc. 22° ATTC, St. Johns, Canada, Pages 44–53, 1989

- NACA66MOD hydrofoil [4]
  chord: c=0.15m
  Angle of Attack: AoA=4°
  $Re=2x10^6$
  Three different cavitating flow regimes: σ=1.00, 0.91, 0.84

$$\sigma = \frac{P_{outlet} - P_v}{0.5\rho_l U^2}$$

- Simulations carried out considering:
  Two-dimensional flow
  Steady state conditions
  k–ε turbulence model

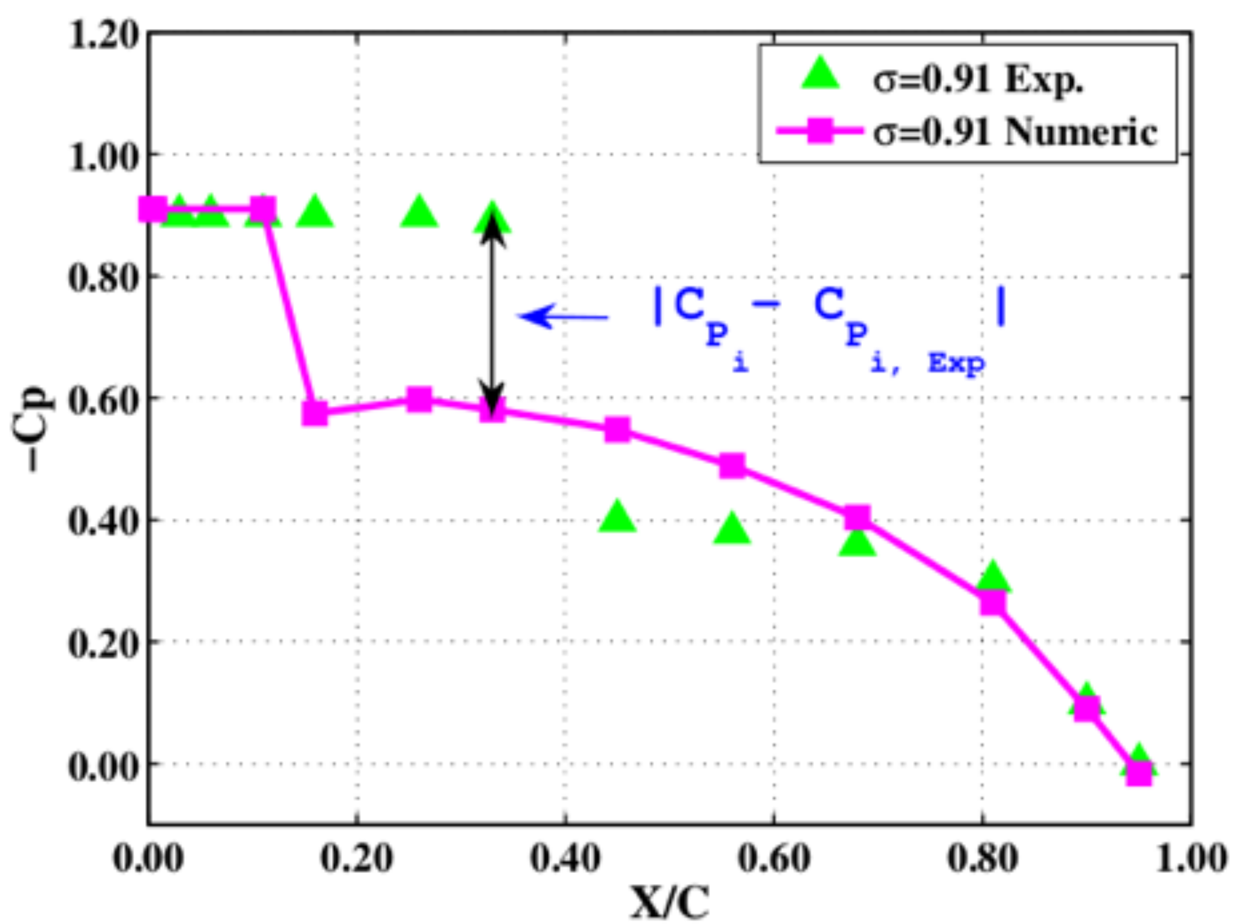
- Computational grid generated with ANSYS–ICEM CFD
  Hexa–structured, 58734 nodes

$\overline{y^+} = 23$

Calibration of mass transfer models

The idea

Search/find the empirical coefficients which minimize the differences between the Numerical and experimental pressure distributions on the suction side of the NACA66MOD hydrofoil, for three different cavitating flow regimes.



Example of numerical and experimental pressure distributions on the hydrofoil suction side

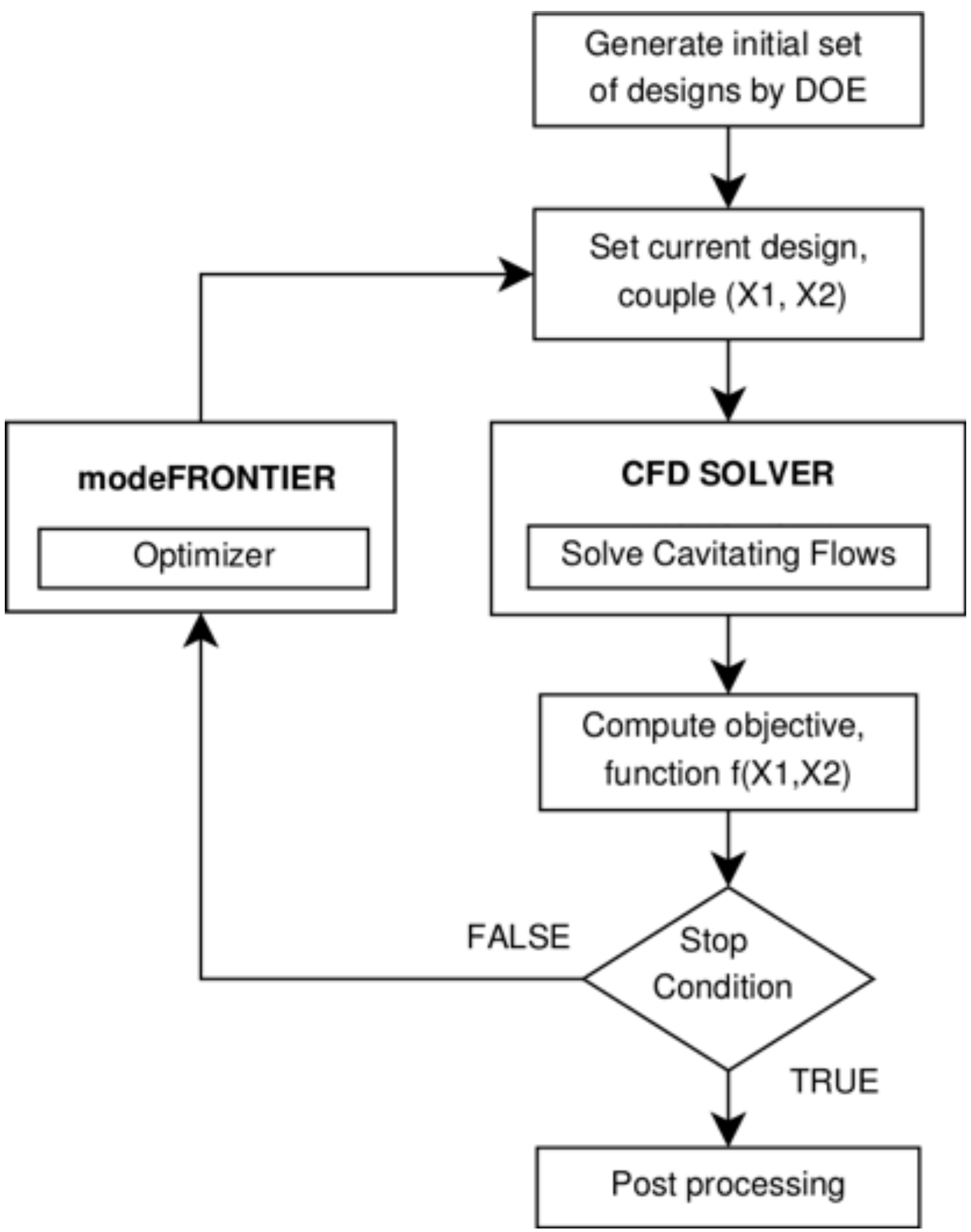
$$f = \sum_{\sigma} \sum_{i=1}^{N} \left| C_{P_i} - C_{P_{i,EXP}} \right|$$

$$\sigma = 1.00, 0.91, 0.84$$

$$N = 12 \; (Pressure\; taps)$$

$$-C_P = \frac{P_{outlet} - P}{0.5 \rho_l U^2}$$

Calibration of mass transfer models



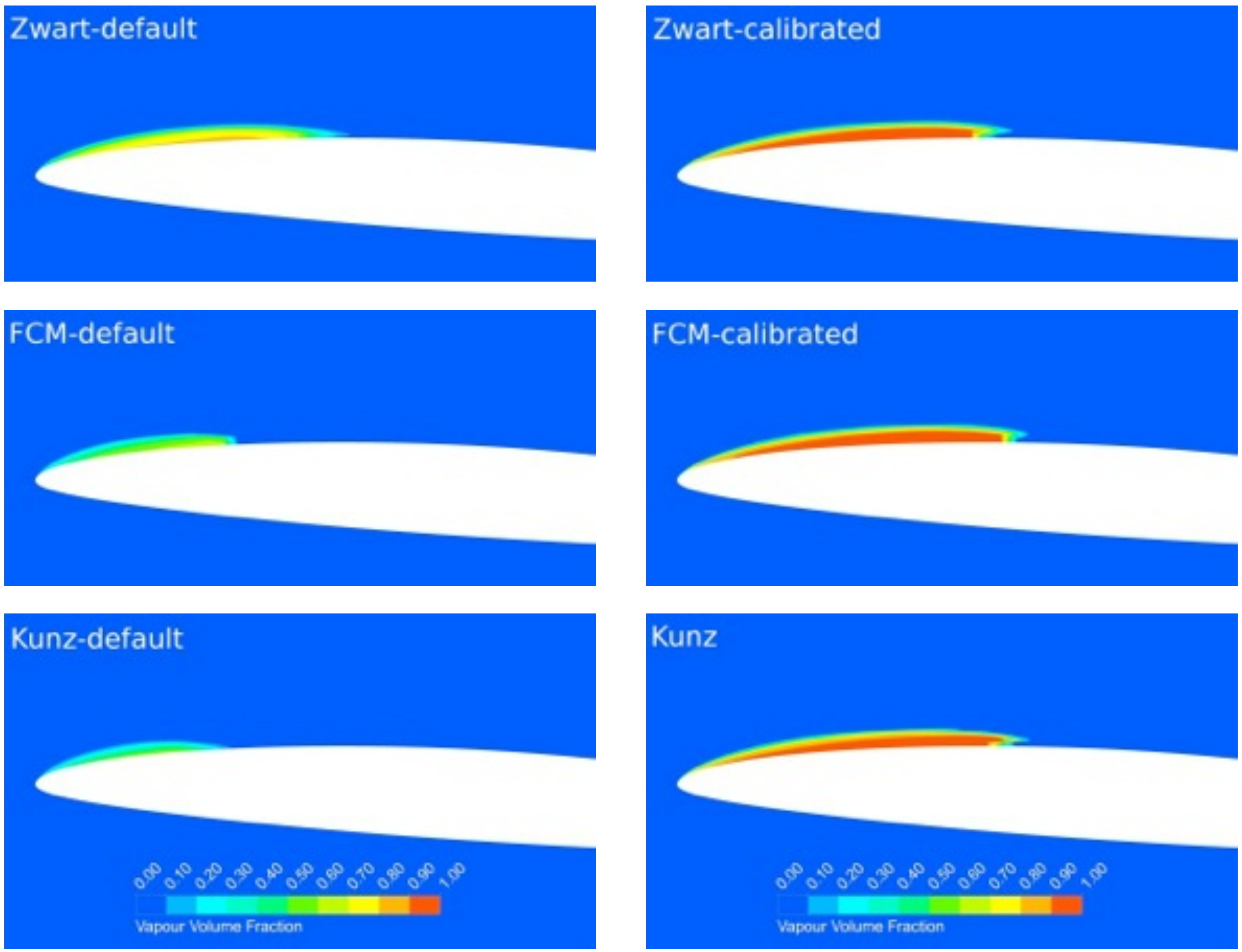
The optimization algorithm (optimizer), during the successive iterations, changes the values of the empirical coefficients of the cavitation models
(F_e, F_c), (C_e, C_c), (C_{prod}, C_{dest})
in order to minimize the Objective function *f*.

The optimizer run until the desired Convergence level or maximum number of iterations is reached.

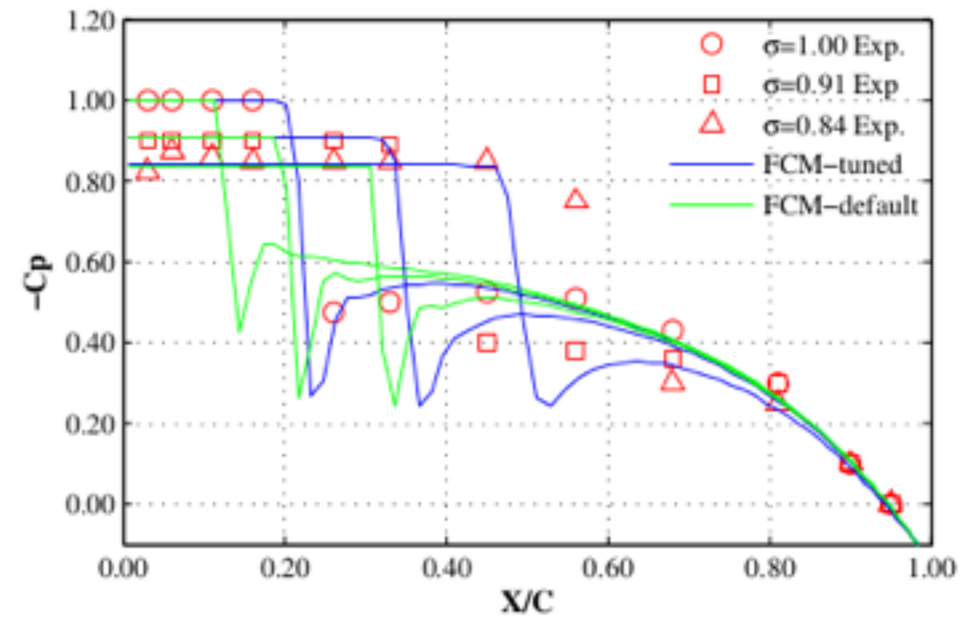
Calibration of mass transfer models

Default and calibrated values for the different mass transfer models

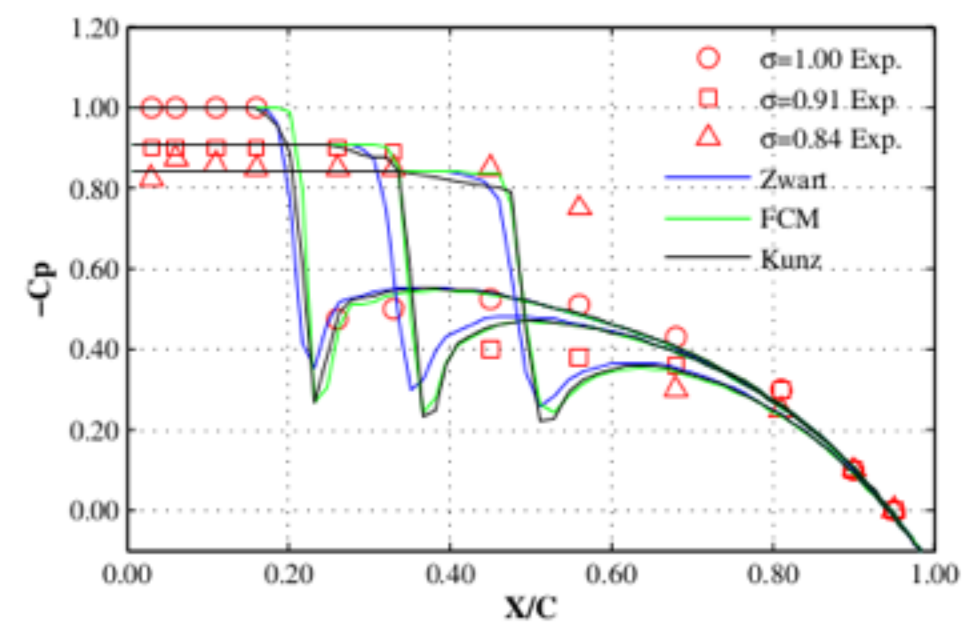
	Zwart		FCM		Kunz	
	Fe	Fc	Ce	Cc	Cdest	Cprod
Default	50	0.01	0.02	0.01	100	100
Tuned	300	0.03	0.40	2.3E-04	4100	455



Numerical sheet cavities computed using non-calibrated (left) and calibrated (right) mass trasfer models for AoA=4°, Re=2x10^6, σ=0.91.



