Development and Application of a CFD Framework for the Simulation of Fully Coupled Electromagnetic and Heat Transfer Process Inside Electric Motors

6th Two-Day Meeting on Propulsion Simulations Using OpenFOAM Technology

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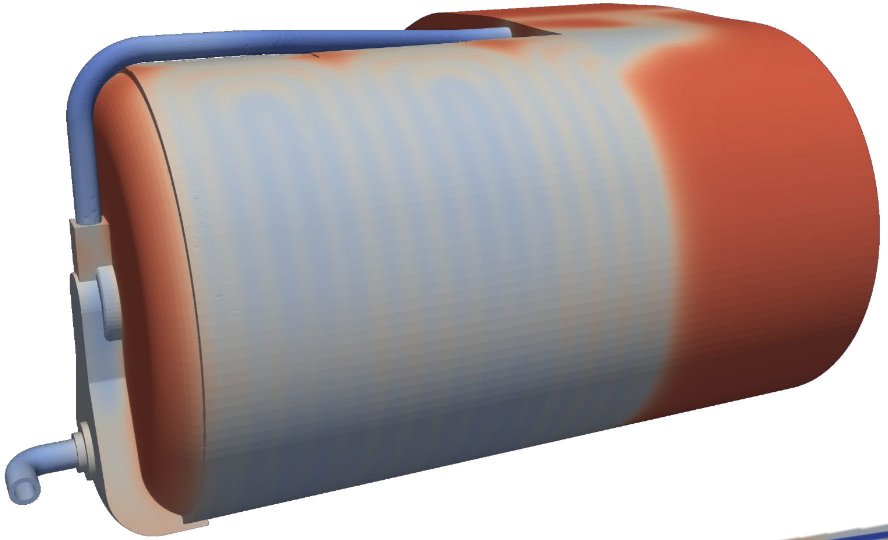
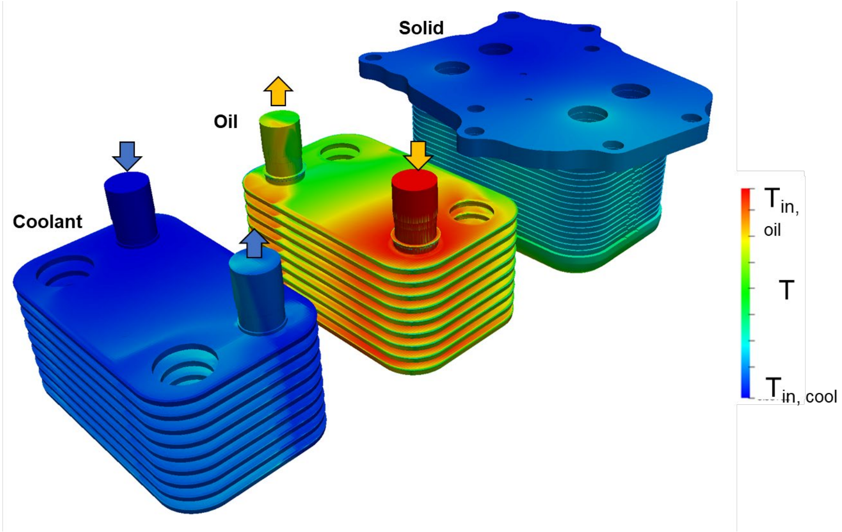
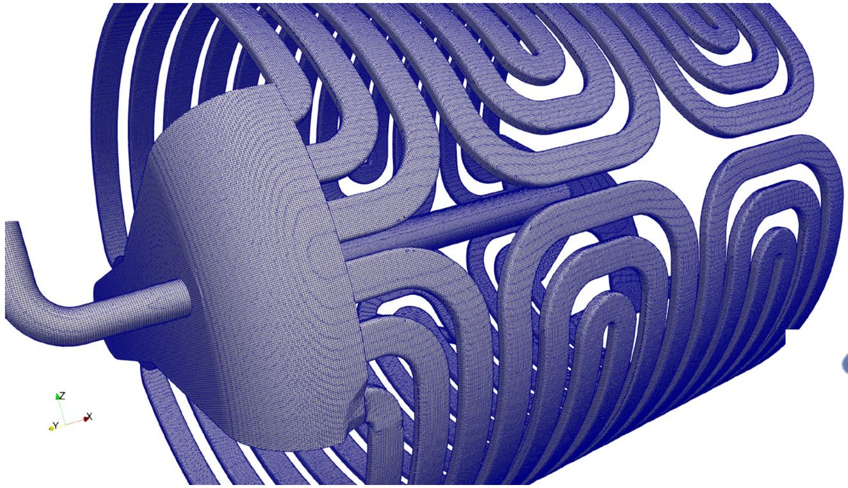
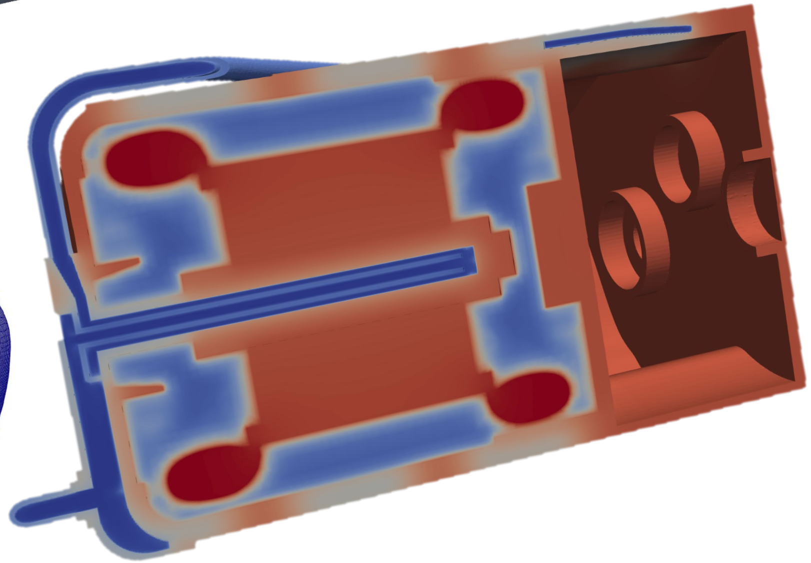
Outline

