VIRTUAL TEST RIG FOR PERFORMANCE EVALUATION OF A ROTATING HEAT EXCHANGER

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HPC enabling of OpenFOAM for CFD Applications

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Who Am I?

Team for Industrial Turbomachinery @ DIMA – Sapienza

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I probably forgot someone
^_^;

Industrial Turbomachinery Solutions
Turbulence Modelling and Simulations
Finite Element and Finite Volume CFD analysis
Energy Systems Simulations

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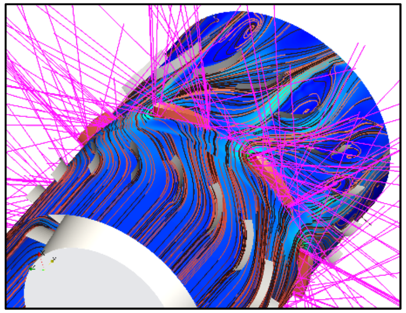
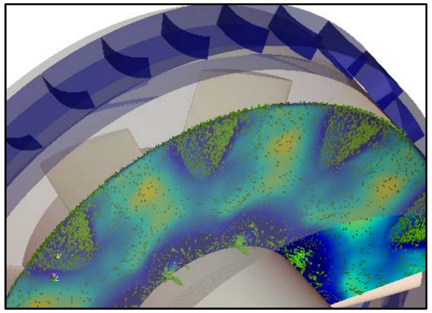
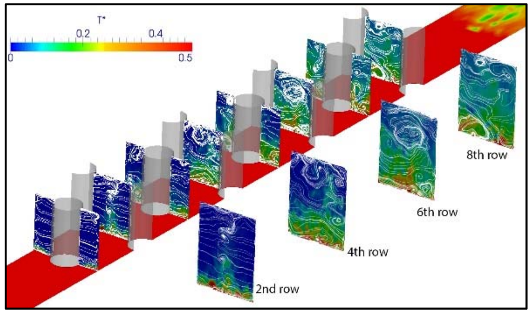
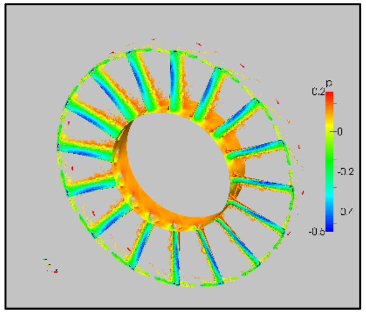
What do I do with OpenFOAM?

I use OpenFOAM as it is coming from ESI for numerical investigations of industrial turbomachinery (fans, pumps, heat exchangers, turbines…)









I develop and implement the source code with new features and models (my PhD was spent investigating URANS, hybrid LES/RANS and LES models for turbomachinery applications)

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As you probably know, turbomachinery and industrial flows are characterised by:

- High Reynolds number (rarely below 10^6)
- Complex three-dimensionality
- Impingment
- Rotation
- Complex geometries

As you know for sure all these features are a pain in the neck for CFD, mostly because of mesh requirements:

- Number of cells -> computing resources required to crunch numbers
- Mesh generation -> time and efforts needed to build a good mesh (for each single configuration)

Brute force (HPC) is not a viable solution for industry in many cases

Brute force (HPC) is not a viable solution for industry in many cases

a. because of time and financial requirements

b. because of skills required

c. because in some cases you just need to derive few integral parameters and DNS/LES/hybrid LES-RANS are too detailed for your requirements

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Industrial turbomachinery (fans, pumps, heat exchangers) more and more require CFD-based solutions that up to few years ago were developed for high-tech applications (aero-engines, power plants turbomachinery)

a. because fans, pumps and similar components are used as ancillaries within complex systems and even if they often represents as low as 1% of the overall cost of the system, if they fail the system is not able to work (think it's fun to have a ventilation fan failing in a gas turbine enclosure?)

b. … and for these reasons customers ask manifacturers for very strict performance guarantee that can easily drive one out of the market if anything goes wrong