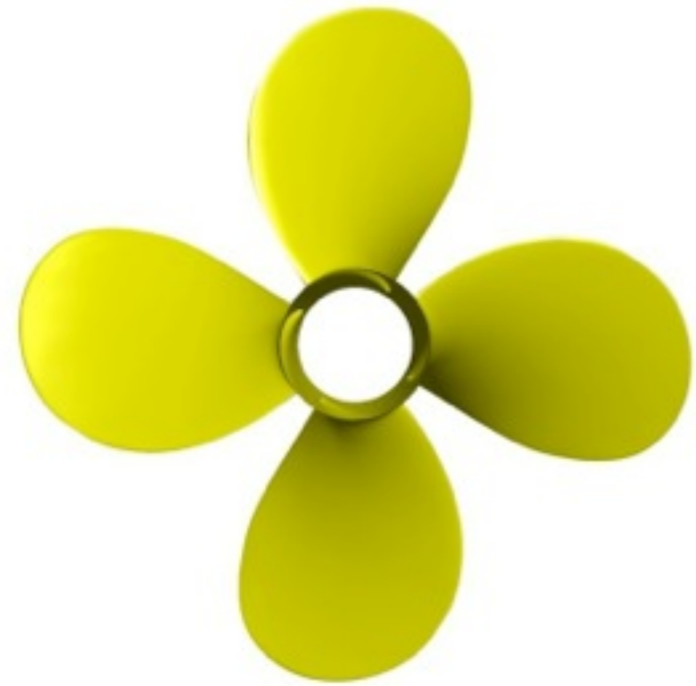
Pressure distributions obtained with FCM using default and tuned values of empirical coefficients



Pressure distributions obtained using the calibrated mass transfer models

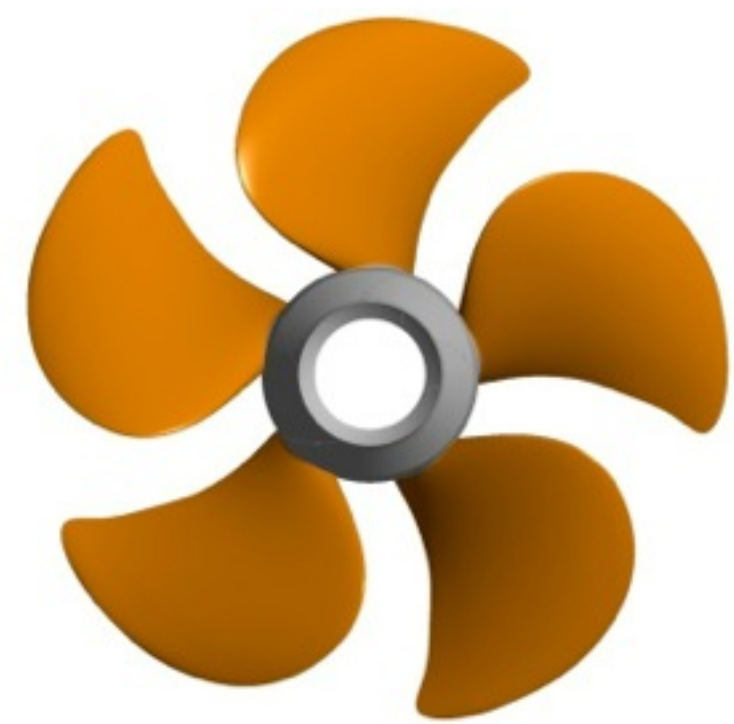
Model scale propellers

E779A
- four bladed propeller
- Diameter D=0.227m
- propriety of CNR-INSEAN



E779A propeller.
View looking suction side

PPTC
- five bladed propeller
- diameter D=0.25m
- propriety of SVA

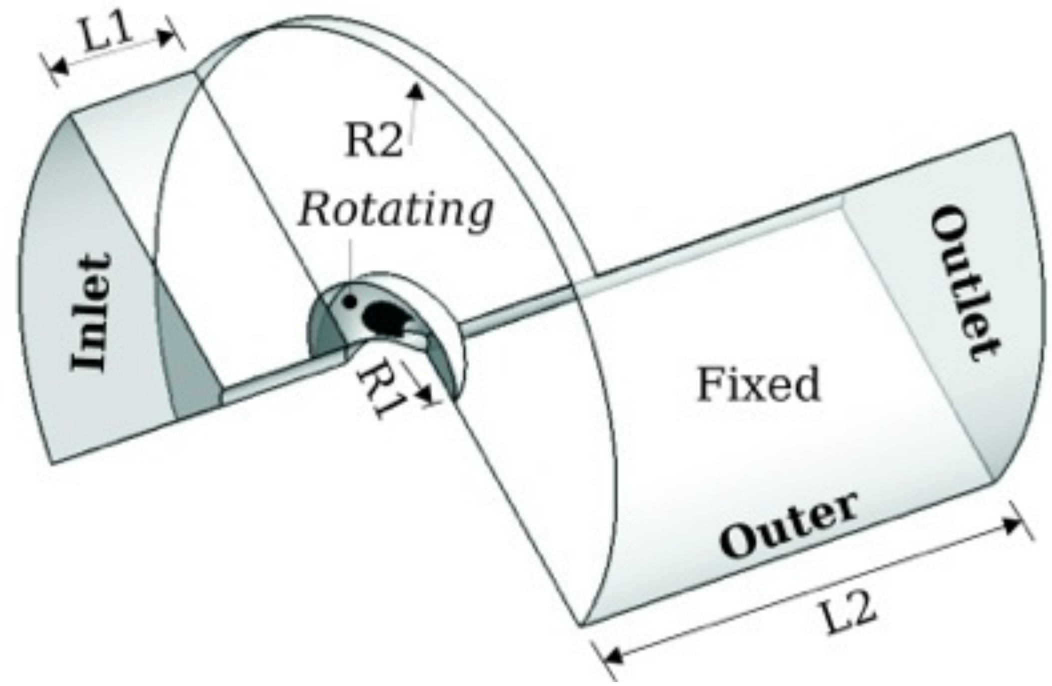


PPTC propeller.
View looking suction side

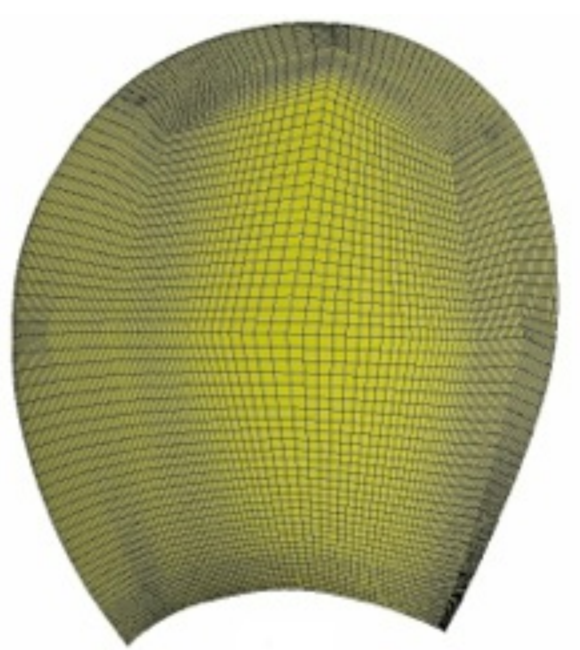
CNR-INSEAN:http//www.insean.cnr.it
SVA:http://www.sva-potsdam.de/pptc.html

Numerical setup

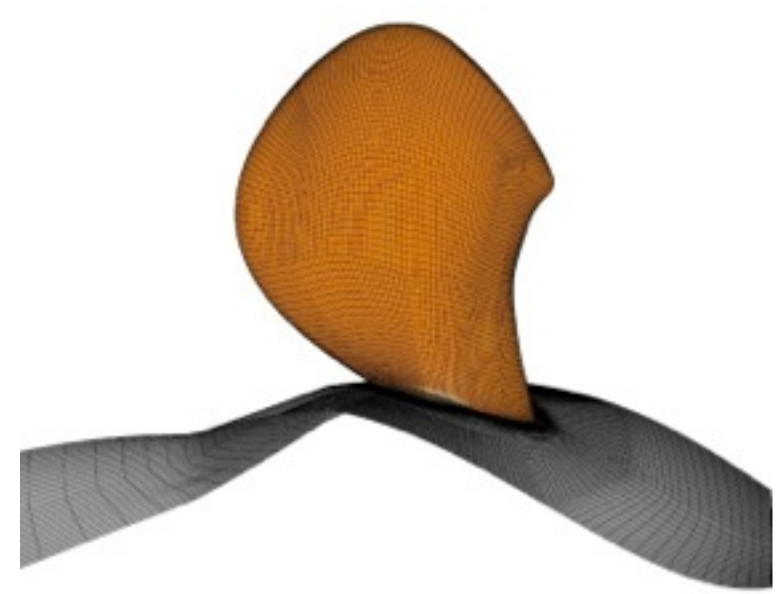
- Simulations performed with:
  ANSYS-CFX
  Steady state simulations
  SST turbulence model
  MRF approach
  Domain split in two regions:
    Rotating region: Rotating
    Fixed region: Fixed
- Computational grids generated with: ANSYS-ICEM CFD



Computational domain covering only one blade passage

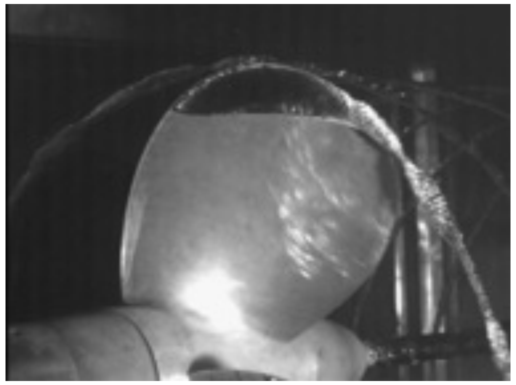


E779A, Hexa-structured surface mesh

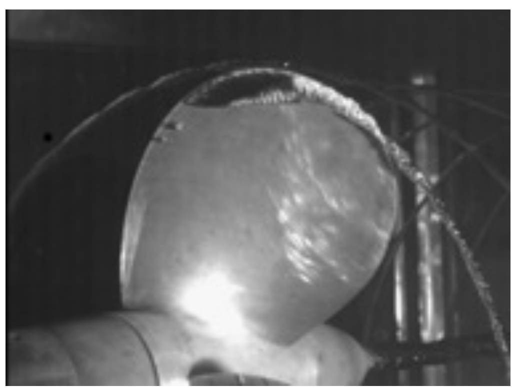


PPTC, Hexa-structured surface mesh

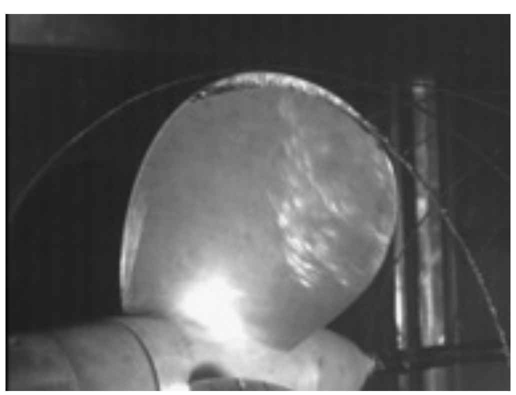
E779A – cavitating flow



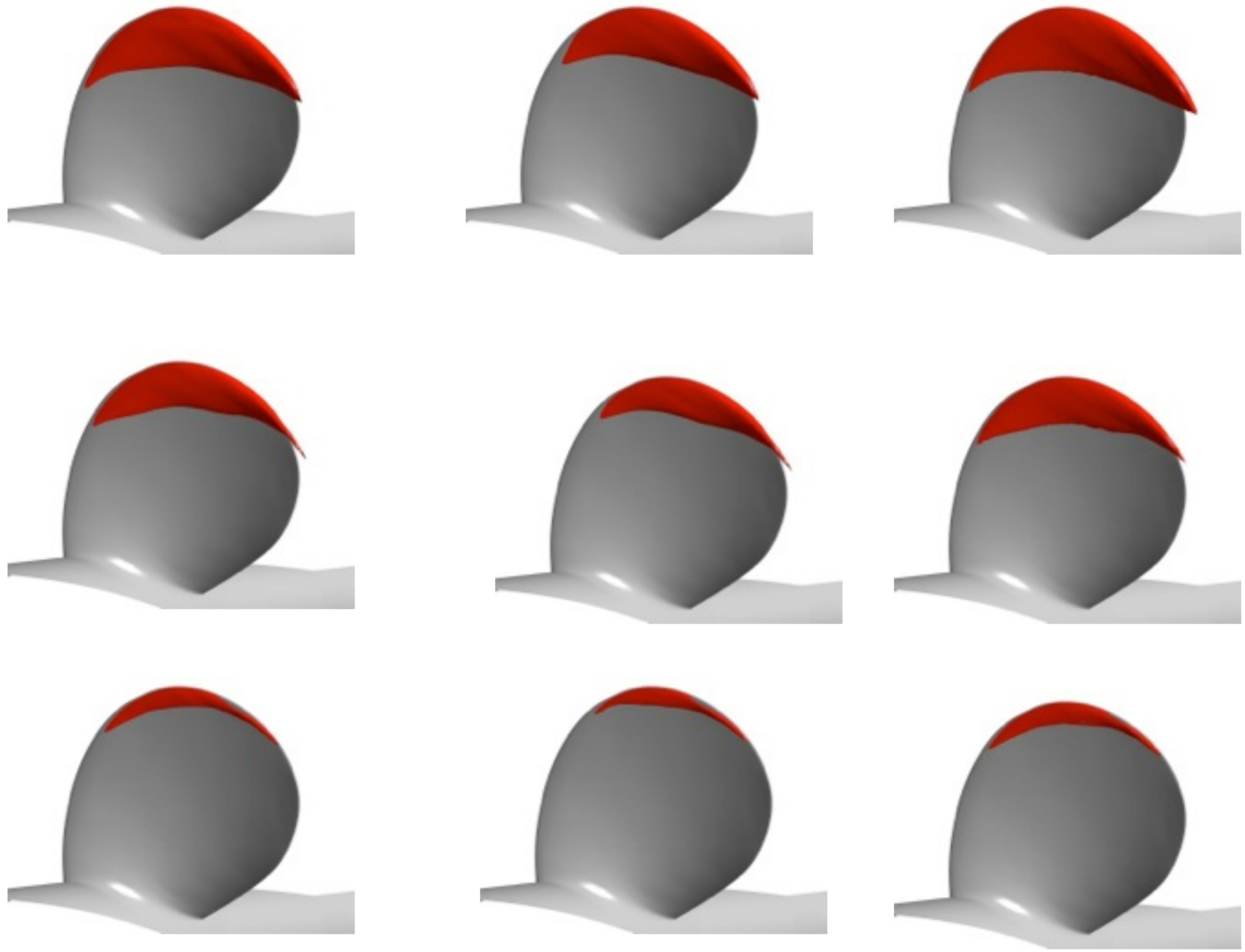
Exp. J=0.71, σ_N = 1.763



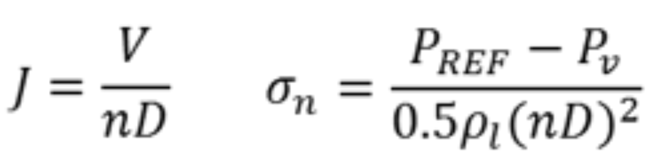
Exp. J=0.77, σ_N = 1.783



Exp. J=0.83, σ_N = 2.063



Zwart FCM Kunz



$$J = \frac{V}{nD} \qquad \sigma_n = \frac{P_{REF} - P_v}{0.5\rho_l (nD)^2}$$

Numerical cavitation patterns depicted as isosurfaces of vapour volume fracrion α=0.5