- Introduction
- Multi-region electromagnetic solver with mesh motion
- Mesh generation and simulation example
- Cooler modeling: micro and macro scale simulation





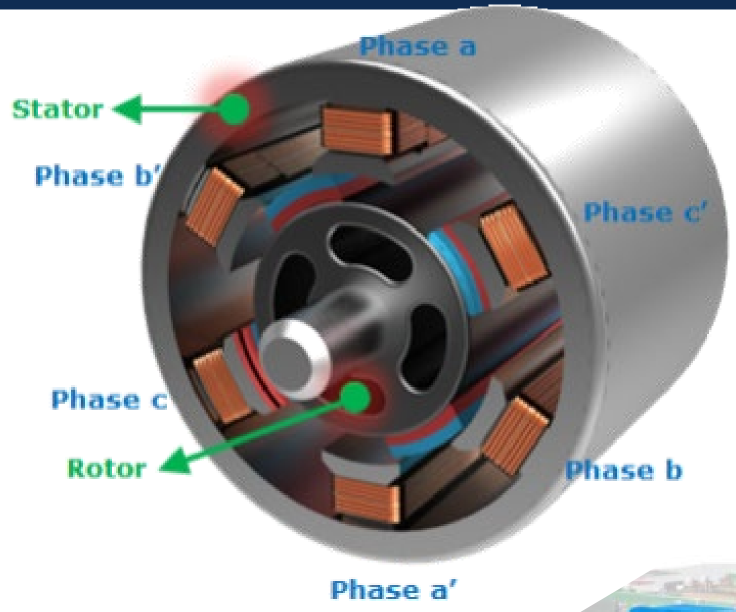


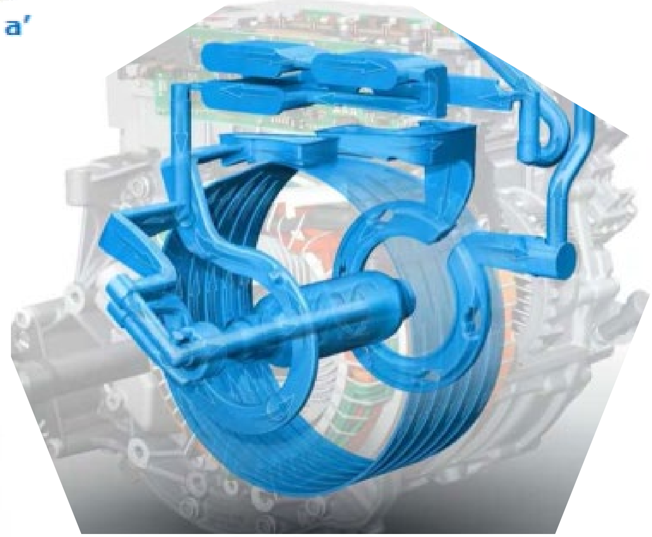


Introduction and background

Increasing electrification introduces new opportunities of the application of CFD:

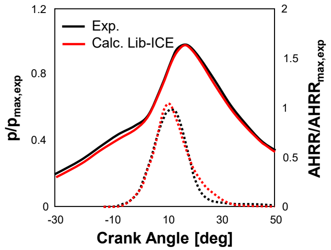
- **Complex thermal systems**: materials with different optimum operating temperature ranges and thermal limits combined. Various heat source and heat exchange mechanism.
- Liquid thermal management system: **cooling jackets** and **shaft cooling**
- **Heat losses**: Iron losses, magnet losses, Joule losses, mechanical losses
- **Cooling unit** must comply with compactness and lightweight requirements

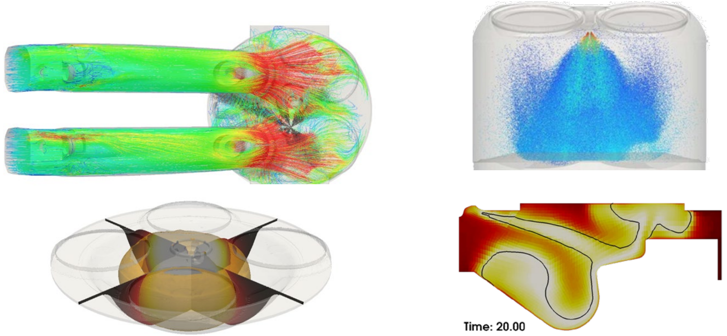




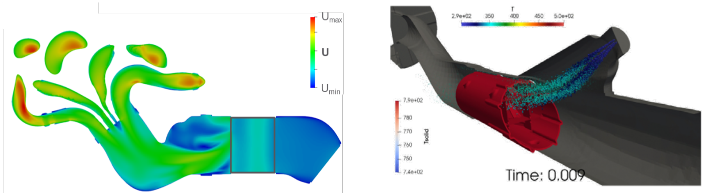
Lib-ICE : engines (and more...) in OpenFOAM