c. because of legal requirements from EU

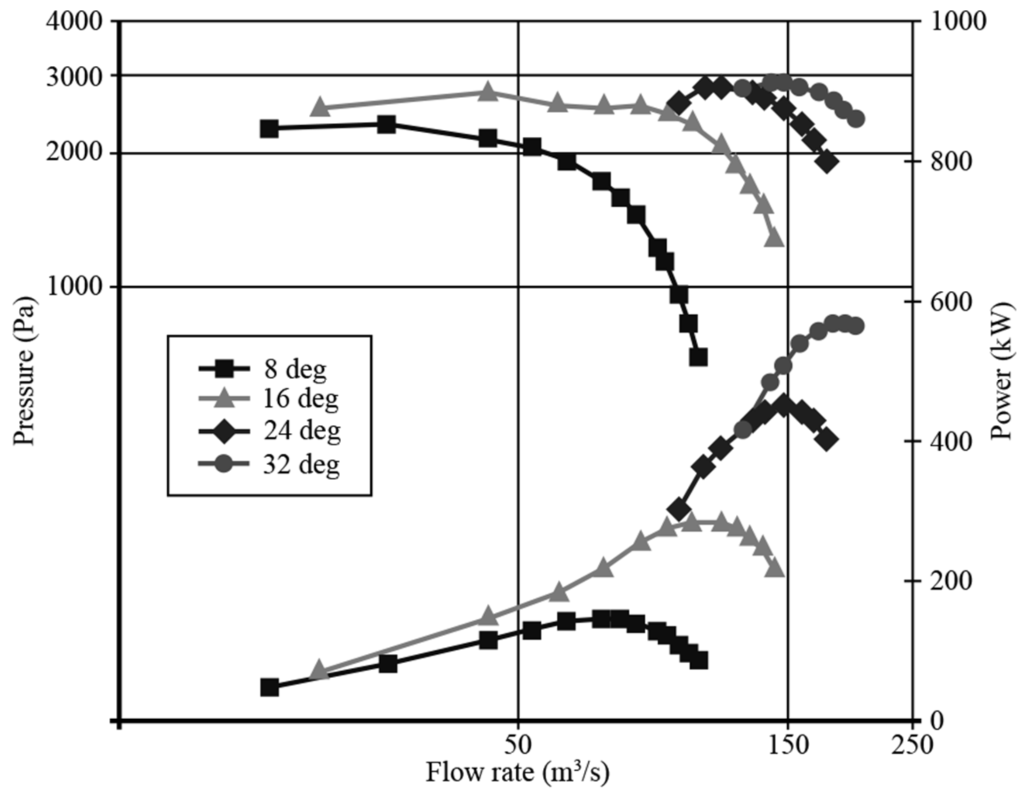
d. competition on the market

Turbomachinery performance are given as characteristic curves

For a fan, for example, you can have curves like these, that give you how the pressure rise and power changes with the flow rate in different blade arrangements (stagger angle)

Characteristics not only certify the performance of a fan, but also its operational range

Too bad these curves are measured (should be) according to ISO standards



What do fan manufacturer want: lot of money from their customers and zero problems

What do fan users want: take the cheapest fan in the market, put it in any kind of crazy arrangement and be guaranteed by the fan manufacturer that it will work and will work well

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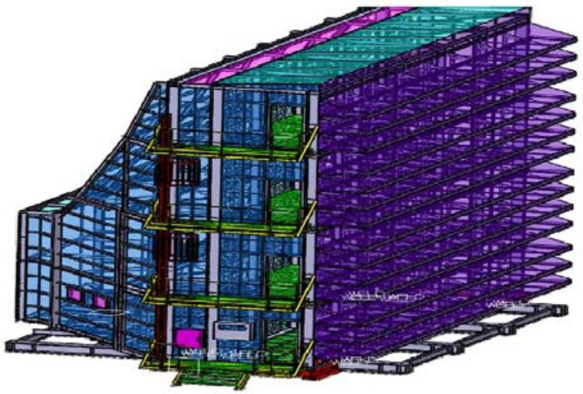
Virtual test rig

In an ongoing project we are developing CFD-based solutions to virtually assess the characteristic curves of industrial components and devices:

1. in ISO condistions
2. in real systems arrangements

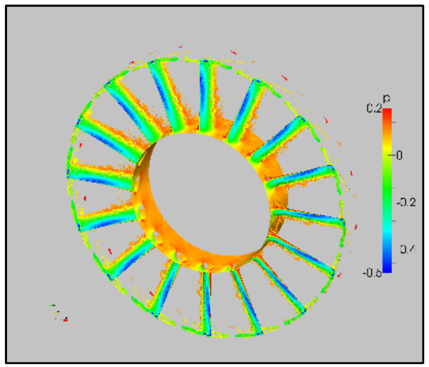
(so components are able to be fitted to a complete ventilation system, and interact with each other)

The key for this approach is not to have to mesh the single component, but to syntetize its effect on the fluid by means of source terms into PDE solved by OpenFOAM



Filter house

Gravity dampers and fire shutters



Axial & centrifugal fans

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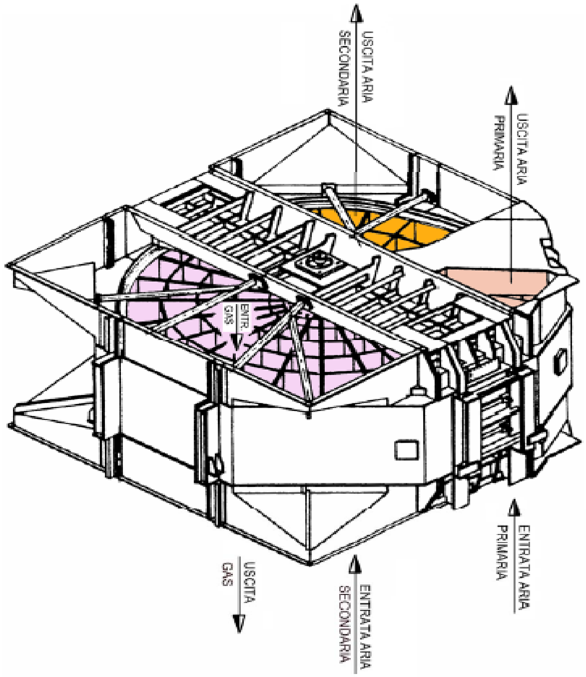
ENEL is the former state-owned electric company

Among *many* other things, they now exercise lots of thermo-electrical power plants

What we did together was to develop a module for our virtual test rig able to assess the performance of a rotating heat exchanger (Ljungstrom)

A Ljungstrom is a rotating heat exchanger used to pre-heat air in steam generators; it is used to recycle waste heat from other cycles and to increase the overall efficiency of a thermo-electric power plant

Other aims of the work were assessment of the weight and dimensions of the Ljungstrom that do not fit the scope of this workshop so I will just drop them



A rotating matrix is used as an intermediate medium between a circuit where hot gases flow and other circuits with air that needs to be heated (one or two, if you need to have primary and secondary air circuits to control the steam generation)

The matrix accomodates a series of honeywell like elements to increase the heat exchange

Meshing the internal ducts of a Ljungstrom is way out of available computational resources