Experimental pictures courtesy of CNR-INSEAN

E779A – cavitating flow

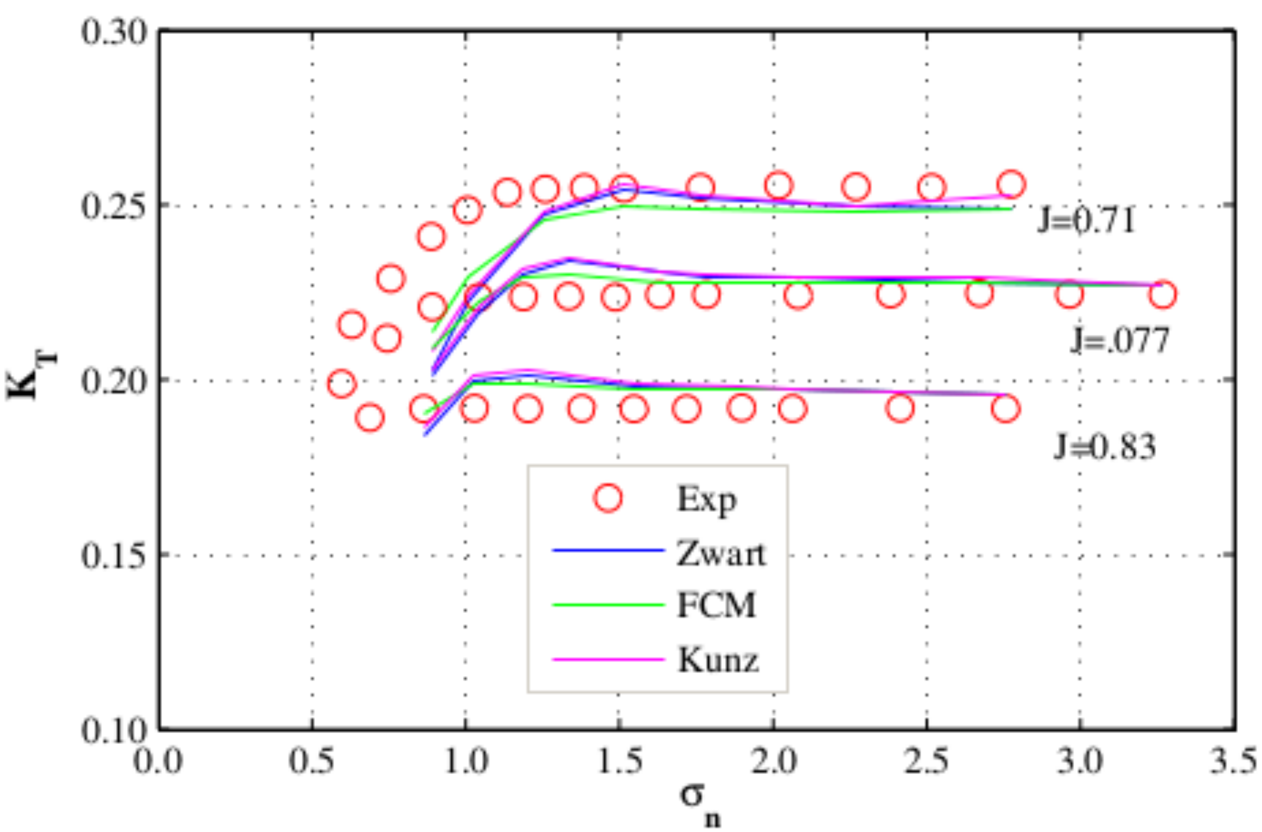
Thrust and Torque

Numerical results at J=0.71 for σ_n=1.763
and for the non cavitating regime

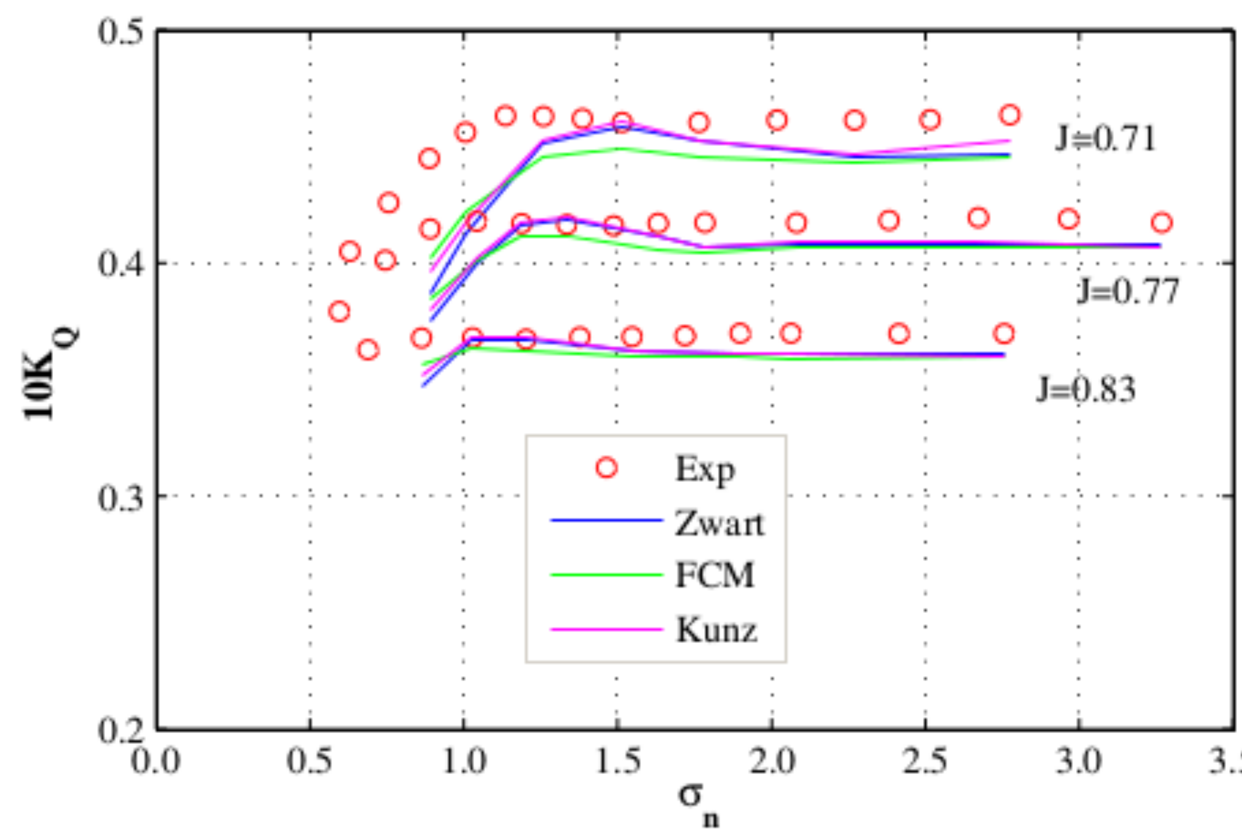
	Non-cavitating		Cavitating	
	K_T	$10K_Q$	K_T	$10K_Q$
Measured	0.256	0.464	0.255	0.46
CFD	0.246	0.442		
CFD-Zwart			0.252	0.453
CFD-FCM			0.249	0.446
CFD-Kunz			0.253	0.453

$$J = \frac{V}{nD} \qquad \sigma_n = \frac{P_{REF} - P_v}{0.5\rho_l (nD)^2}$$

$$K_T = \frac{T}{\rho_l n^2 D^4} \qquad K_Q = \frac{Q}{\rho_l n^2 D^5}$$



Influence of the cavitation number σ_N and of the mass transfer model on the thrust coefficient



Influence of the cavitation number σ_N and of the mass transfer model on the torque coefficient

Second International Symposium on Marine Propulsors 2011

Workshop: Propeller performance

17 - 18 June 2011, Hamburg, Germany

- Potsdam Propeller Test Case (PPTC)
- Cavitation Tests with the Model Propeller VP1304
- Case 2.3
- Blind Benchmark
- Proceedings available on-line:

http://www.marinepropulsors.com/smp/files/downloads/smp11_workshop/smp11_workshop/

SMP11 - Workshop Propeller performance

Group	Solver	Acronym
Berg-Propulsion	Procal	Berg-Procal
Cradle	SC/Tetra	Cradle-SC/Tetra
CSSRC	ANSYS Fluent	CSSRC-Fluent
HSVA	QCM	HSVA-QCM
	PPB	HSVA-PPB
INSEAN	PFC	INSEAN-PFC
SSPA	ANSYS Fluent	SSPA-Fluent
TUHH	FreSCO+	TUHH-FreSCO
University of Genua	Panel	UniGenua-Panel
	StarCCM+	UniGenua-StarCCM
University of Triest	ANSYS CFX(FCM)	UniTriest-CFX(FCM)
	ANSYS CFX(Kunz)	UniTriest-CFX(Kunz)
	ANSYS CFX(Zwart)	UniTriest-CFX(Zwart)
VOITH	Comet	VOITH-Comet
VTT	FinFlo	VTT-FinFlo

SMP11 - Thrust coefficient

Table 3: Thrust coefficients of cavitating propeller

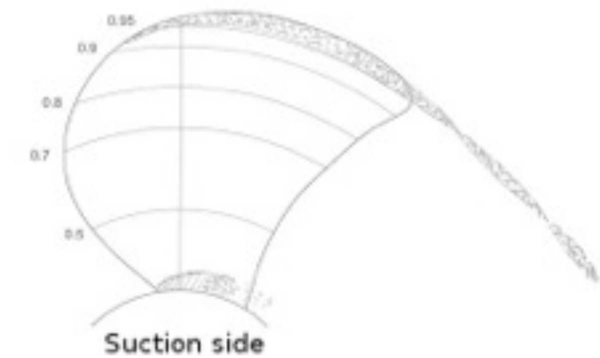
	case 2.3.1	case 2.3.2	case 2.3.3
	K_T [-]	K_T [-]	K_T [-]
Exp. (non-cavitating)	**0.3870**	**0.2450**	**0.1670**
Exp. (cavitating)	**0.3725**	**0.2064**	**0.1362**
Berg-Procal	0.3760		
Cradle-SC/Tetra	0.3750	0.1990	0.1380
CSSRC-Fluent	0.3740	0.1940	0.1320
INSEAN-PFC	0.3570	0.2330	0.1610
SSPA-Fluent	0.3880	0.2050	0.1440
TUHH-FreSCO+	0.3830		0.1440
TUHH-FreSCO+ (small-large coef.)		0.2420 - 0.1370	
UniGenua-Panel	0.3922	0.2369	0.1378
UniGenua-StarCCM	0.3782	0.2035	0.1306
UniTriest-CFX(FCM)	0.3740	0.2030	0.1300
UniTriest-CFX(Kunz)	0.3750	0.2100	0.1330
UniTriest-CFX(Zwart)	0.3730	0.1960	0.1330
VOITH-Comet	0.3852	0.2101	0.1513
VTT-FinFlo	0.3860	0.2020	0.1420

SMP11 - Thrust coefficient

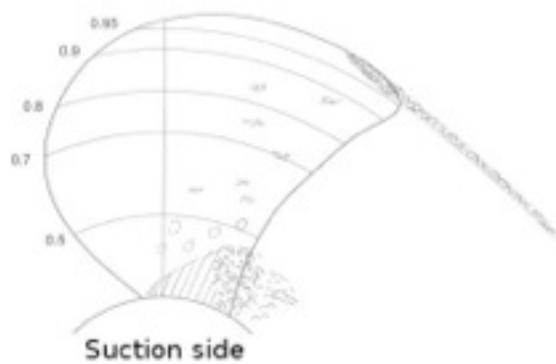
Table 4: Difference between computed and measured thrust of cavitating propeller

	case 2.3.1 ΔK_T [%]	case 2.3.2 ΔK_T [%]	case 2.3.3 ΔK_T [%]
Berg-Procal	0.94		
Cradle-SC/Tetra	0.67	-3.59	1.32
CSSRC-Fluent	0.40	-6.01	-3.08
INSEAN-PFC	-4.16	12.89	18.21
SSPA-Fluent	4.16	-0.68	5.73
TUHH-FreSCO+	2.82		5.73
TUHH-FreSCO+ (small-large coef.)		17.25 - -33.62	
UniGenua-Panel	5.29	14.78	1.17
UniGenua-StarCCM	1.53	-1.41	-4.11
UniTriest-CFX(FCM)	0.40	-1.65	-4.55
UniTriest-CFX(Kunz)	0.67	1.74	-2.35
UniTriest-CFX(Zwart)	0.13	-5.04	-2.35
VOITH-Comet	3.41	1.79	11.09
VTT-FinFlo	3.62	-2.13	4.26

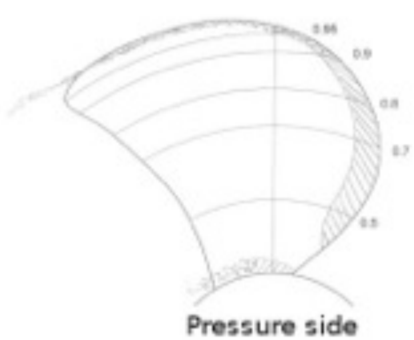
SMP11 - Cavitation patterns



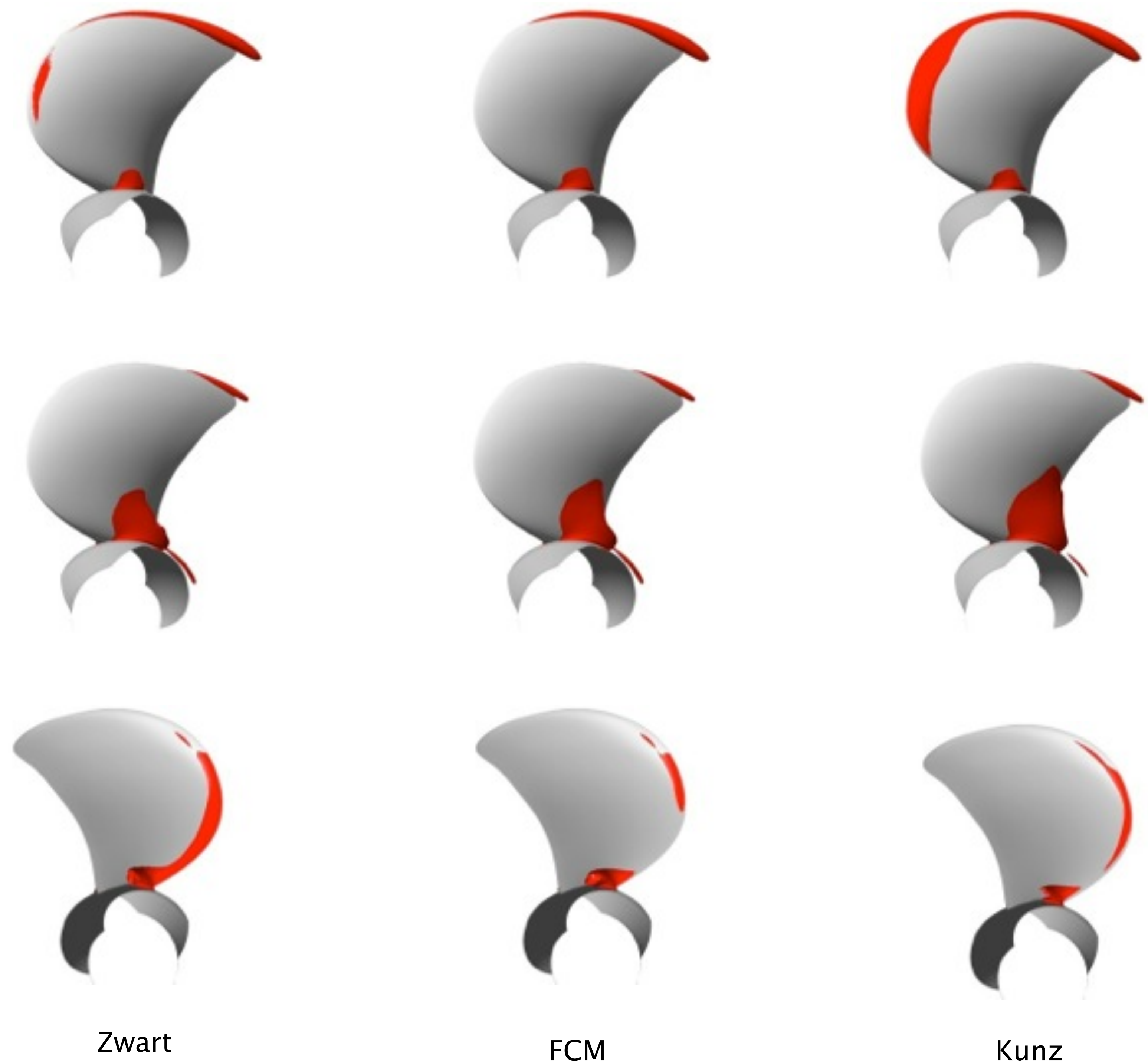
Exp. J=1.019, σ_n=2.024



Exp. J=1.269, σ_n=1.424



Exp. J=1.408, σ_n=2.000

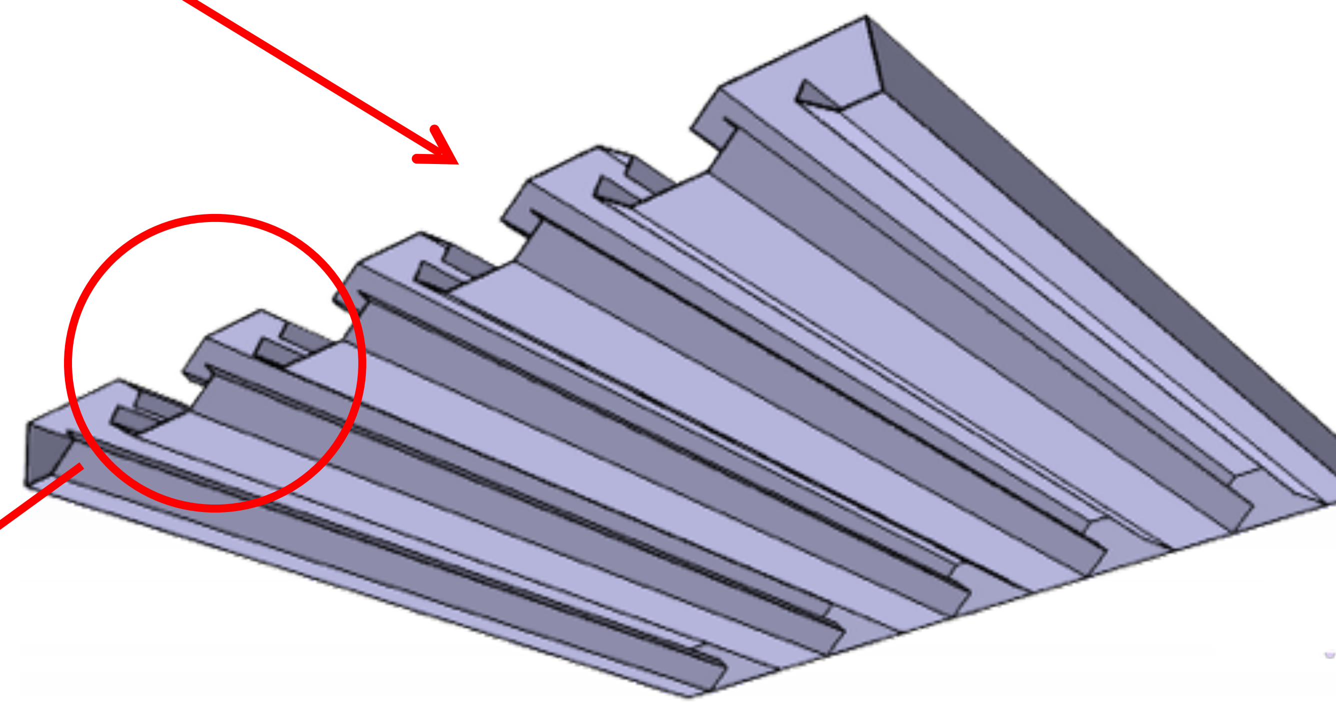


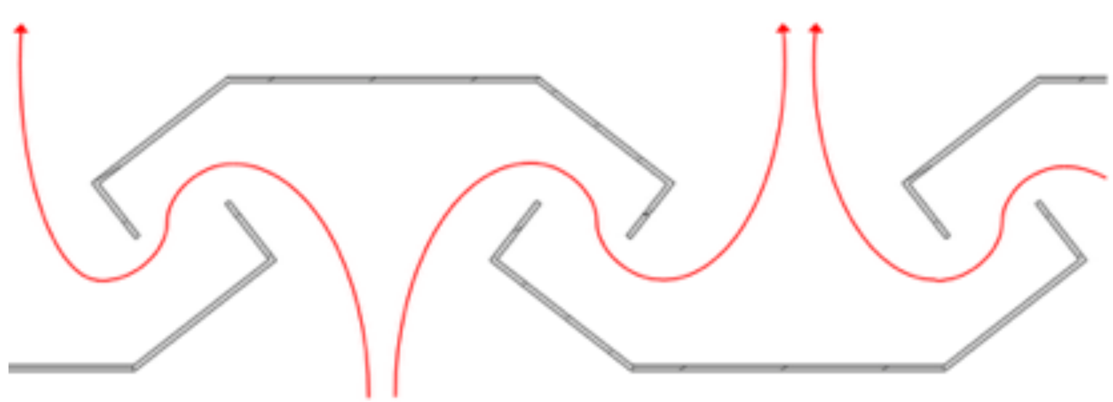
Numerical cavitation patterns depicted as isosurfaces of vapour volume fraction α = 0.5