Internal combustion engines

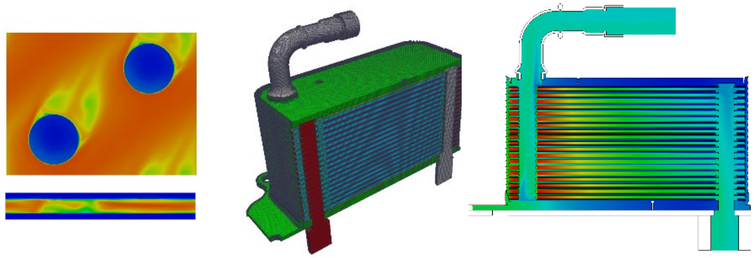




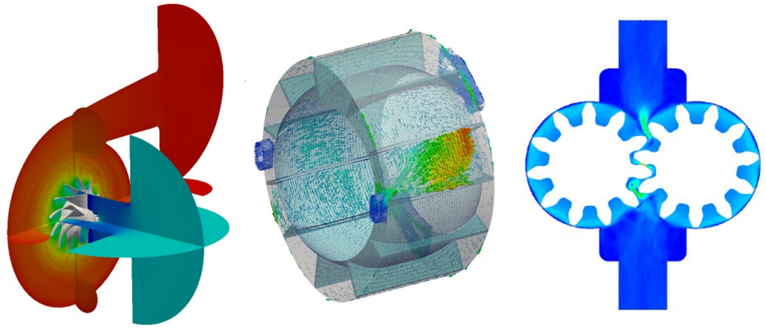
After treatment systems



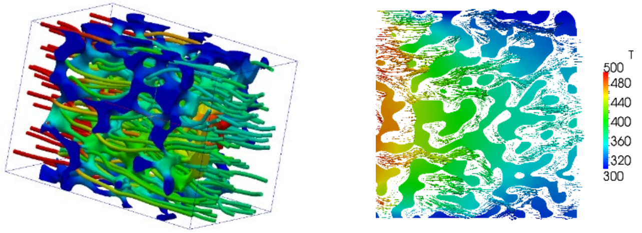
Thermal management



Fluid machines



Porous media



Electromagnetic analysis

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}$$

Ampere Maxwell law: magnetic fields can be generated by electric currents in a closed circuit, it is proportional to the current flowing in it.

$$\nabla \cdot \boldsymbol{B} = 0$$

Gauss law for magnetic field: the magnetic field is always generated by a magnetic dipole. The flux of magnetic field B around a closed surface is always null, B is a solenoidal vector field

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

Faraday-Maxwell law: describes the electromagnetic induction. It shows how the variations of magnetic field in time induce an electric field.

$$\nabla \cdot \boldsymbol{D} = \boldsymbol{\rho}$$

Gauss law: The electromagnetic flux around a closed surface is proportional to the value of the charge density

Constitutive relations

$$\boldsymbol{D} = \sigma \boldsymbol{E}$$

$$\boldsymbol{B} = \mu \boldsymbol{H}$$

$$\boldsymbol{J} = \sigma \boldsymbol{E}$$

Steady state assumption

$$\nabla \times \boldsymbol{H} = \frac{1}{\mu} \nabla \times (\nabla \times \boldsymbol{A}) = \boldsymbol{J}$$

$$\begin{cases} \nabla \times (\nabla \times \boldsymbol{A}) = \nabla(\nabla \cdot \boldsymbol{A}) - \Delta \boldsymbol{A} \\ \nabla \cdot \boldsymbol{A} = 0 \end{cases}$$

- H = magnetic field intensity
- B = magnetic flux density
- E = electric field intensity
- D = electric flux density
- J = current density
- A = magnetic vector potential
- V = electric scalar potential

Electromagnetic analysis

Electromagnetic quantities computed from **magnetic vector potential**: $\boldsymbol{B} = \boldsymbol{\nabla} \times \boldsymbol{A}$

$$-\frac{1}{\mu_0\,\mu_r}\nabla^2 \boldsymbol{A} = 0 \qquad \boldsymbol{H} = \frac{\boldsymbol{B}}{\mu_0\,\mu_r}$$

Solid regions
ferromagnetic or diamagnetic materials

$$\frac{1}{\mu_0\,\mu_r}\nabla^2 \boldsymbol{A} = -\frac{\boldsymbol{Br}}{\mu_0\,\mu_r} \qquad \boldsymbol{H} = \frac{\boldsymbol{B}-\boldsymbol{Br}}{\mu_0\,\mu_r}$$

Magnet regions
permanent magnets

Iron losses:

$$P_{fe} = \alpha B^2$$

$$-\frac{1}{\mu_0\,\mu_r}\nabla^2 \boldsymbol{A} = 0$$

Fluid regions
fluids in the motor

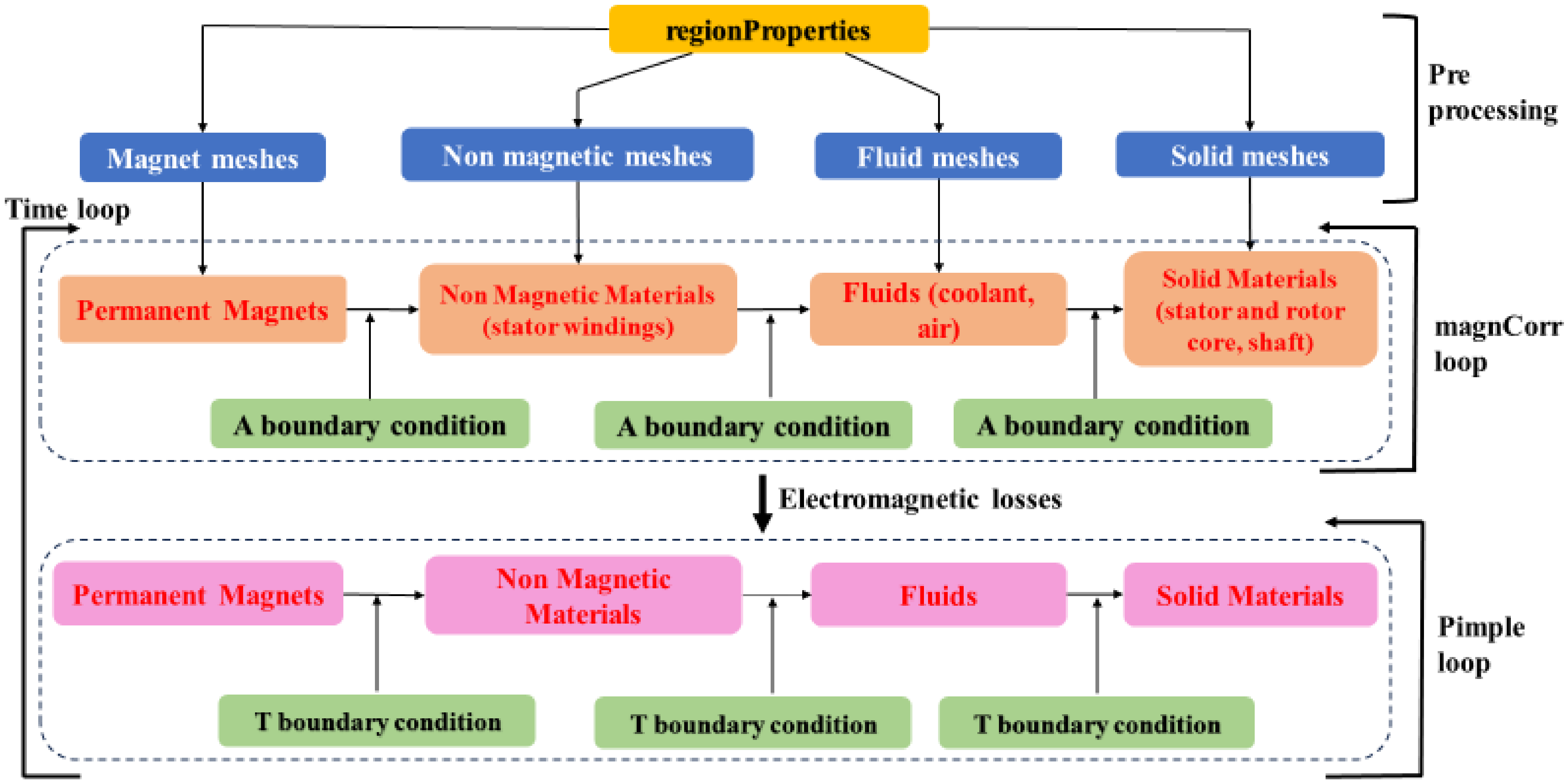
$$-\sigma\nabla^2 V = 0 \quad \boldsymbol{J} = -\sigma\boldsymbol{\nabla} V \quad \frac{1}{\mu_0\,\mu_r}\nabla^2 \boldsymbol{A} = -\boldsymbol{J}$$