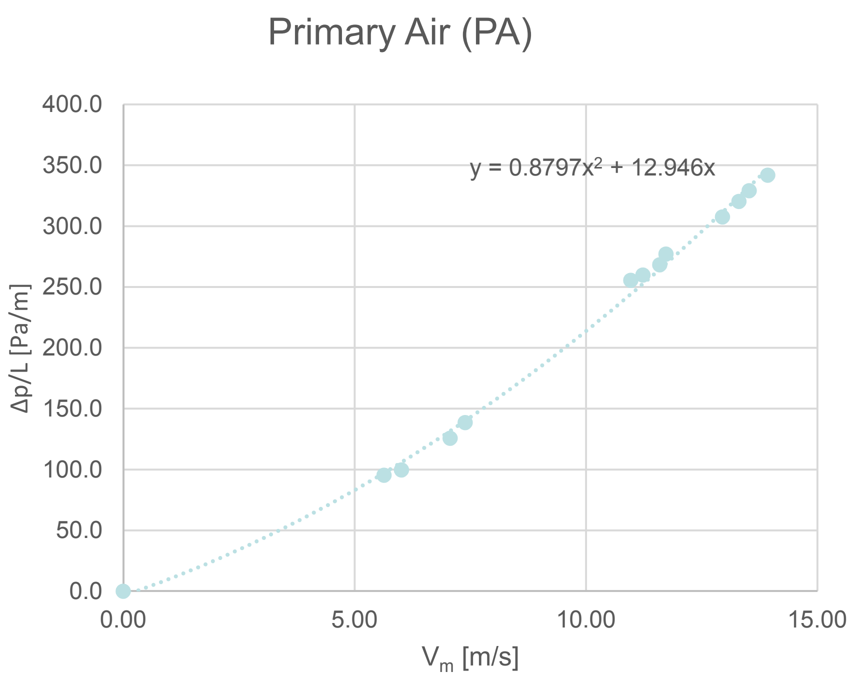
(yesterday we saw something about the resources needed to account for porosity thanks to a previous speaker)

What we need to assess the performance of the Ljungtrom is a modelled characterisation of:

- Δp: pressure drop inside the matrix
- ΔT: temperature rise/drop in air/gas flow
- Rotation

Pressure drop can be assessed using the porous characterisation of Darcy−Forchheimmer law: $\frac{\Delta p}{L} = \alpha\, v^2 + \beta\, v$

Experimental coefficients that characterise the porous medium can be derived by known duty points of the heat exchanger: $f = \frac{2\,\alpha}{\rho} \quad d = \frac{\beta}{\mu}$

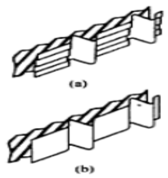


	PA	SA
f	2.7	6.2
d	6.95 e5	1.17 e6

- Heat exchange can be characterised with a source term: q = h ΔT.

- Sheer (2006) measured h for two configurations of the porous medium in Ljungstrom heat exchangers
- He also derived an experimental correlation between the Coulbourn factor j and Re:

a) $j = 0.1059\, Re^{-0.3218}$ b) $j = 0.0382\, Re^{-0.2272}$

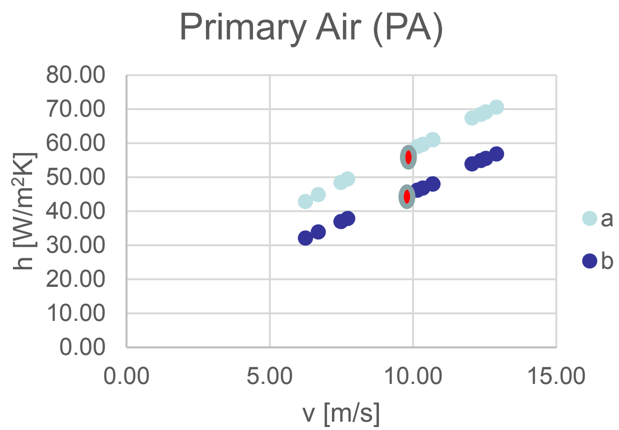


- j can be linked to h as a function of Pr and St:

$$j = \frac{St}{Pr^{2/3}} \qquad St = \frac{\boldsymbol{h}}{\rho\, v\, c_p} \qquad Pr = \frac{\mu}{c_p k}$$

We derived the trend of h as a function of the velocity inside the Ljungstrom and compared it with the data from Sheer

	PA	SA
h [W/m²K]	65	75



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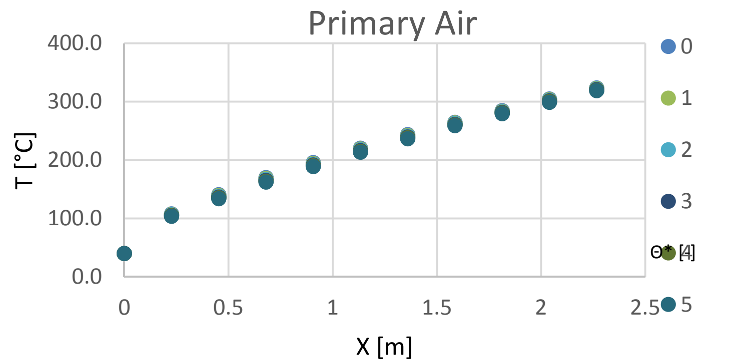
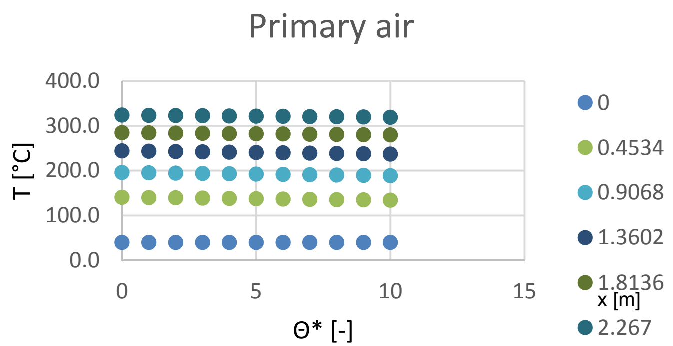
The temperature distribution inside the matrix was derived starting from an adimensional model of *Molinari, 1985*