Filter for professional kitchen

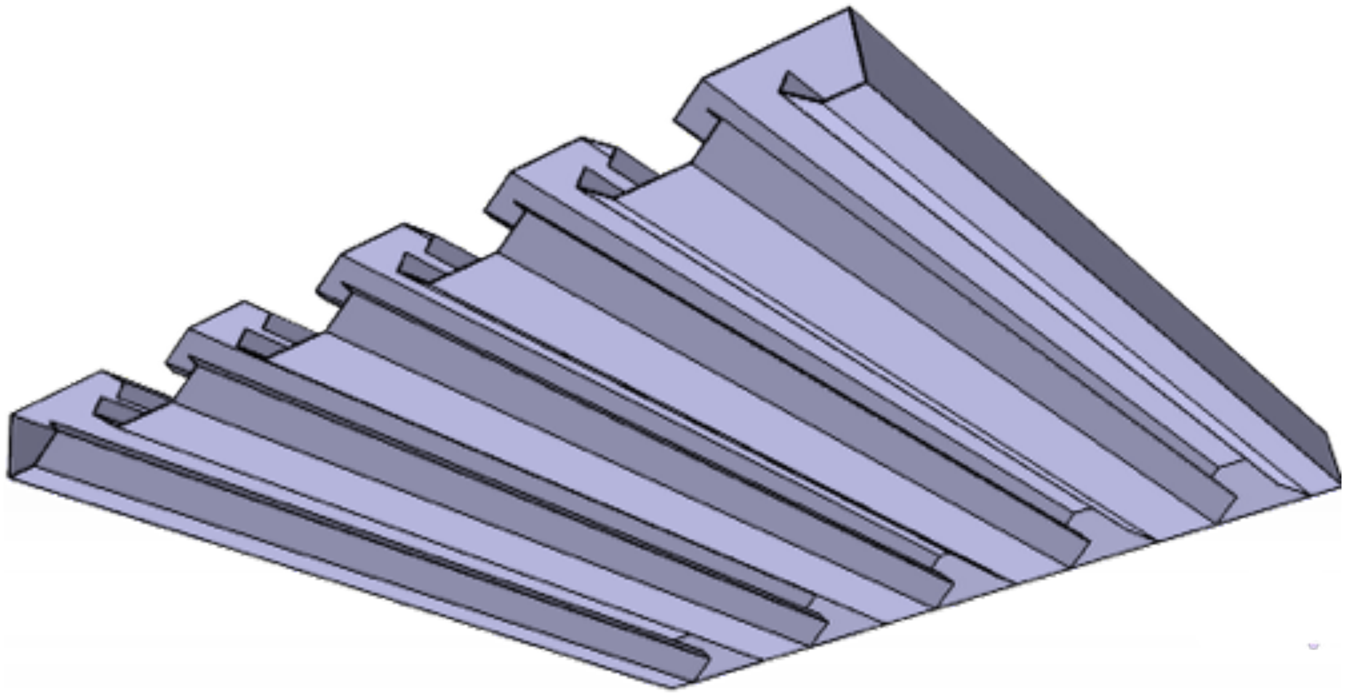
Filtro tra i più diffusi sul mercato delle cucine industriali.

Il dispositivo è composto da una serie di lamierini di acciaio inossidabile piegati in modo tale da formare i canali di passaggio per l’aria.

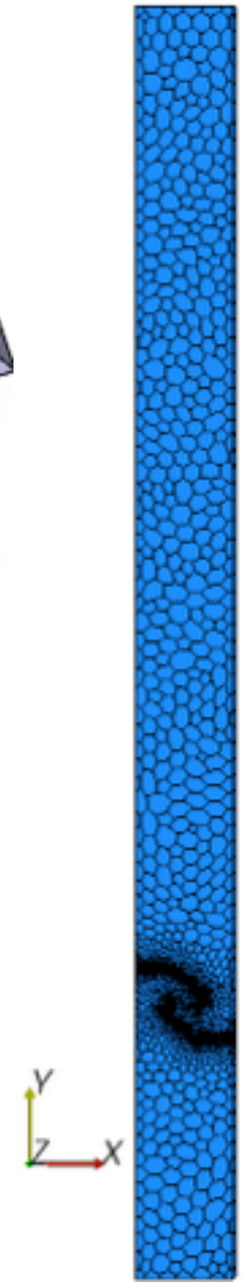


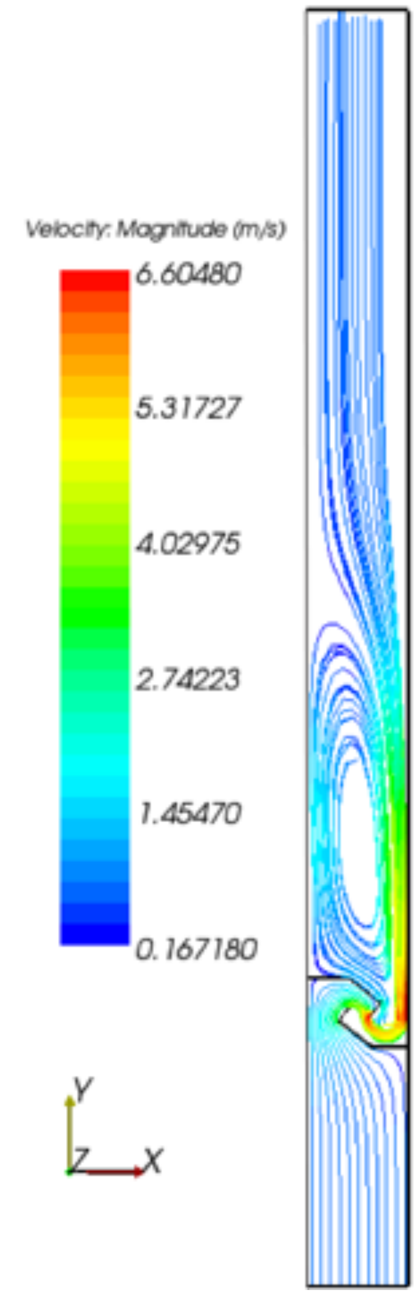


Simple periodic model

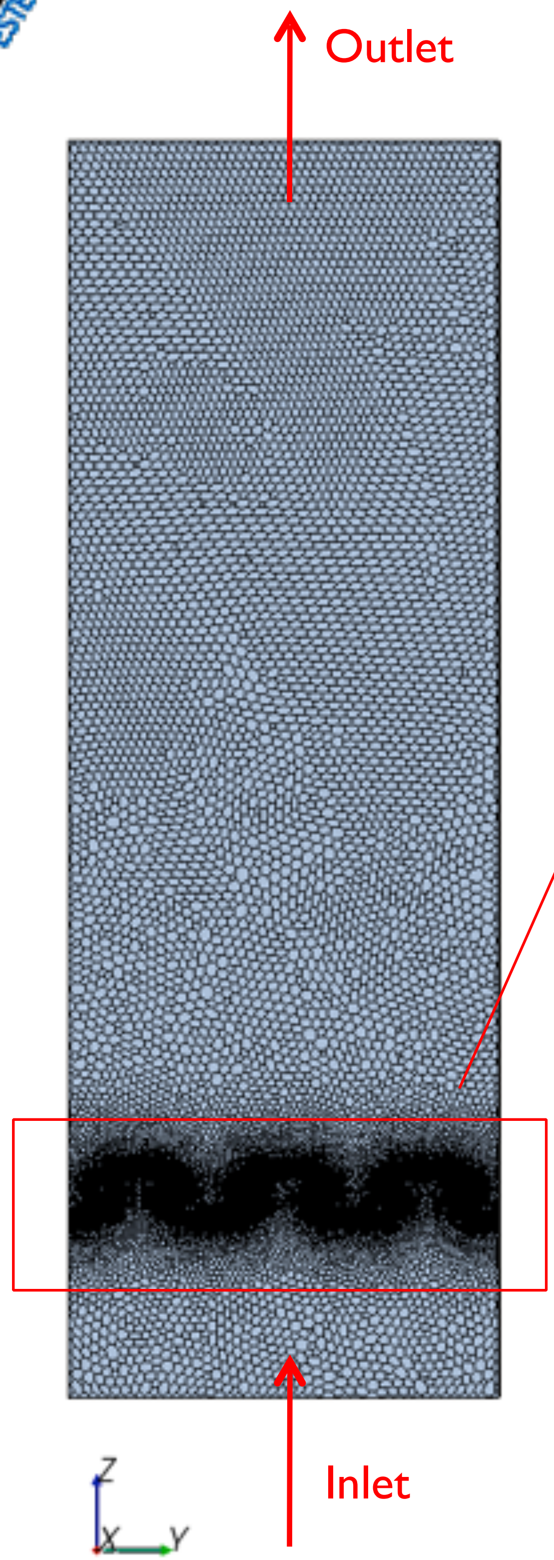


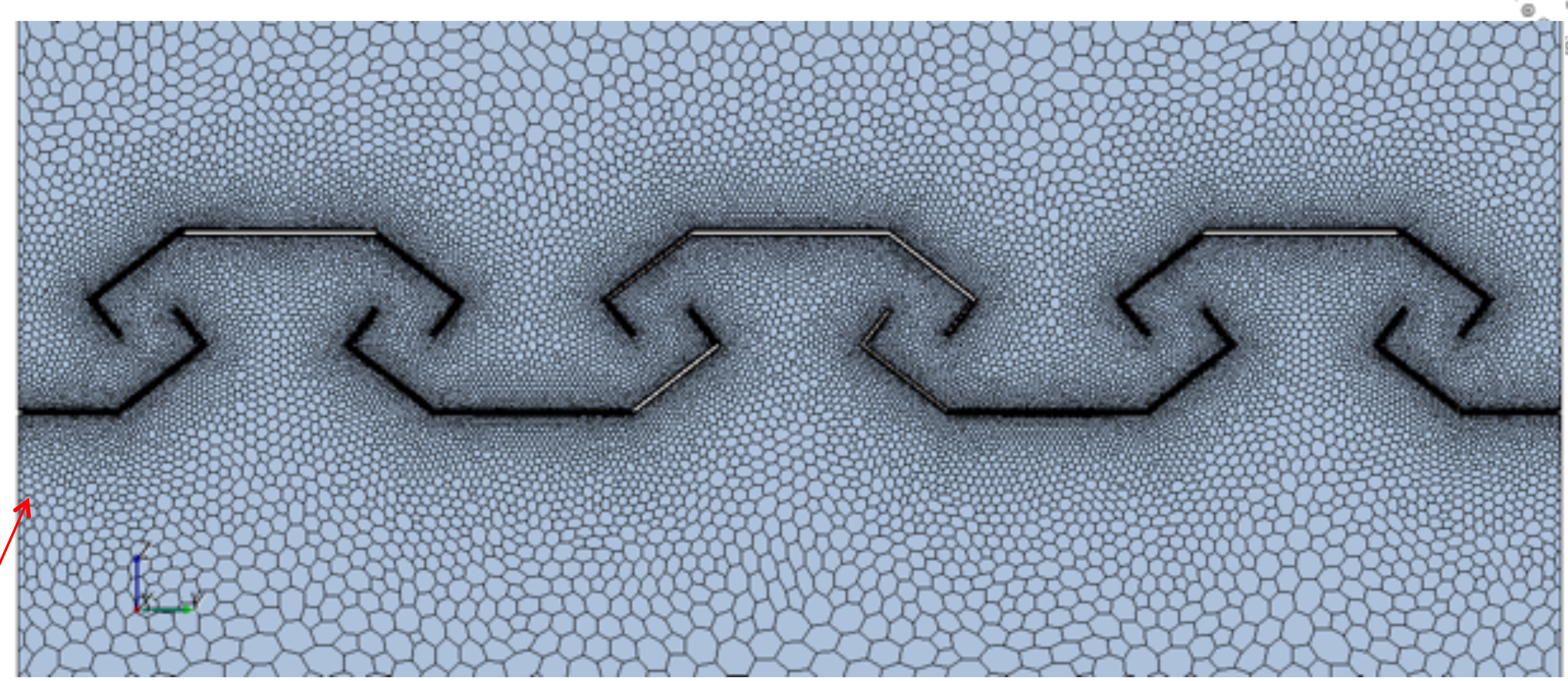
Simple periodic model is NOT ABLE TO PREDICT the flow pattern!





Simulazioni numeriche CFD

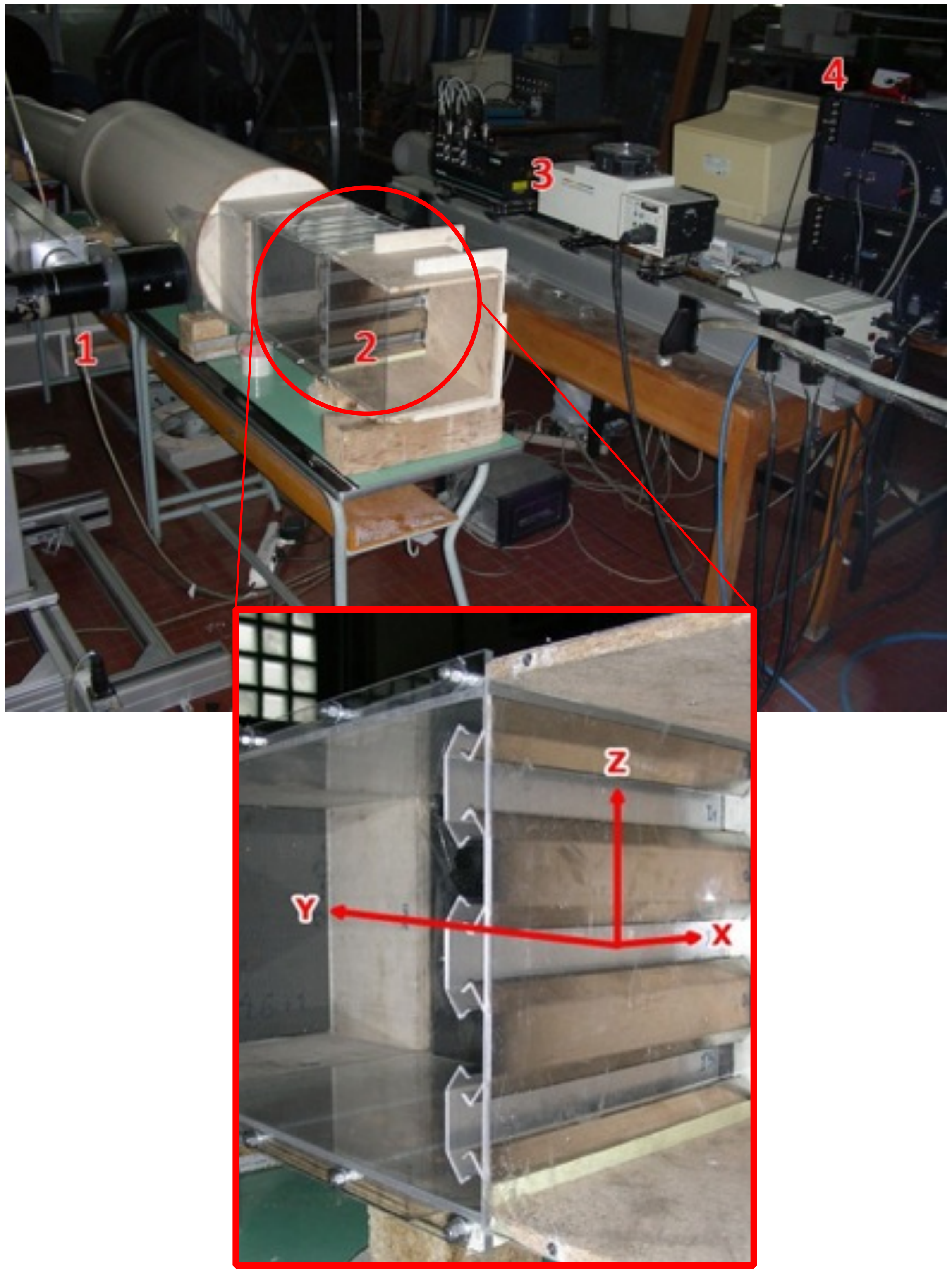




Star-CCM+

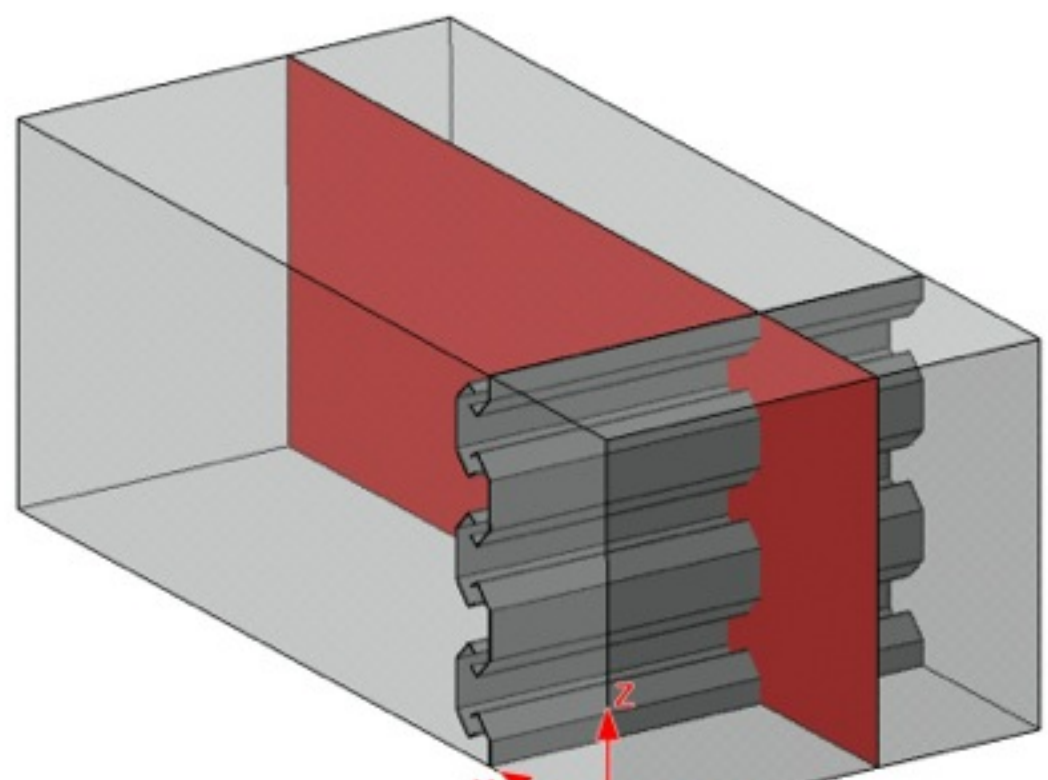
Mesh 2D	Poliedri + strato di prismi a parete = ~500.000 celle
Inlet	• Aria a T = 23°C e densità costante • Pressione Standard • Portate = 300 ÷ 450 ÷ 600 m • Gravità : 0, 0, –9.81 m/s
Outlet	• Pressione statica = 0 Pa • Pressione di riferimento = 101325 Pa
Turbolenza	Modello k-ω
Tempo	Modello non stazionario - Δt = 10 sec (step 1/10 sec)
Multifase	Modello lagrangiano (olio, 800 kg/m min)

Verifiche sperimentali



Laser Doppler Velocimetry:

- plexiglass trasparente da 5mm
- Portata: 600 m^3/h → 0.83 m/s
- Spray di acqua e glicerina (10%/volume)
- Rilevamenti 2D (piani ZY simmetrici lungo l'asse X)
- Griglia da 12000 punti di misura (media su 30/60 sec.)