Non Magnetic regions
stator winding

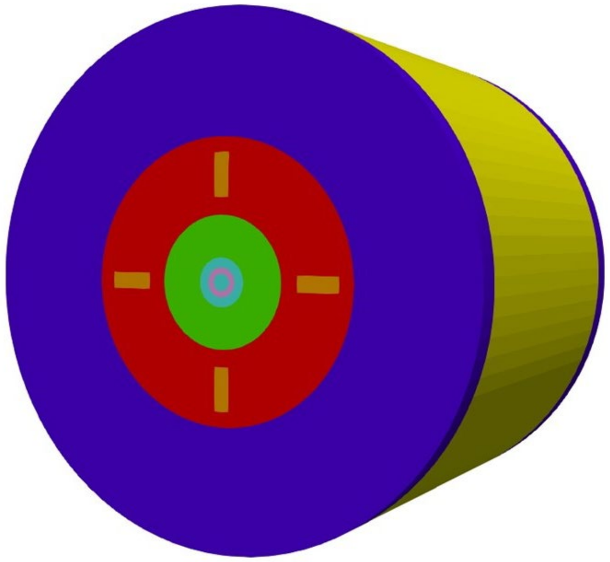
Jule losses:

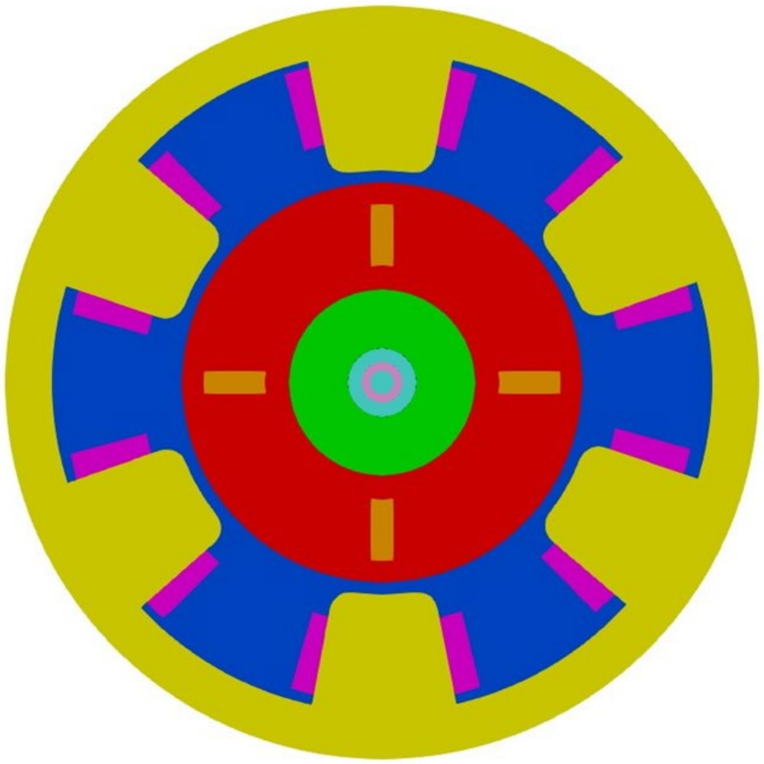
$$P_j = \frac{\rho}{\gamma} J^2$$

Solver structure



Test case: Permanent Magnet Sincronous Motor



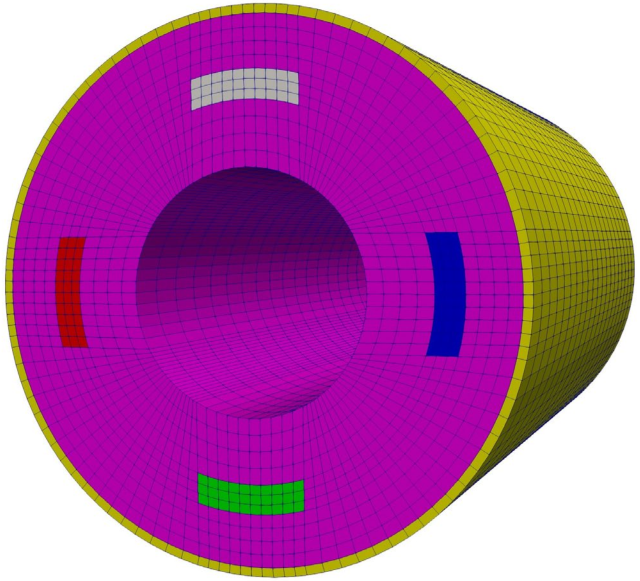


Rotor
Stator
Air
Shaft
Permanent magnets
Shaft internal duct
Cooling channel
Stator windings