- Temperature in axial direction for 5 azimuthal sectors

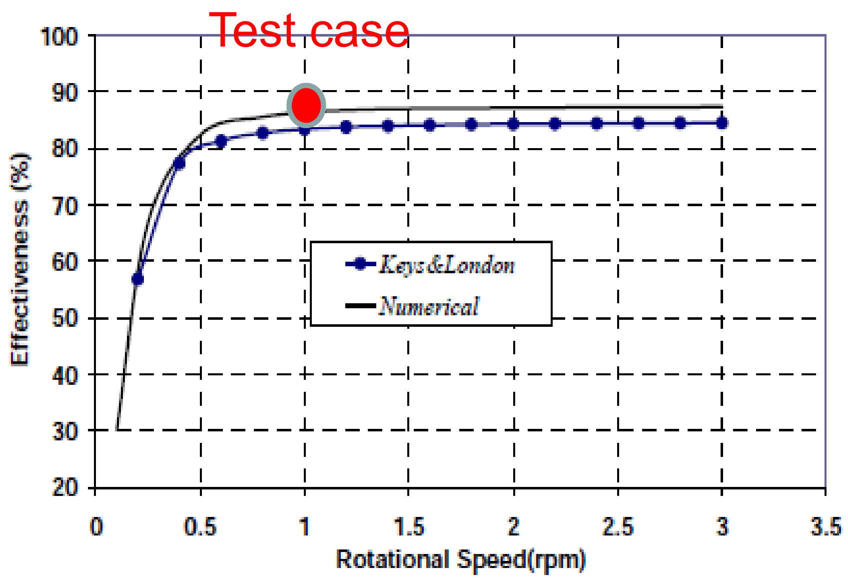
- Temperature in azimuthal direction at 5 different axial immersions

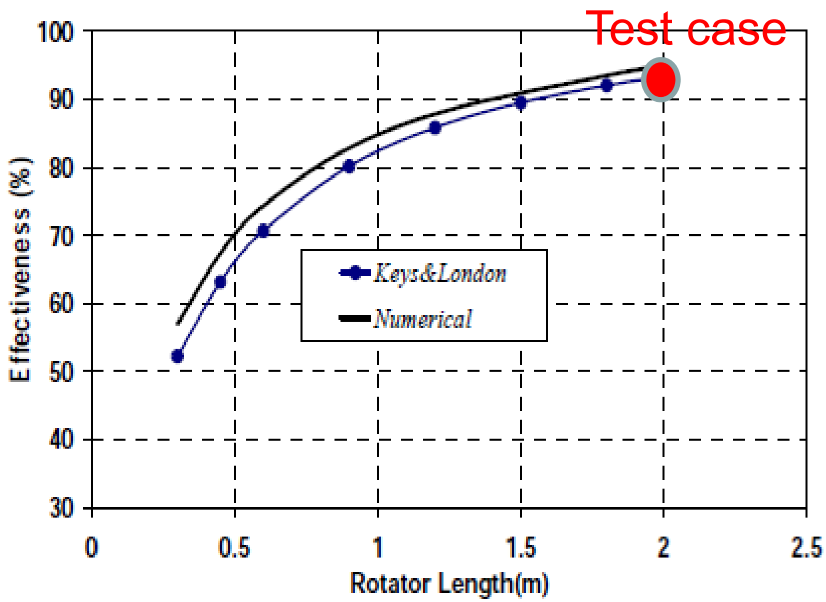
- Each for Primary air, secondary air and the matrix



	Average ΔT
PA/matrix	105 °C
SA/matrix	100 °C

The rotational velocity of the matrix and its axial lenght directly affect the efficiency of heat exchange (Keys & London, 1984)





OpenFOAM 2.3.x

RANS closure: k-ε (high-Re)

Incompressible flow Ma<0.2

The matrix is treated as a porous medium with coefficients derived as explained before

Temperature equation accounts for the heat exchange:

$$\frac{dT}{dt} = \frac{k}{\rho\, c_p}\nabla^2 T \pm \frac{\eta}{\rho\, c_p}\, h\, \frac{1}{d_h}\left(T_f - T_w\right)$$

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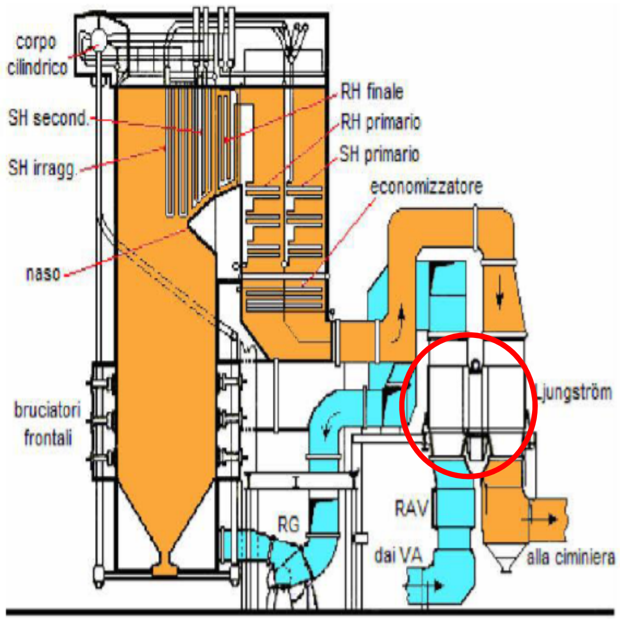
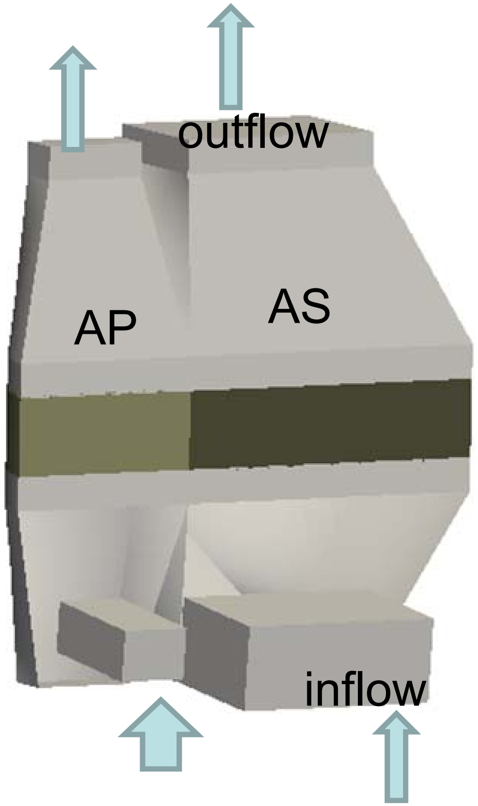
Geometry of the computational domain