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Verifiche sperimentali

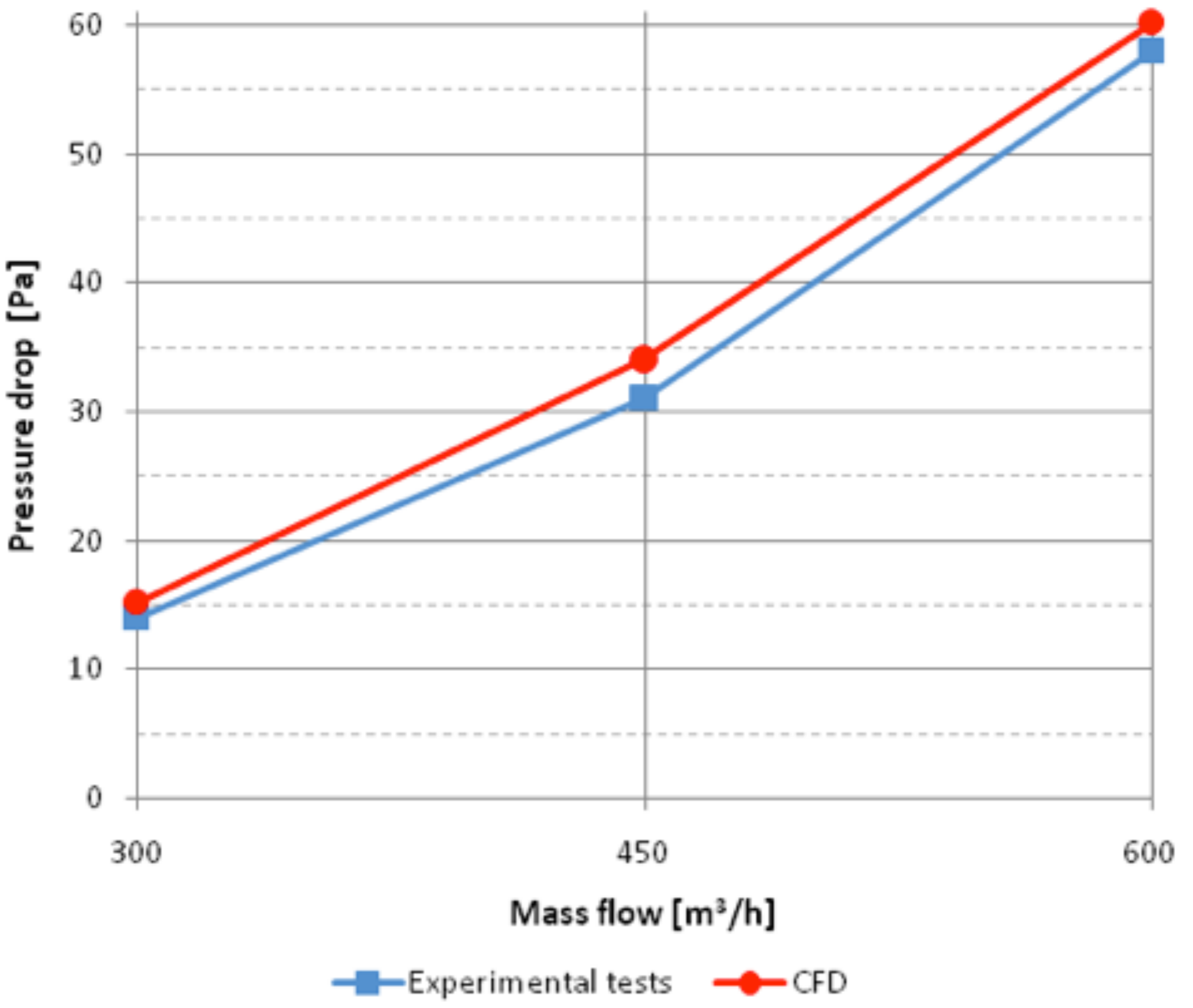
Pressione

← Laser Doppler Velocimetry

↓ Particle Size Analyzer

Risultati

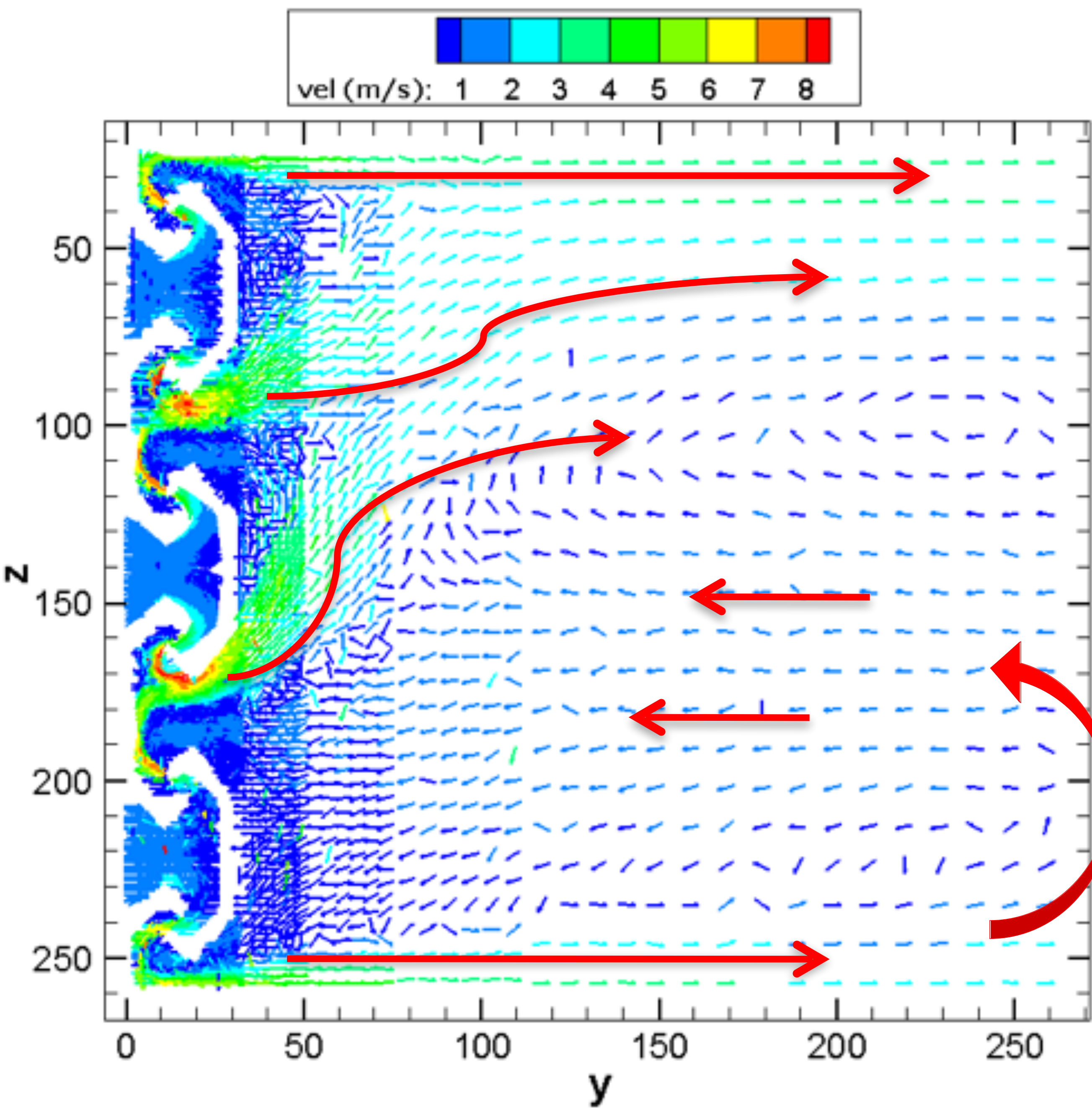
Portata [m	Pressione [Pa] CFD	Dati sperimentali	Errore rel. [%]
300	15.198	14	8.6
450	34.034	31	9.8
600	60.257	58	3.9



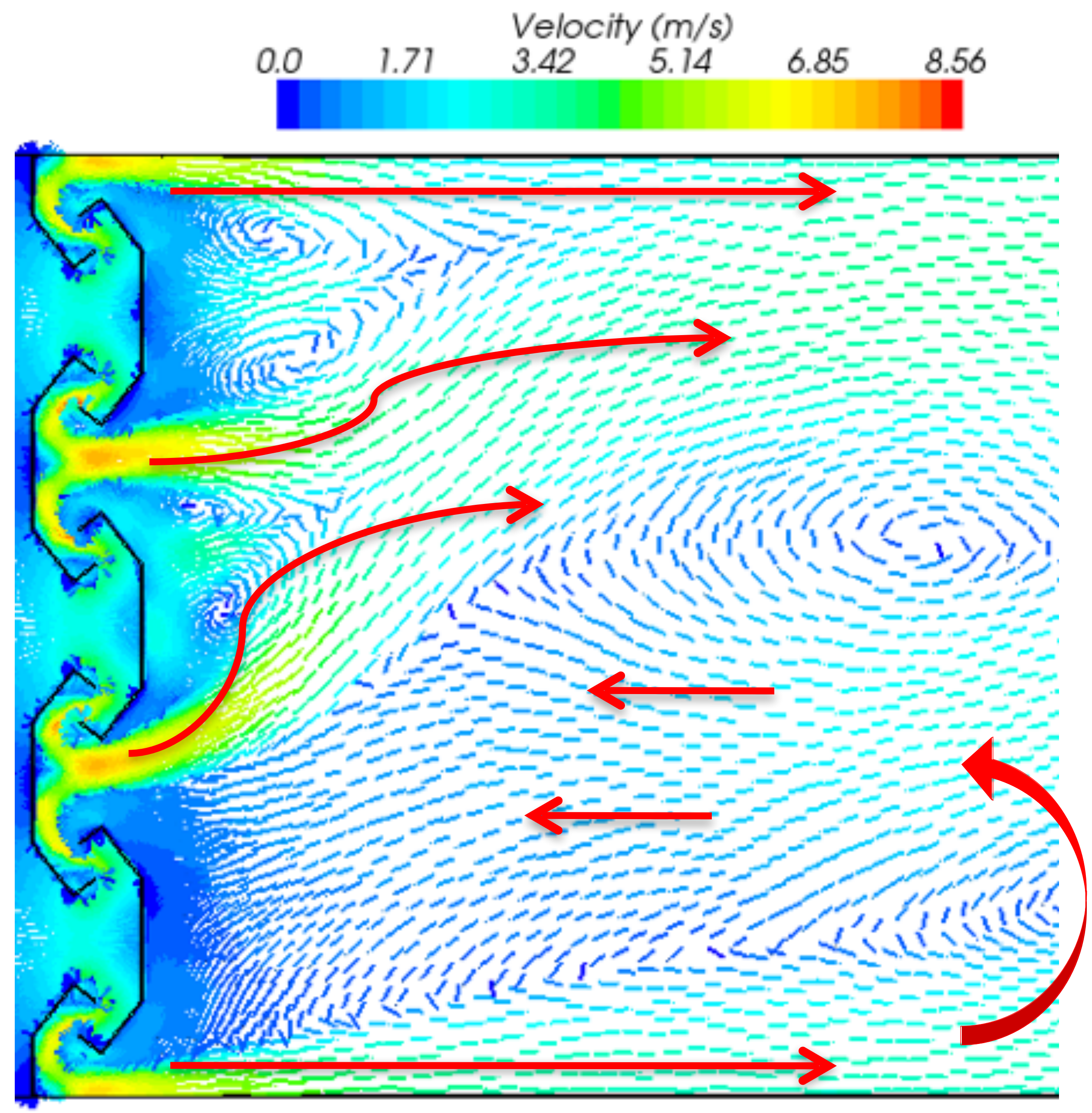
Risultati

Vettori di velocità (m/s)