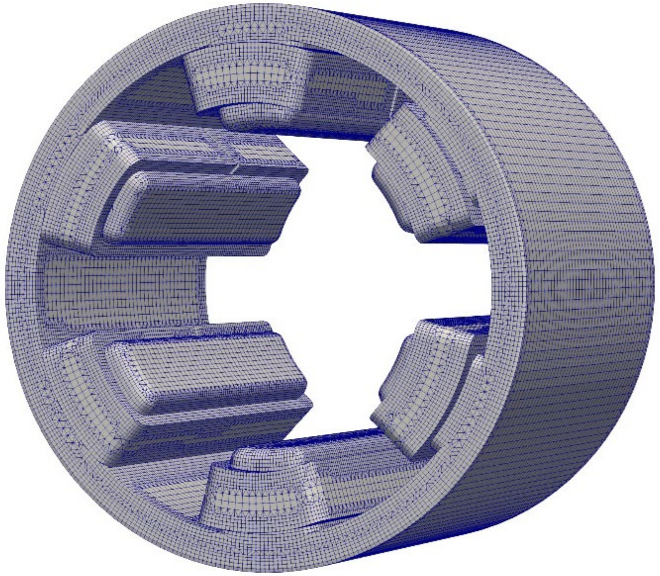
PMSM parameters:

- **Four poles**
- **Six concentrated windings**
- **Four interior permanent magnets**
- **Rotational speed 1500 rpm**
- **Shaft liquid cooling system 3.6 Kg/h**