Diameter	14.5 m
Axial lenght	2.267 m
PA	35°
SA	145°

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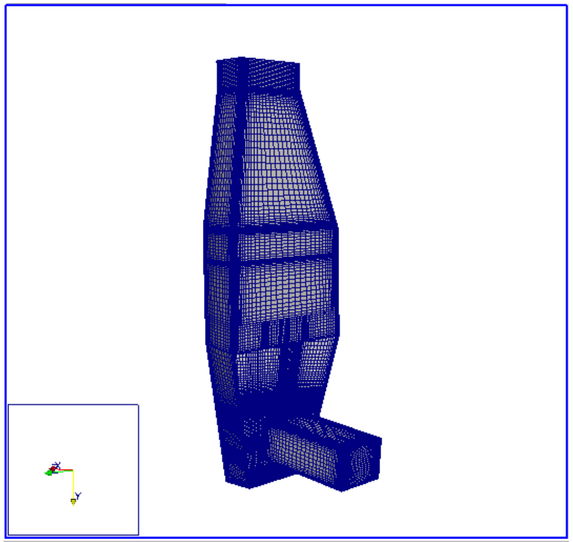
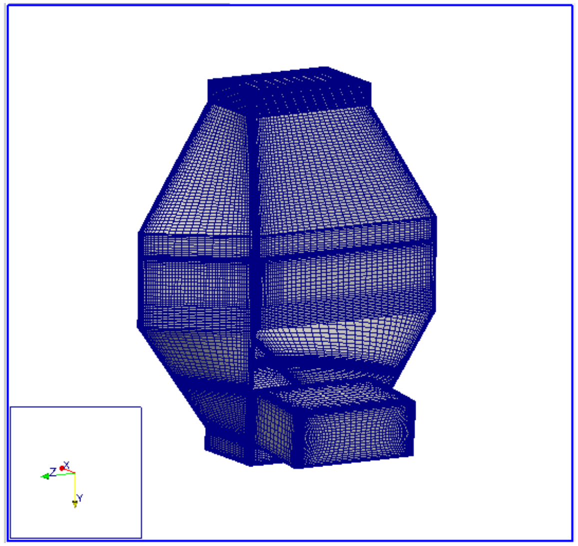
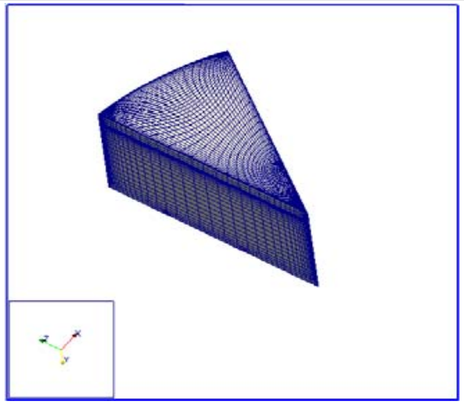
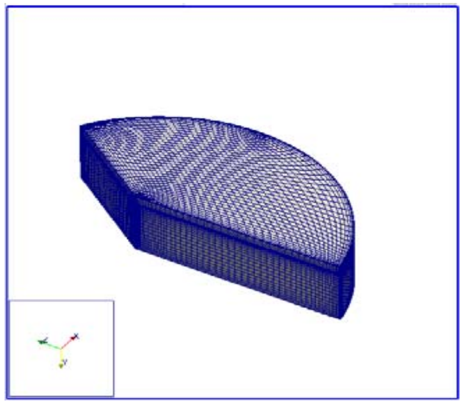
	AP	AS
Celle	890976	659669
Skewness	0.26	0.21
AR	21	22









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Boundary	**U**	**p**	**T**	**k**	**ε**
Inflow	Q_{in}	zeroGradient	T_{in}	TI = 5%	L_{ε} = 7% d_h
Outflow	zeroGradient				
Walls	No slip	zeroGradient	zeroGradient	Wall function	