Dati sperimentali

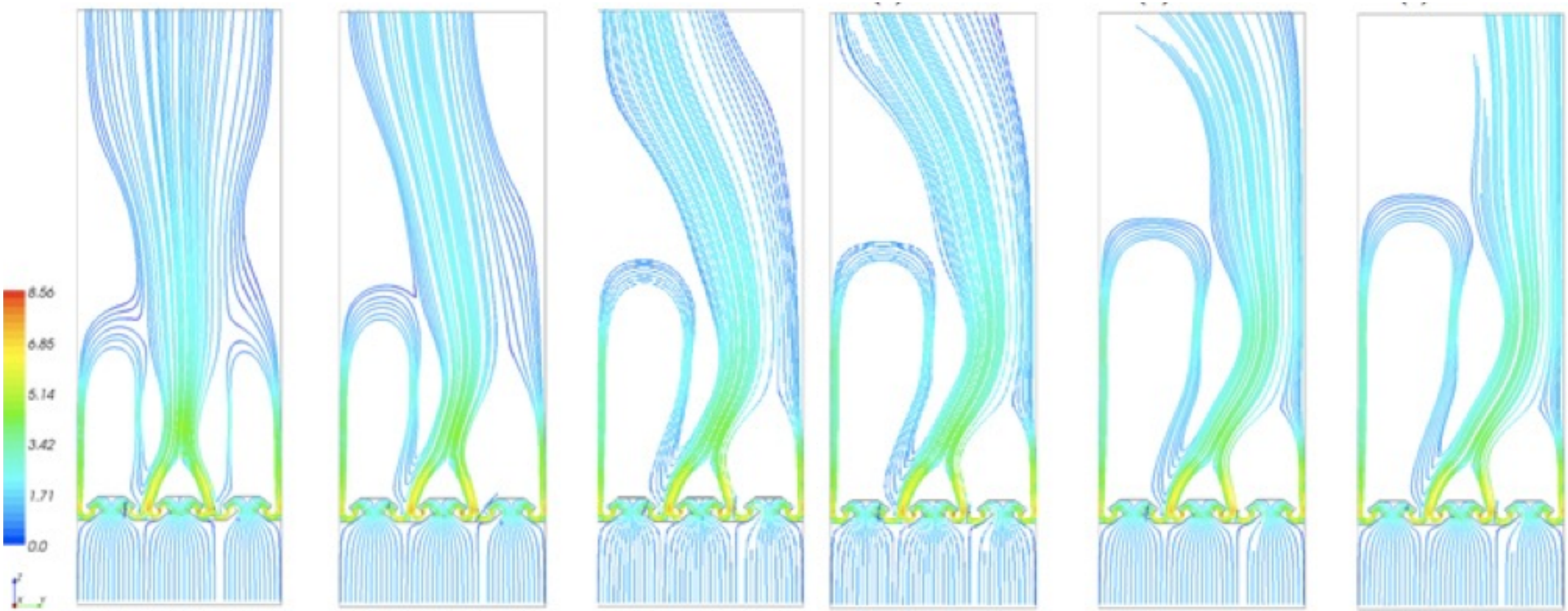


CFD



Risultati

CFD – streamline

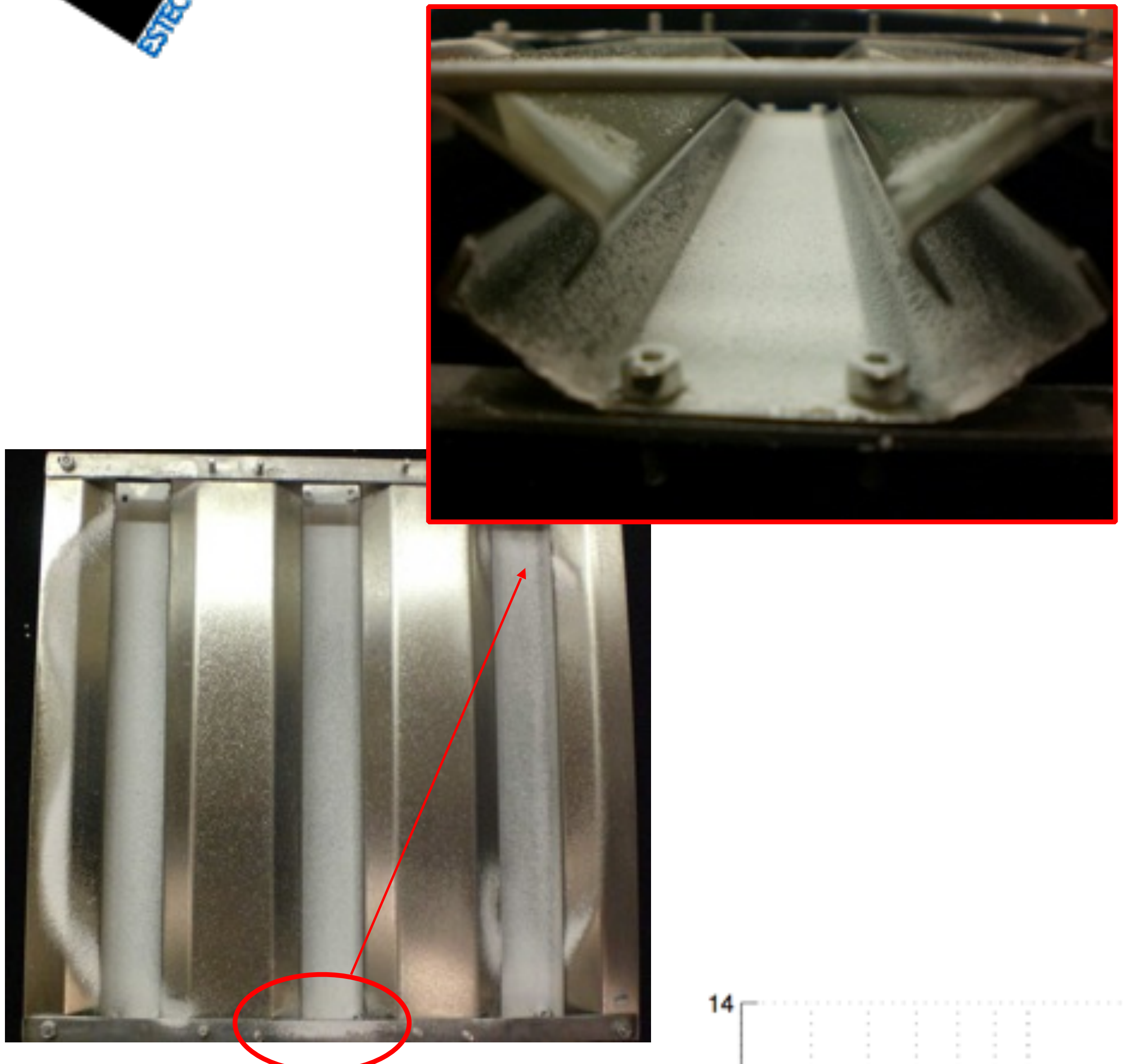


(a) 0.5 sec (b) 1.0 sec (c) 1.5 sec (d) 2.0 sec (e) 2.5 sec (f) 3.0 sec

0<t<3 sec : unsteady

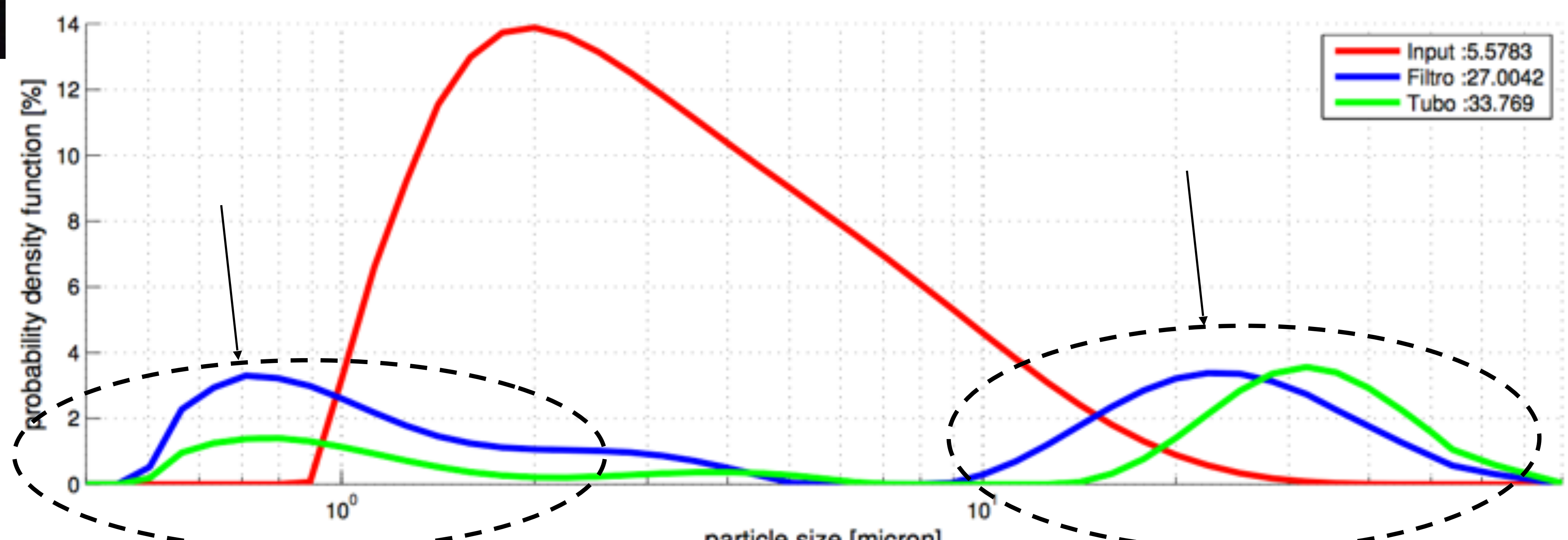
3<t<10 sec : steady

Verifiche sperimentali



Particle Size Analyzer:

- Struttura posta verticalmente
- Inseminazione di particelle di vetro finemente frantumate
- Diametri = 1-40 micron (PDF rossa)



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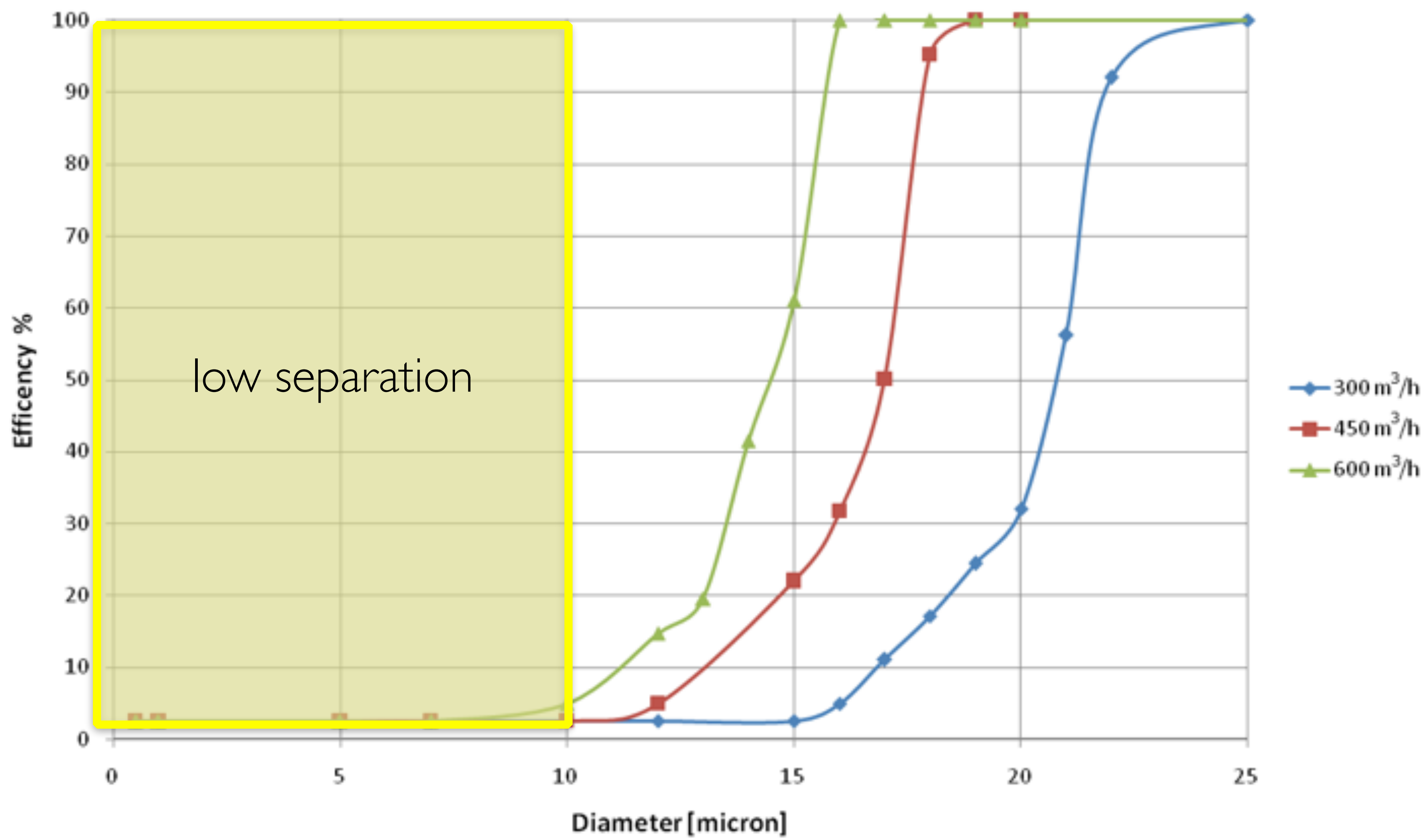
Results

<u>Separation efficiency by CFD changing flow rate</u>:



<u>very low efficiency for D < 12 micron</u> due to:

- 2D flow
- reduced residence inside the filter

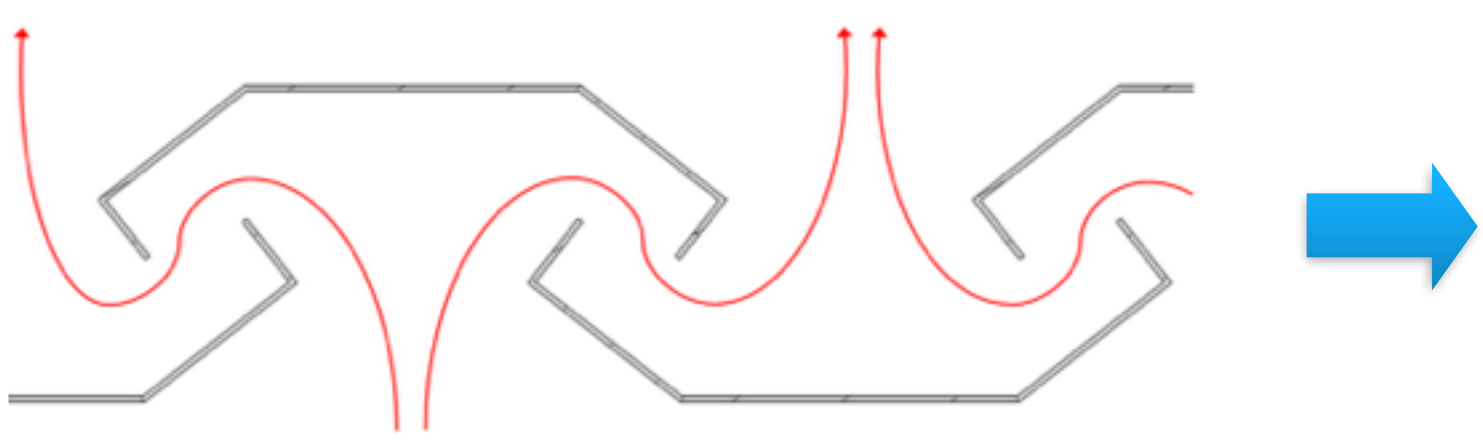
Shape optimization of the filter

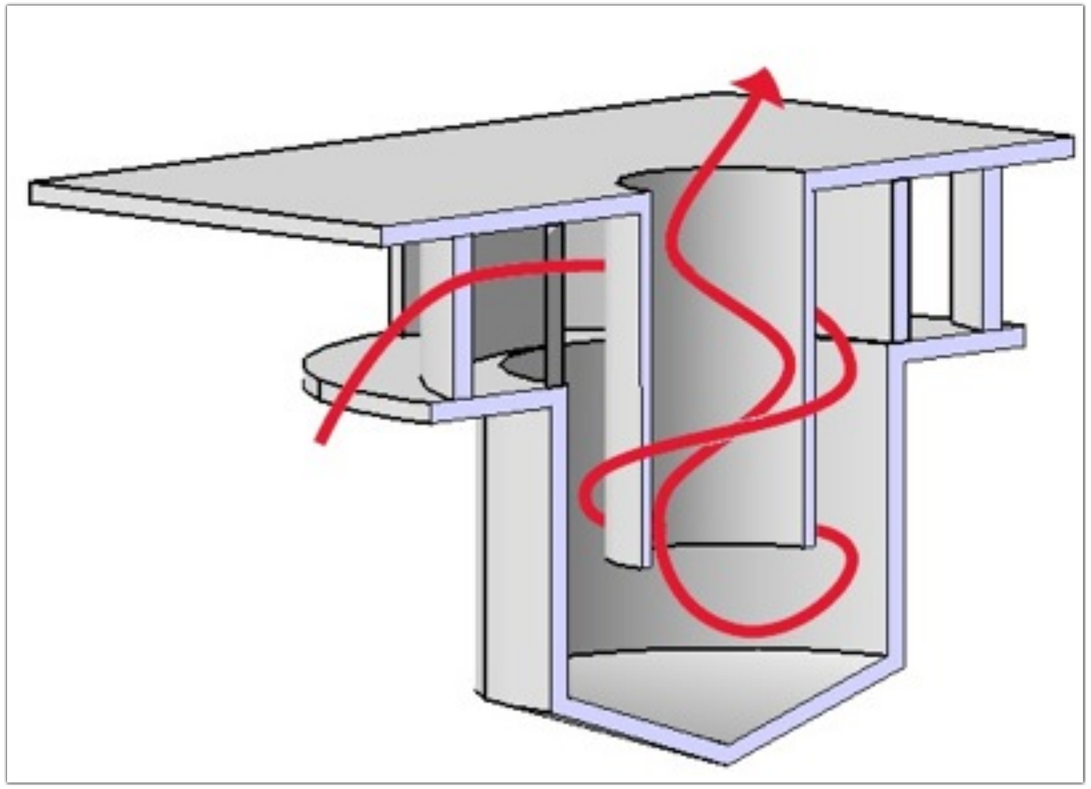
Shape optimization by modeFRONTIER

- ↑ Max separation efficiency
- ↓ Min pressure losses

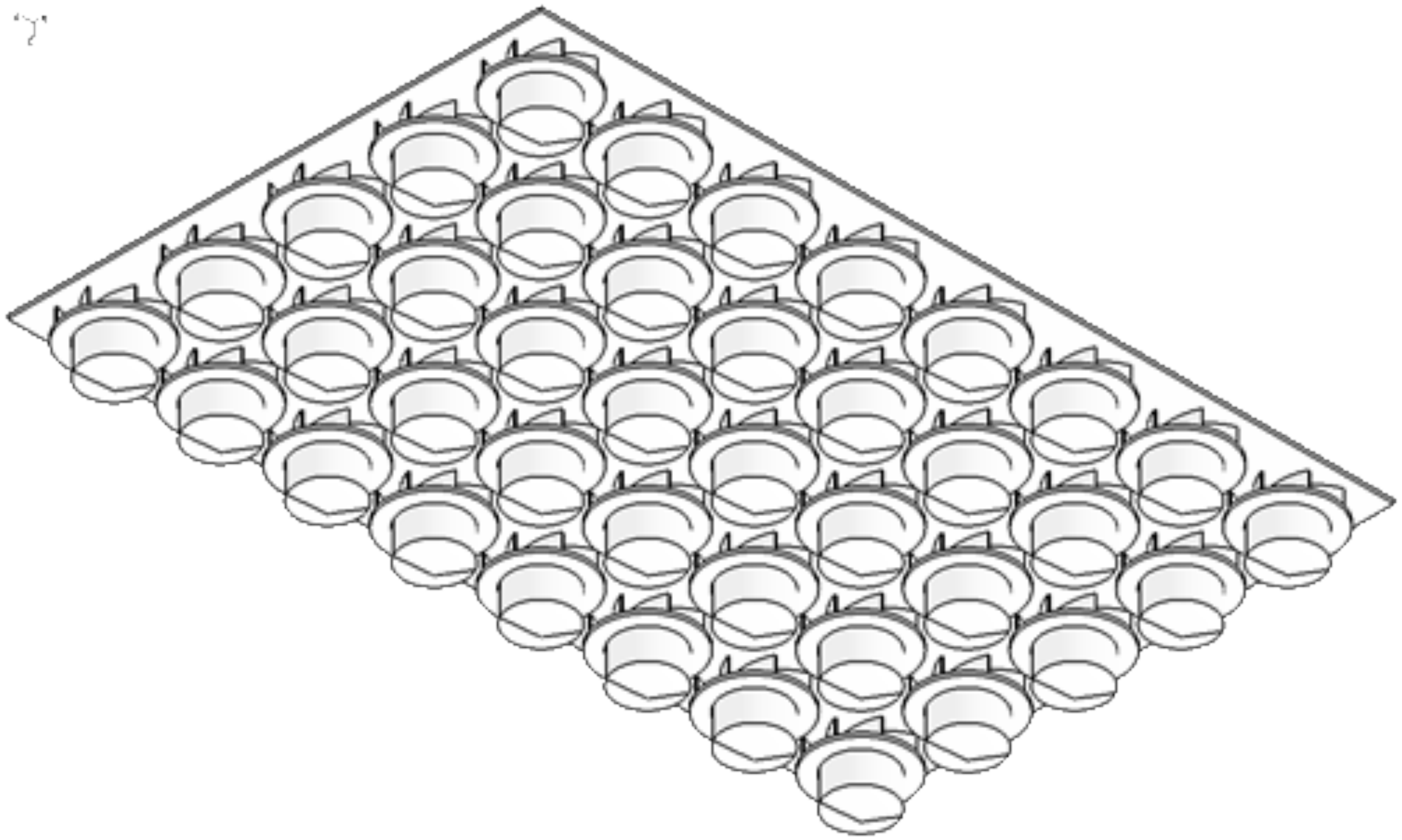
New device

- develop an efficient filter for small particles (8 micron)
- create a 3D flow pattern
- have longer residence time inside the filter