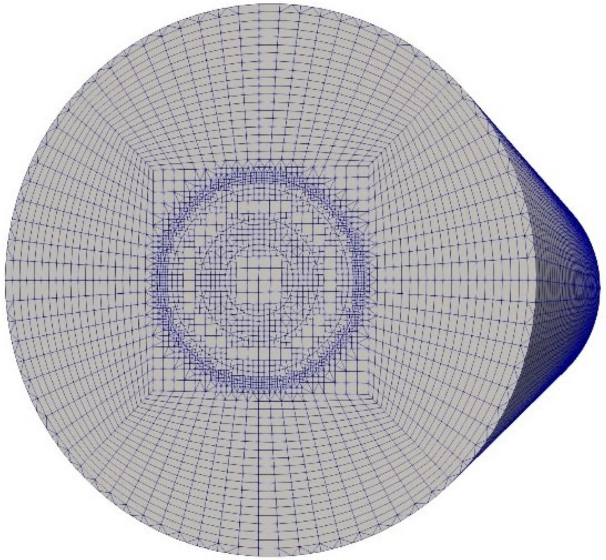
Mesh generation procedure



Rotor *blockMesh*



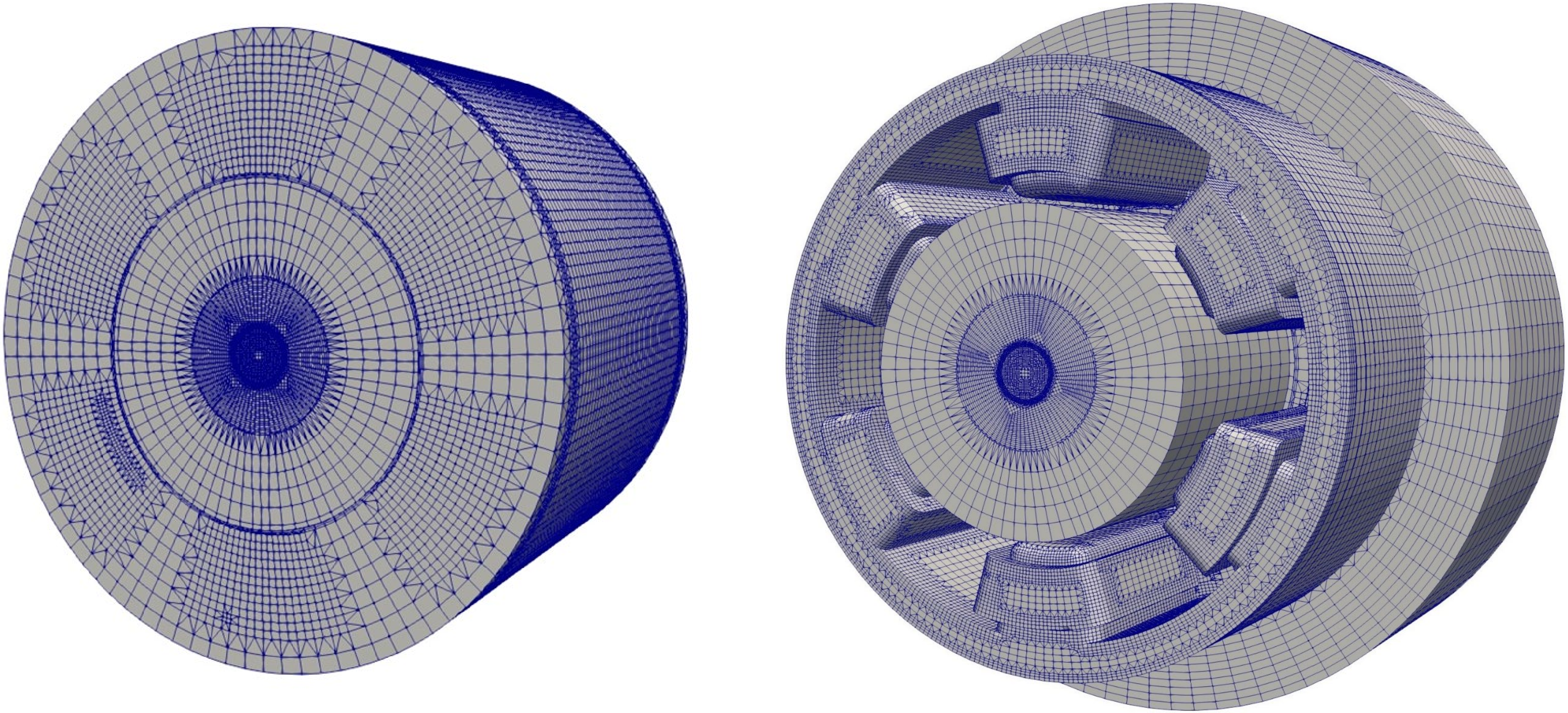
Stator mesh after
snappyHexMesh process



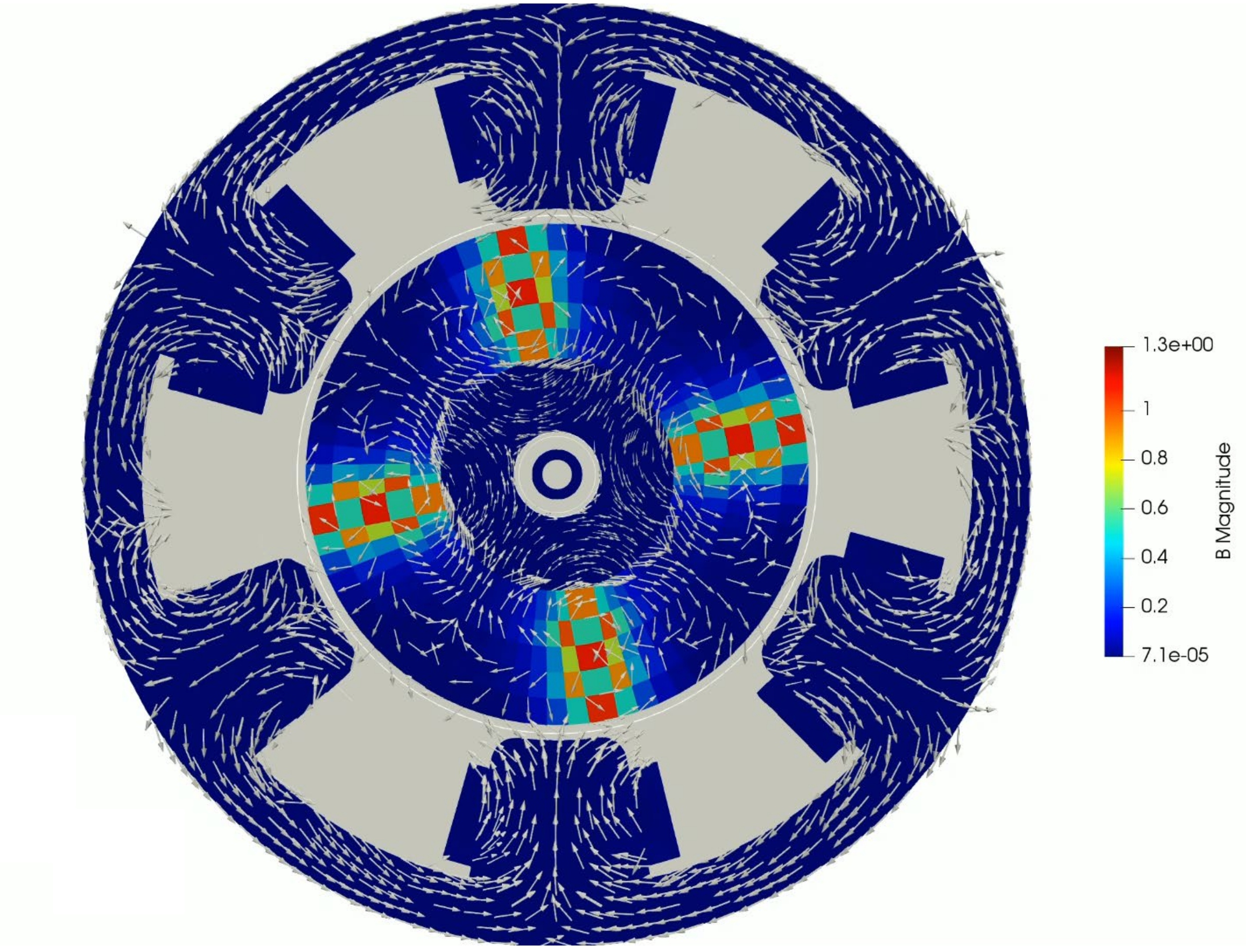
Shaft mesh after