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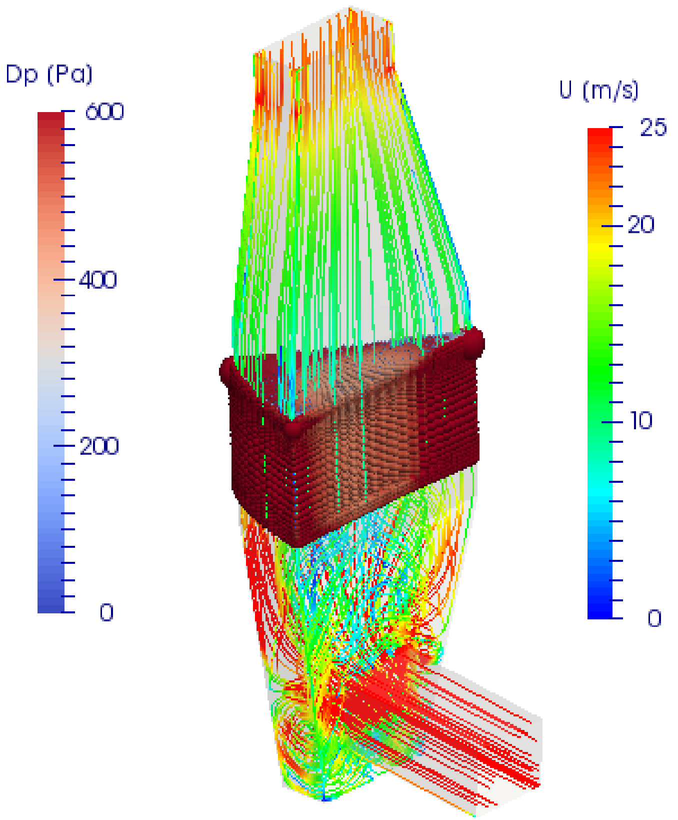
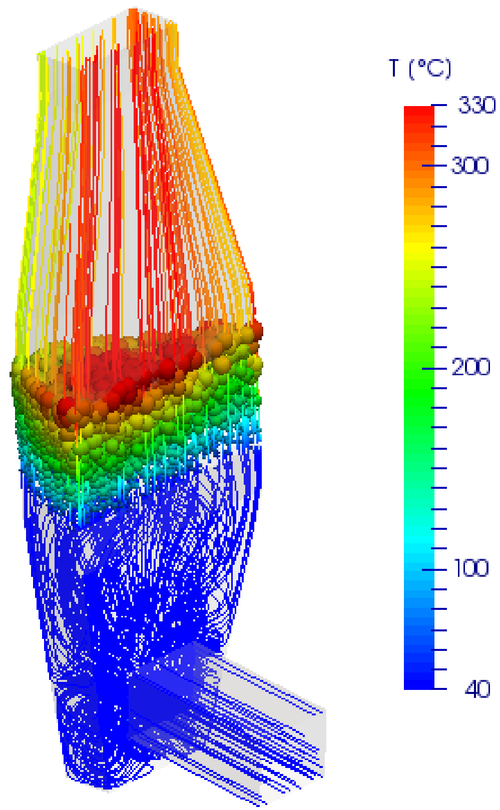


Streamlines colored with U
Glyps: Δp

Δp is a function of velocity and it's not uniform due to the secondary motions at the inlet of the Ljungstrom

For the same reasons T increase is not uniform



Streamlines colored with T
Glyps: T

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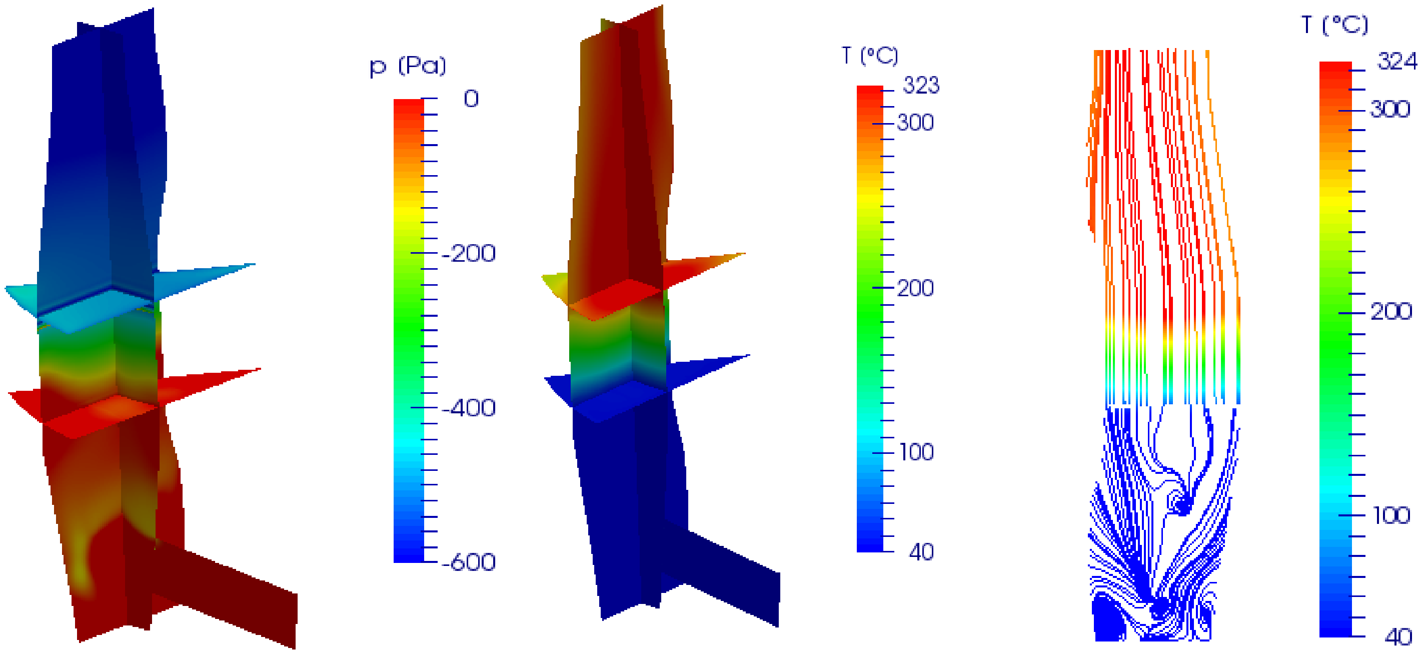
Primary air



The secondary motions at the inlet of the ljungstrom are responsible for a non-uniform distribution of pressure drop and temperature rise