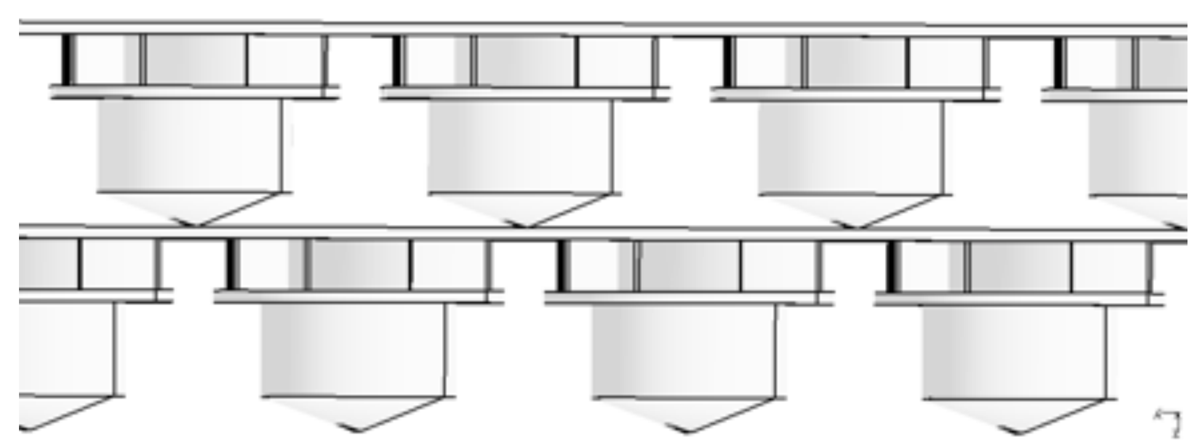


New device

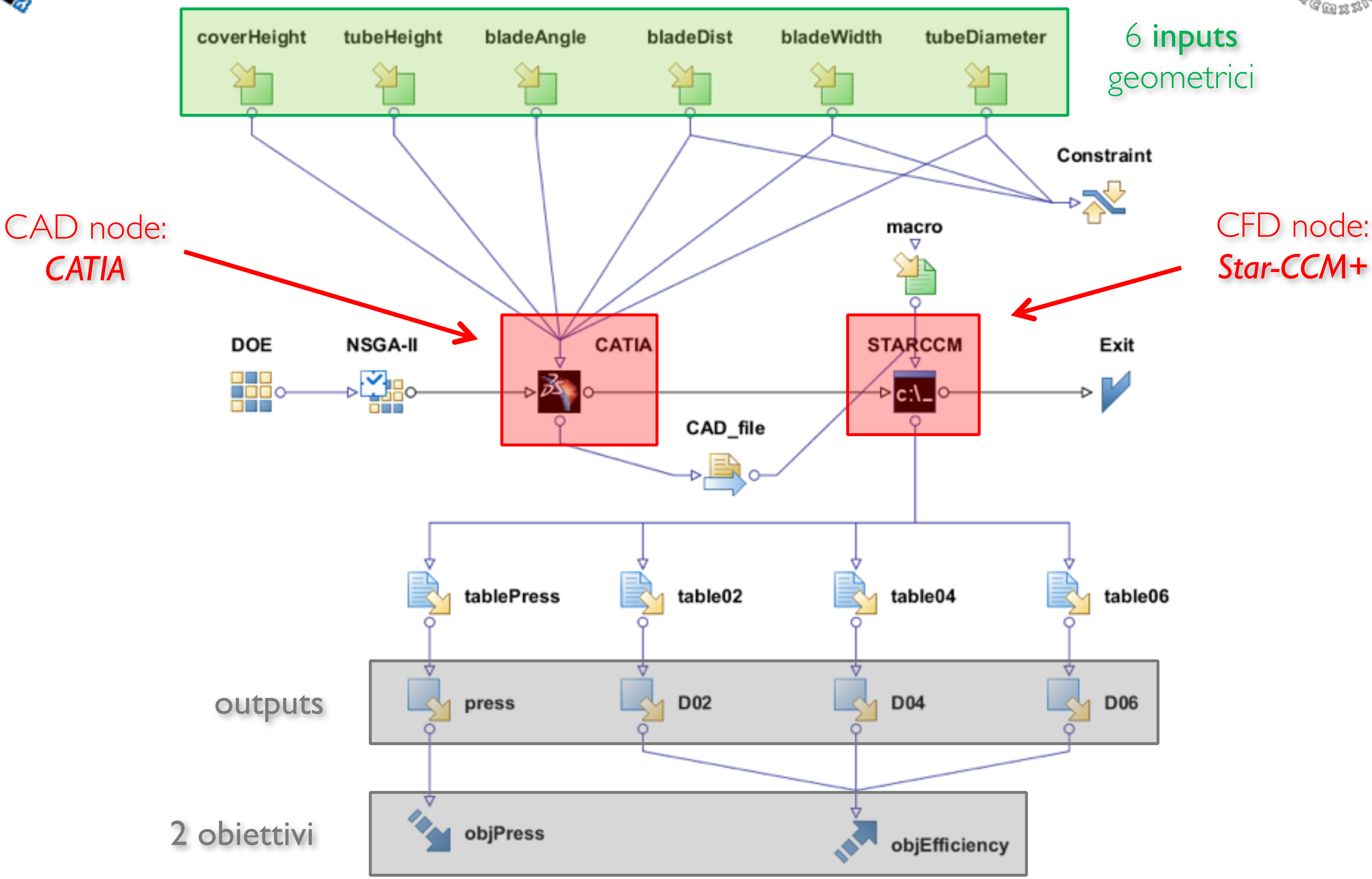


"flat" filter made of many modules

possibility of having a series of filters mounted in series

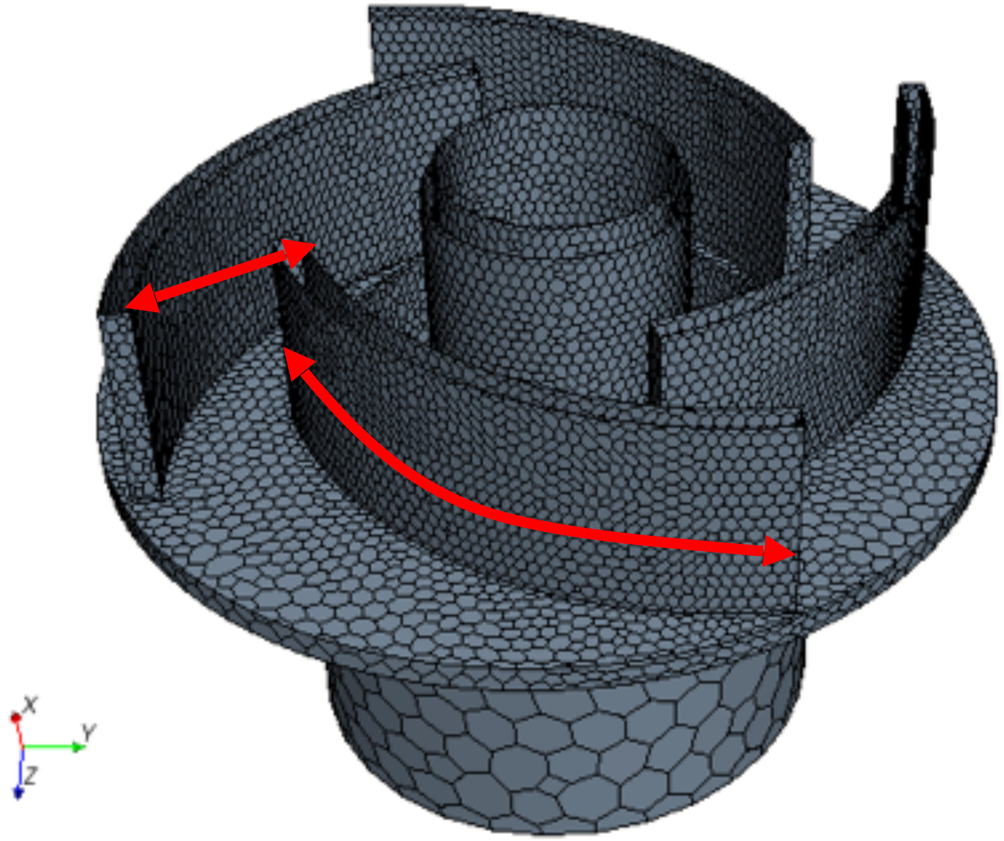


Nuovo dispositivo – Ottimizzazione

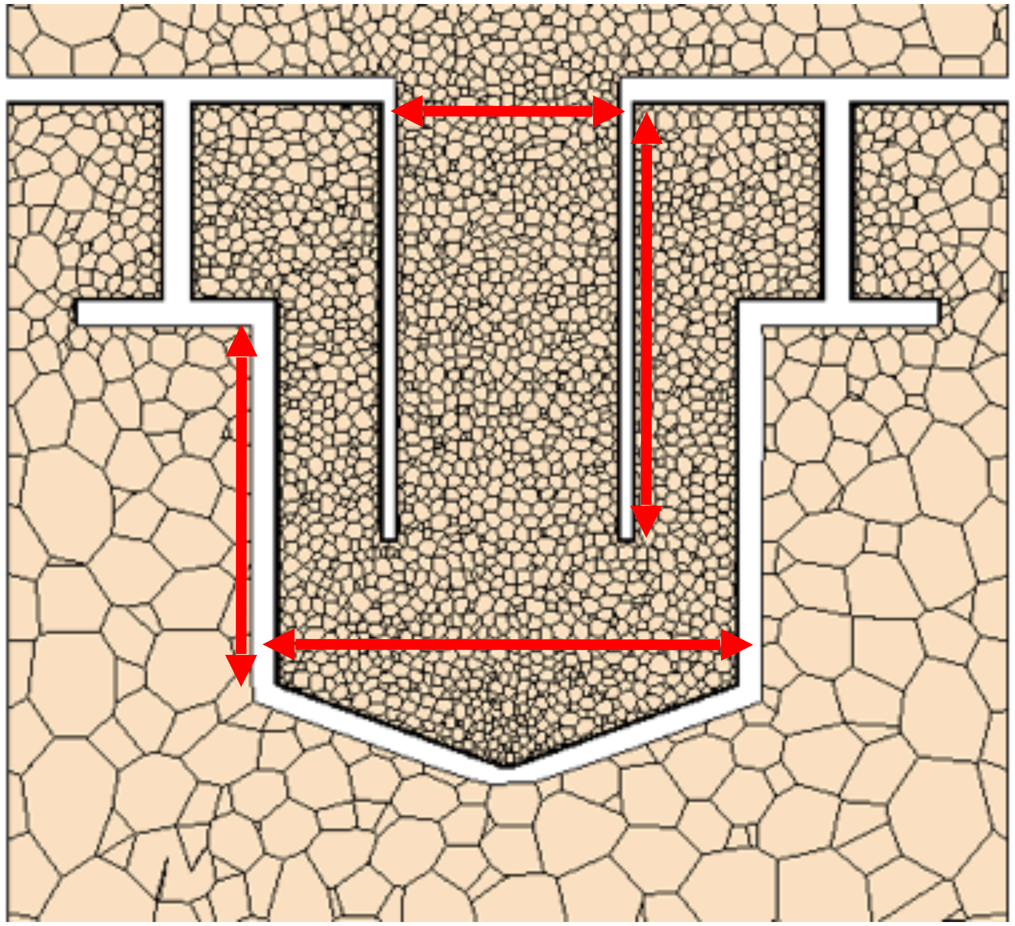


Nuovo dispositivo – Ottimizzazione

6 Inputs geometrici

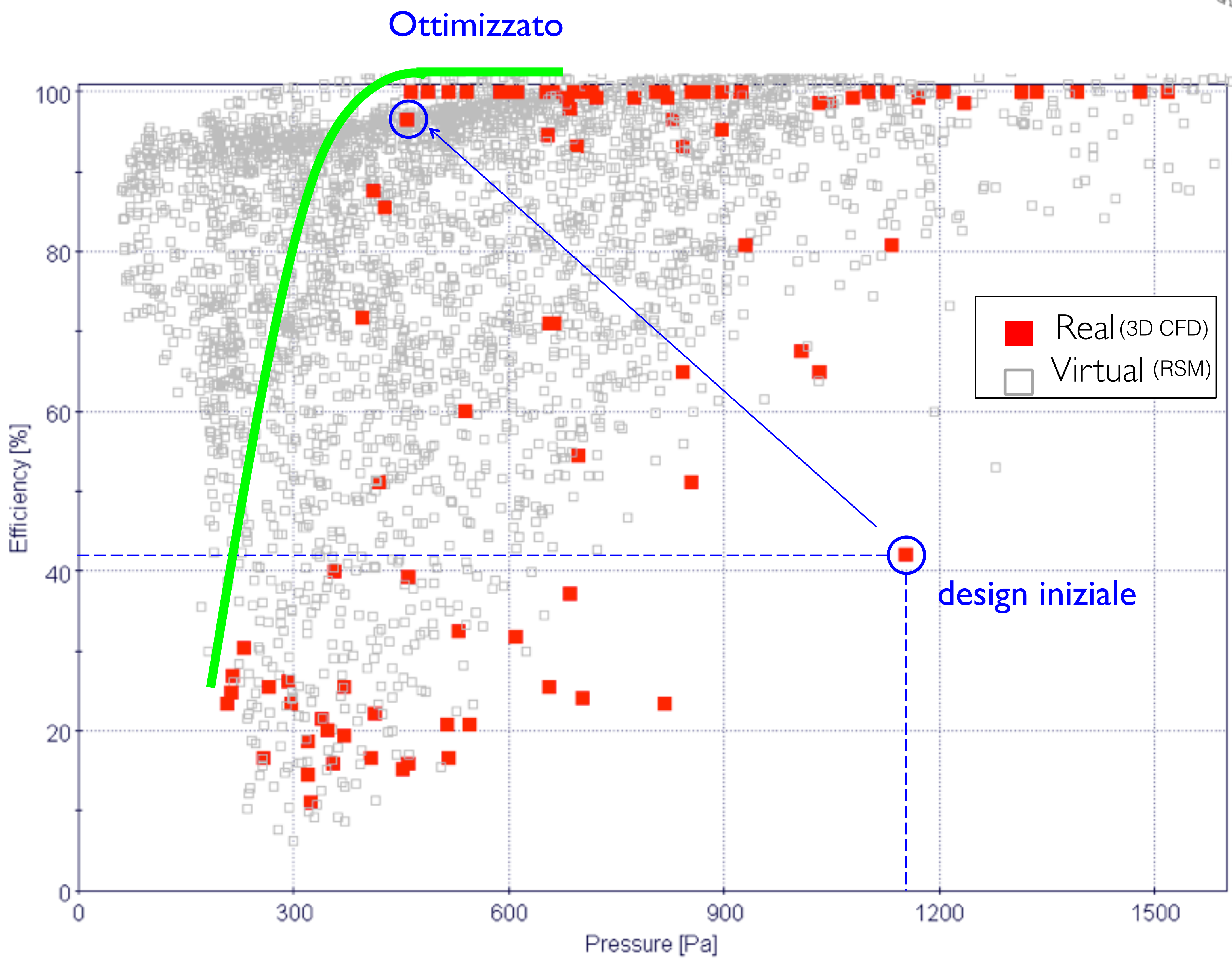


Vista dall'alto



Sezione frontale

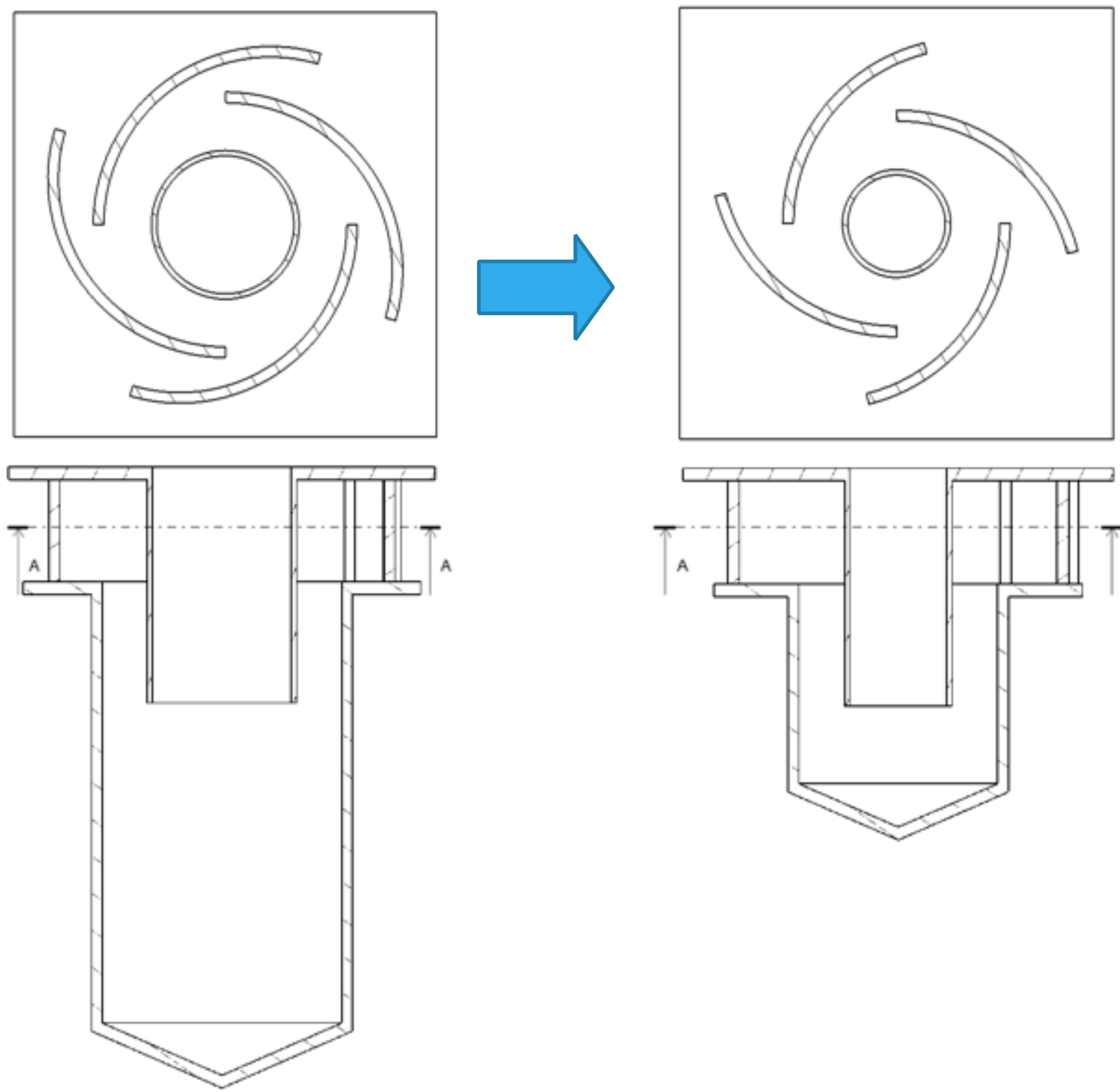
Nuovo dispositivo – Ottimizzazione



Nuovo dispositivo – Ottimizzazione

sezione
A-A

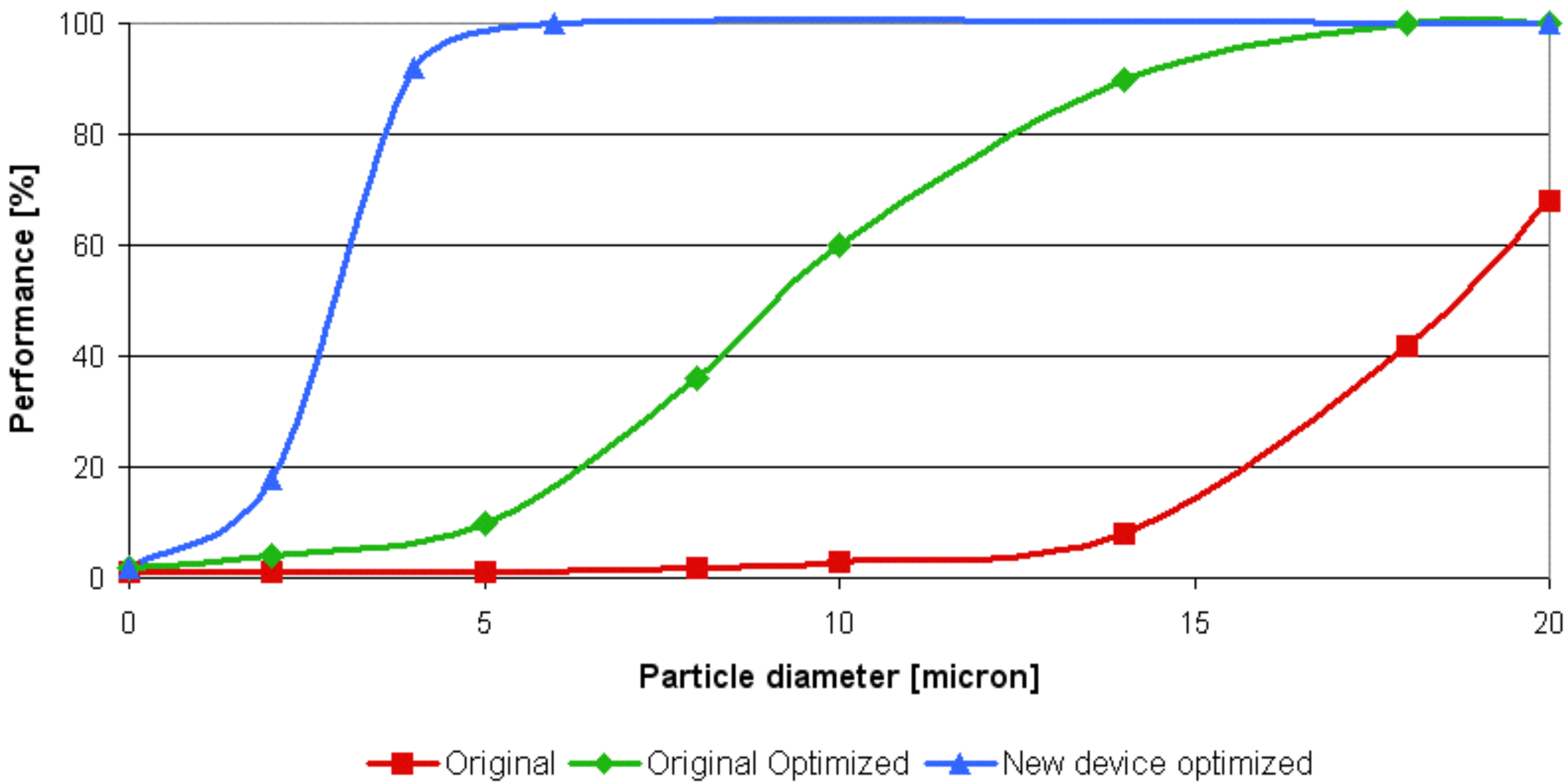
Design
iniziale



sezione
A-A

Design
ottimizzato