snappyHexMesh process

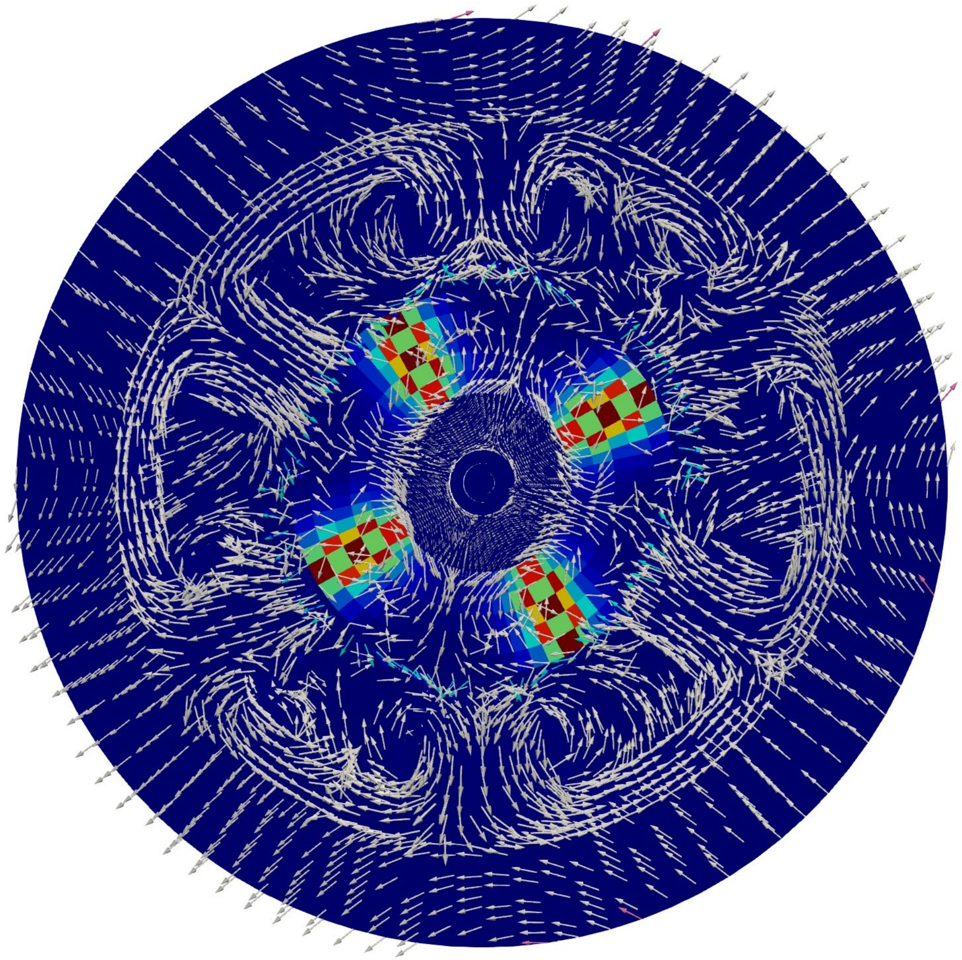
- Mesh based on *blockMesh utility*
- **Parametric meshes** according to number of magnets and windings
- **Flexible mesh procedure** for machines with different number of poles and sizes