The effect of the porous medium is to suppress secondary motions inside the duct

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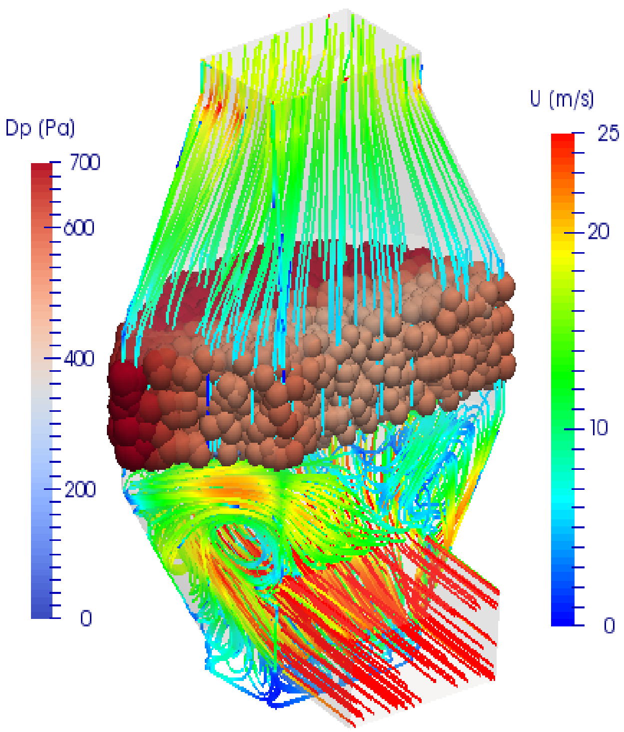
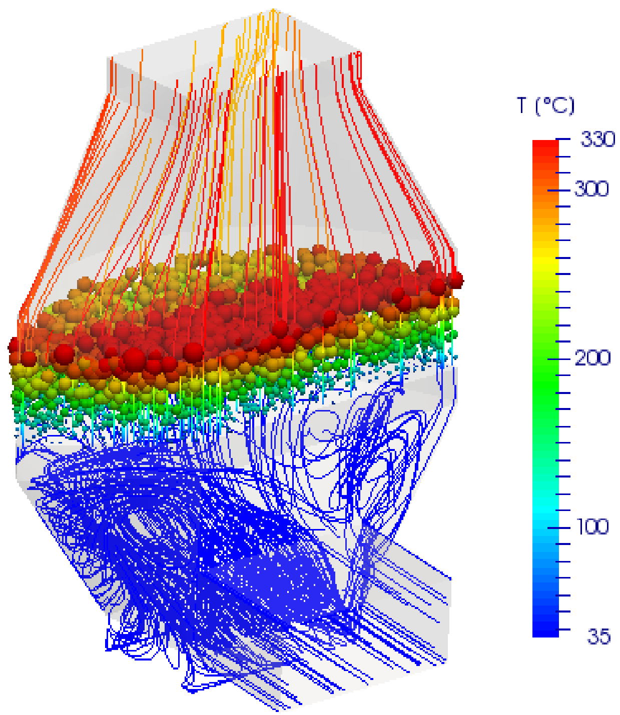


Streamlines colored with U
Glyps: Δp



Streamlines colored with T
Glyps: T

Similar figures apply to secondary air, even if in this case the secondary motions are more evident due to the larger section and flow rate

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PA	**T_{out} [°C]**	**Δp [Pa]**
Enel	324	598
OpenFoam	313	577
Δ	11	21

SA	**T_{out} [°C]**	**Δp [Pa]**
Enel	338	638
OpenFoam	331	686
Δ	7	48

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A synthetic model for the characterisation of a rotating heat exchanger was derived from available literature and implemented in OpenFOAM

This model, previously validaded inside a 1D design tool was numerically tested against a real-geometry Ljungstrom heat exchanger working on an ENEL plant

Integral parameters from CFD further validate the model and allow to assess the geometry of the inlet duct

CFD can be used (will be used) to derive other duty points of the characteristic curve of the heat exchanger