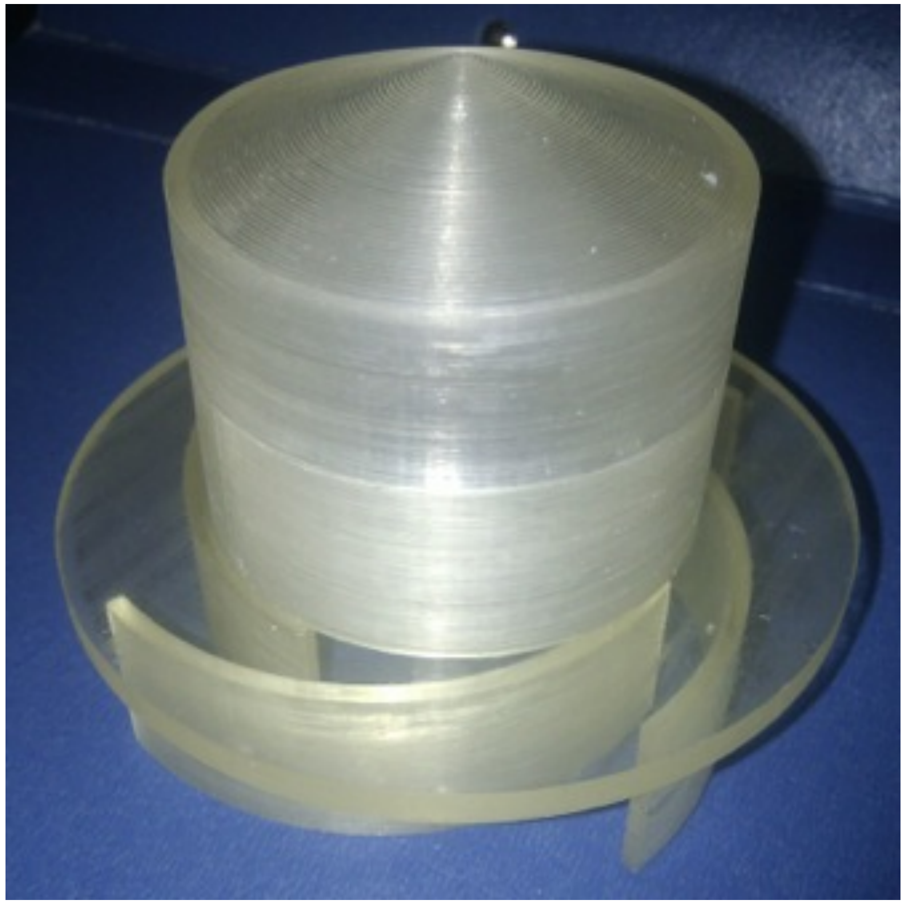
Risultati



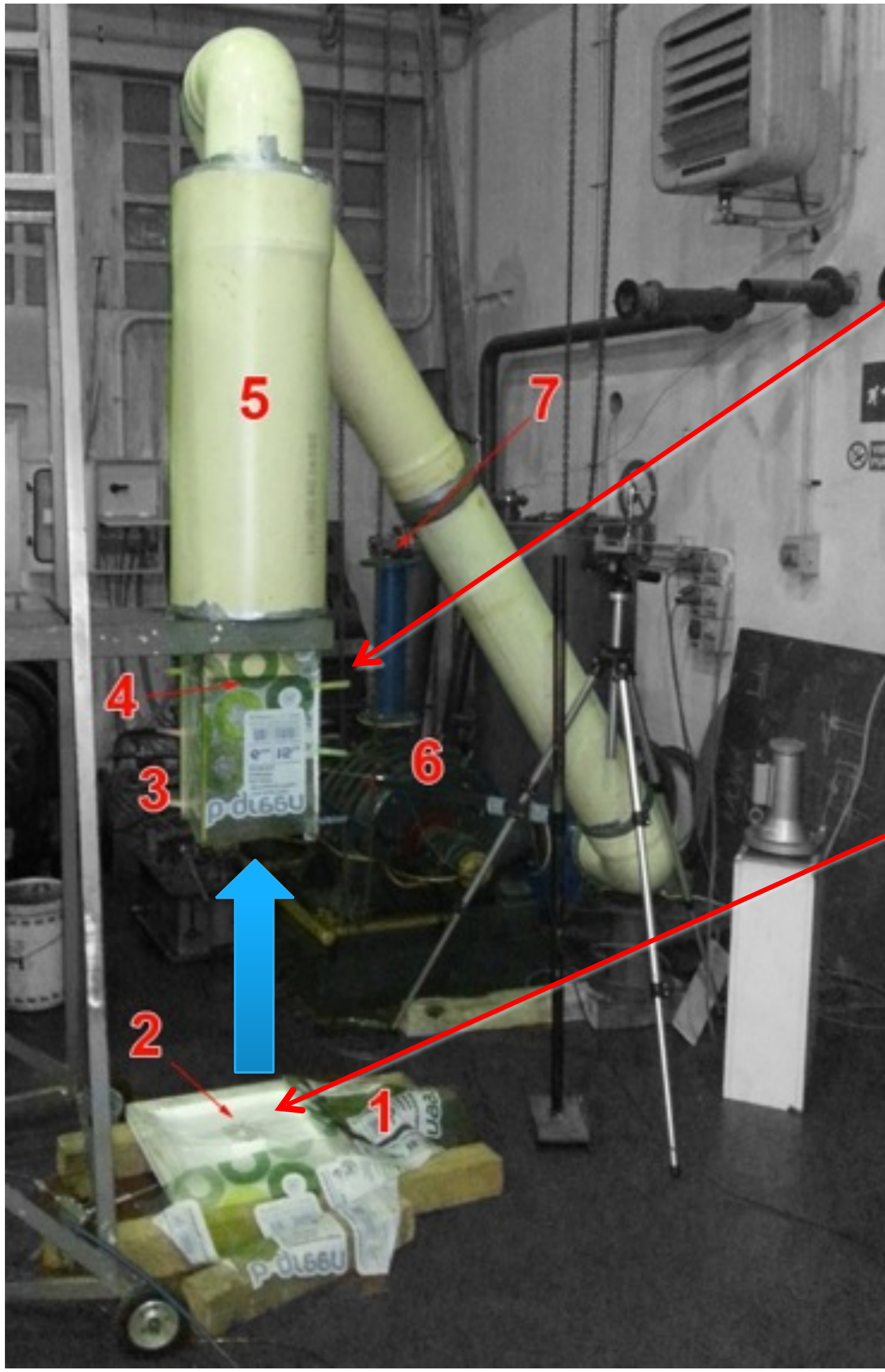
100
80
60
40
20
0
Performance [%]
0
5
10
15
20
Particle diameter [micron]
Original
Original Optimized
New device optimized

Verifiche sperimentali

Realizzazione dispositivo ottimizzato attraverso prototipazione rapida

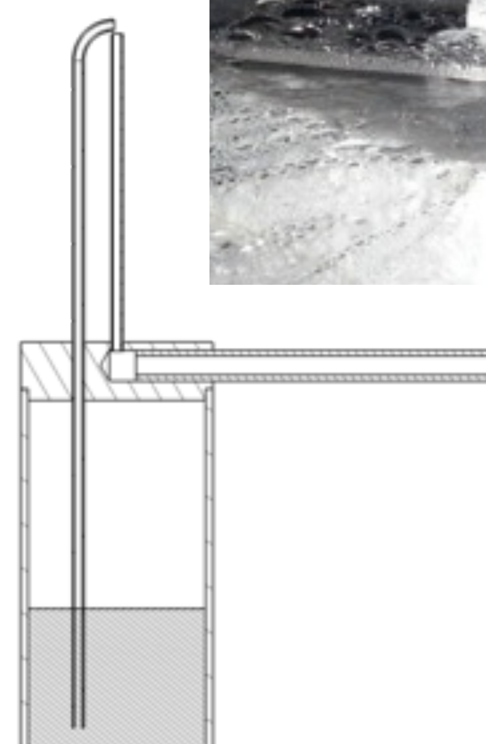


Verifiche sperimentali



Filtro

Nebulizzatore



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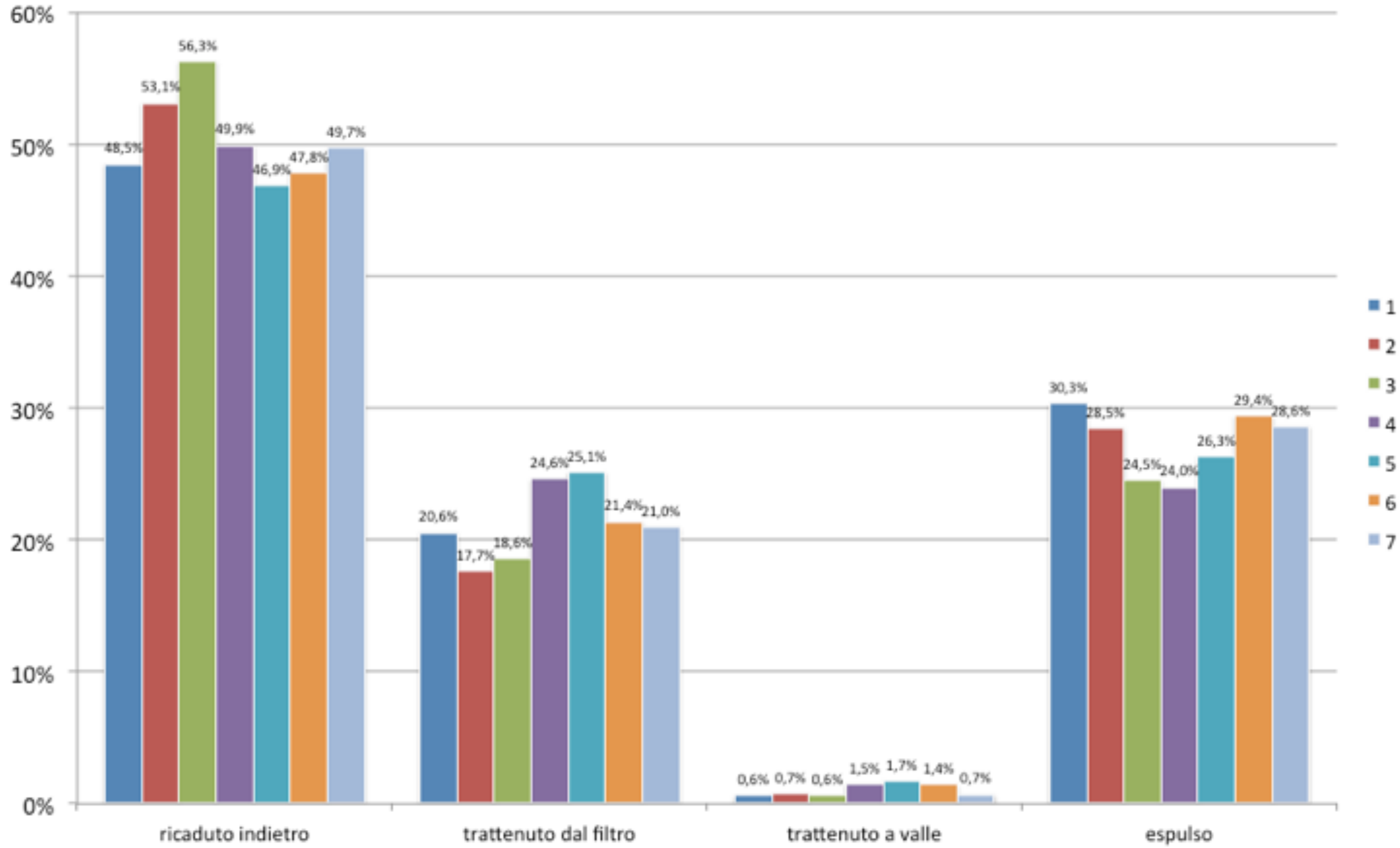
Risultati



Efficienza globale media = **72.6%**

Conclusion

George Box stated that "*all models are wrong, but some are useful*"…

Optimization can make models even more useful!

Thank you for your attention