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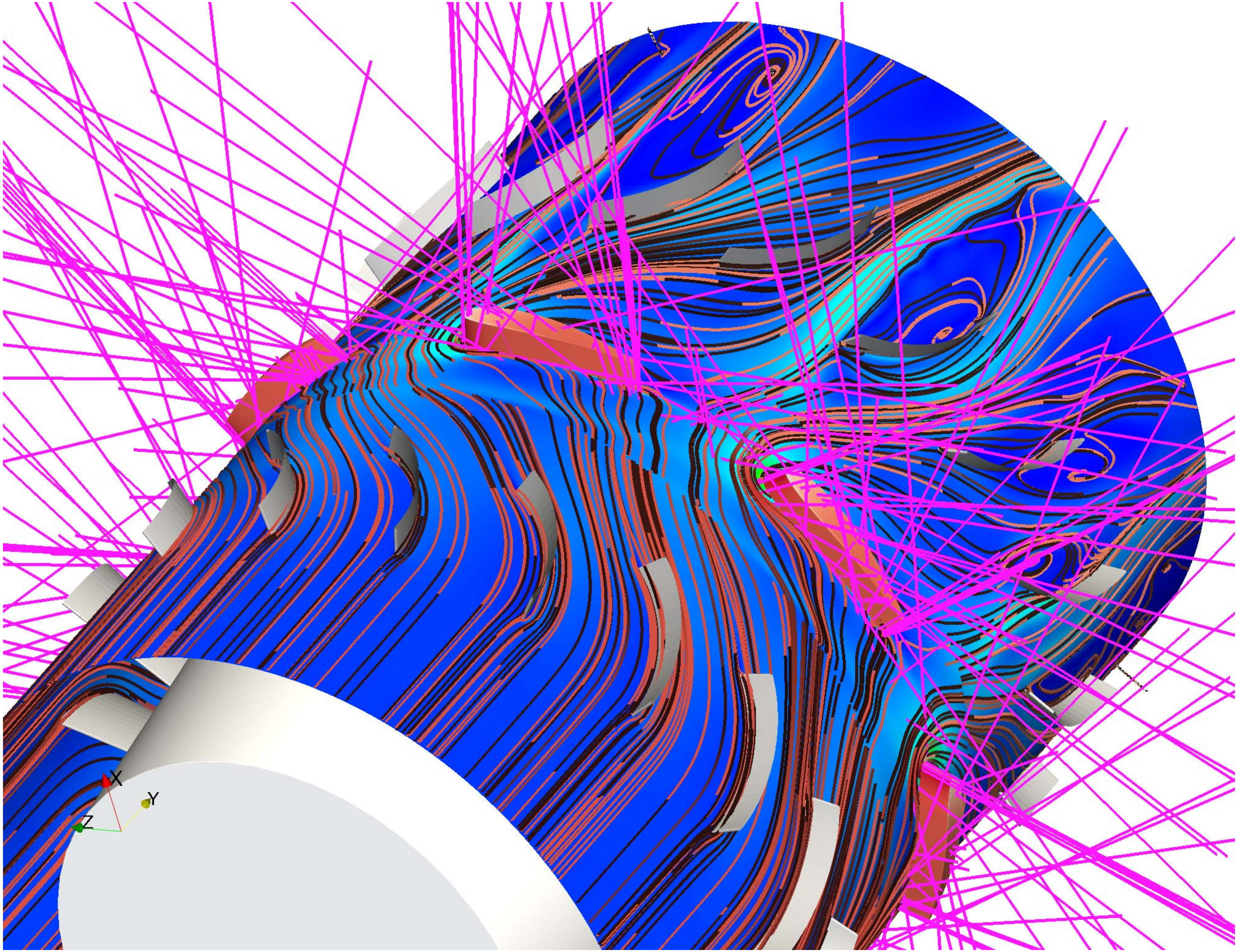
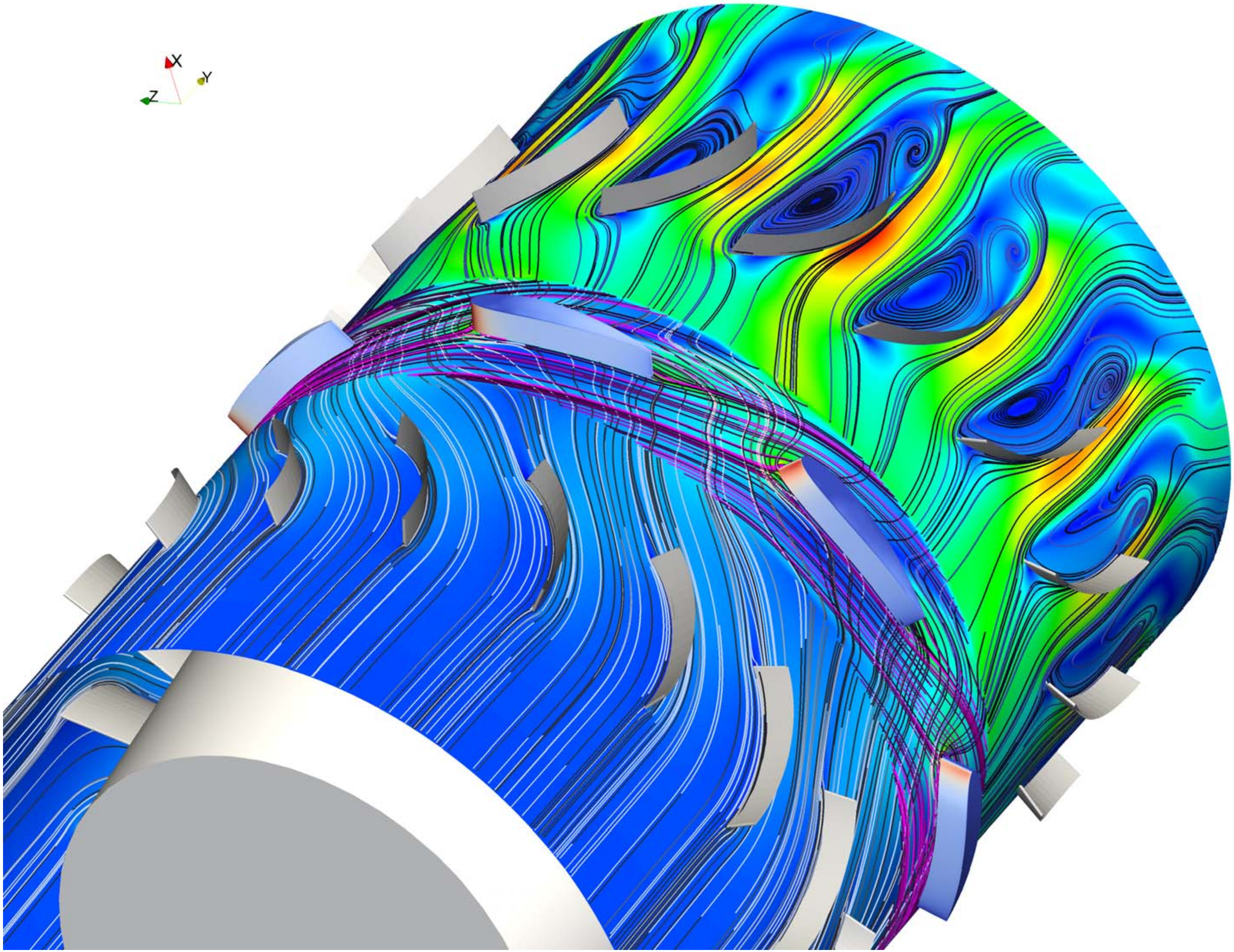


X
Y
Z


X
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