Complete mesh

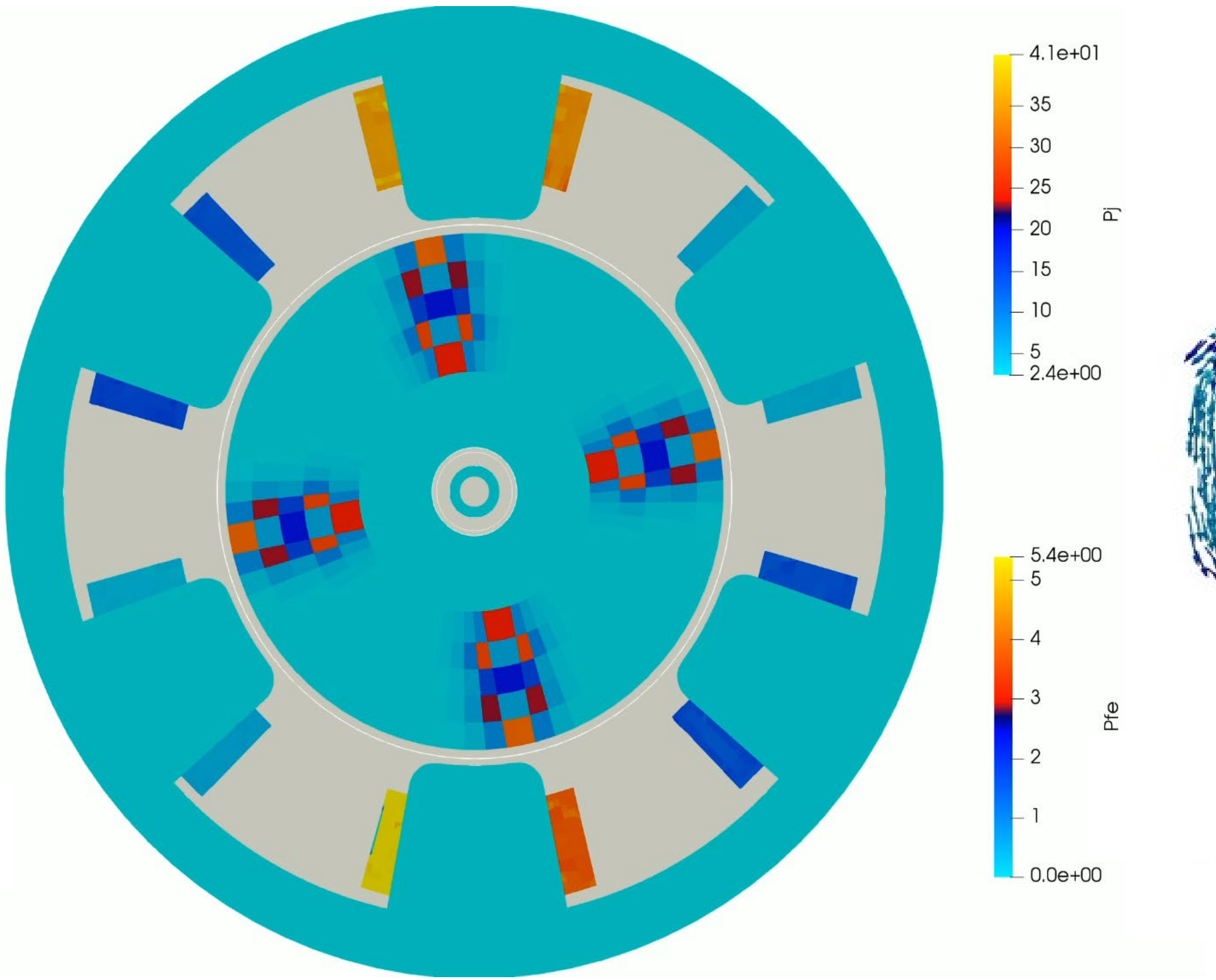


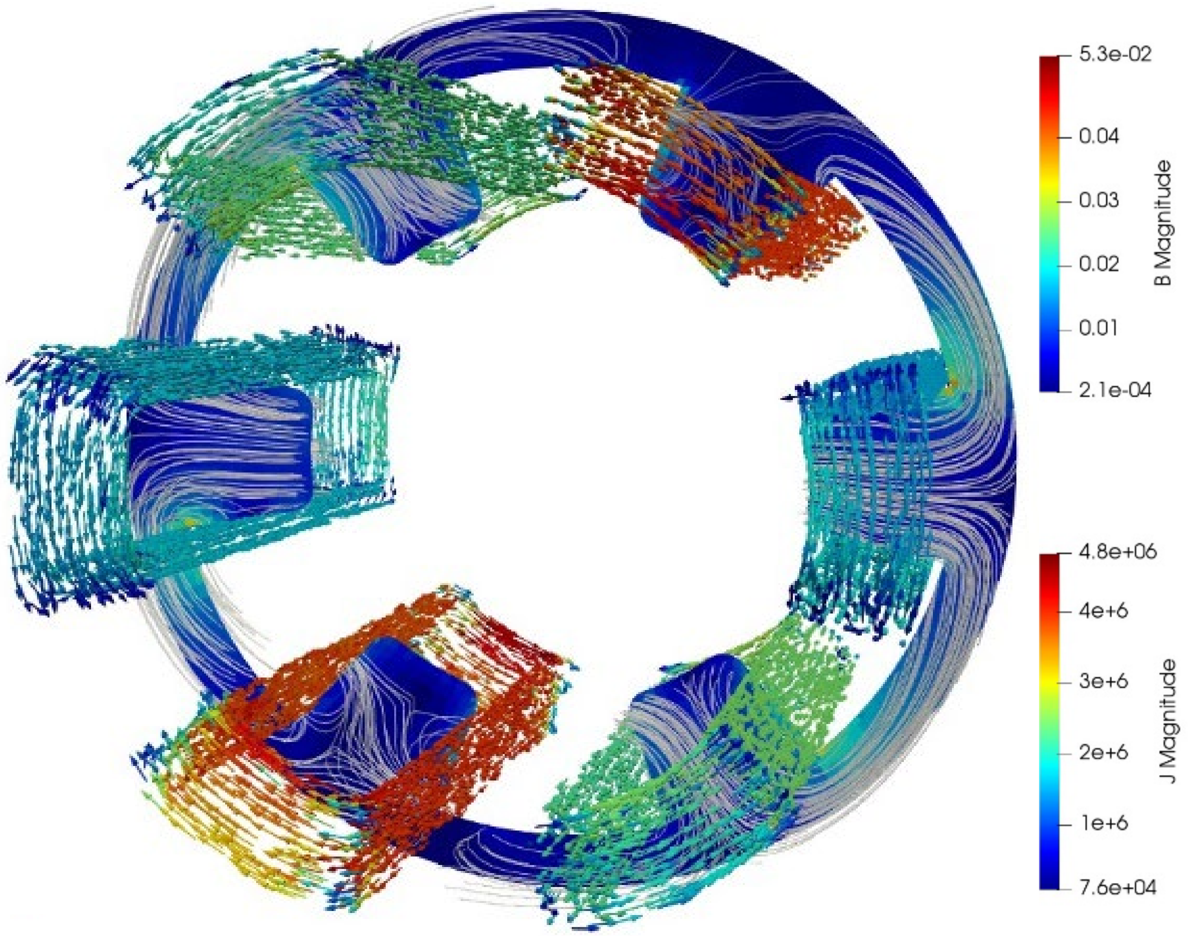
Magnetic flux density



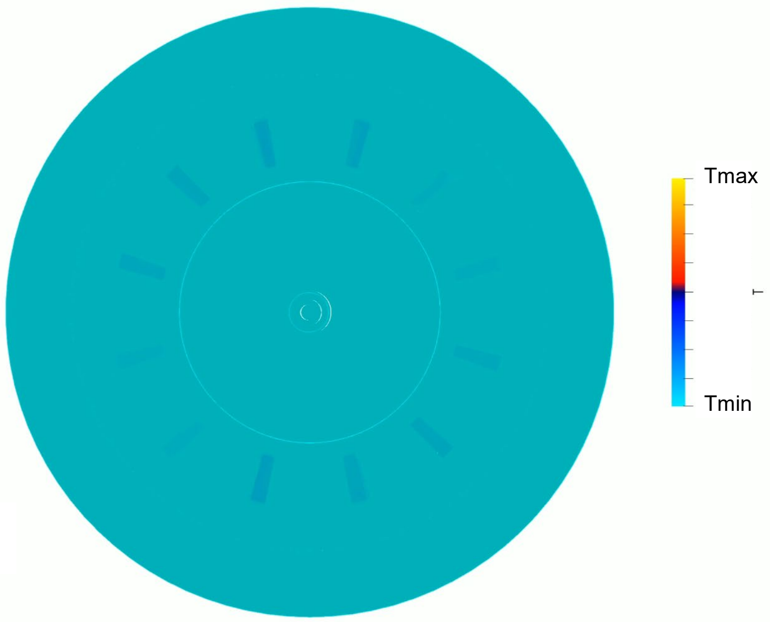


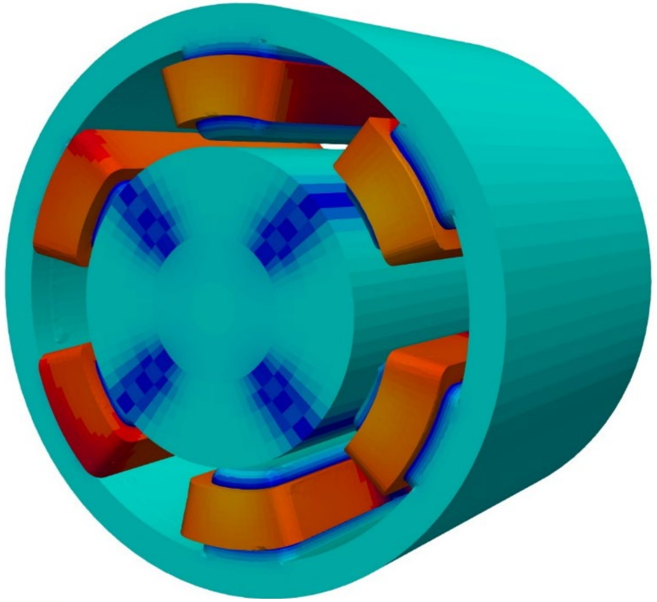
Electromagnetic losses

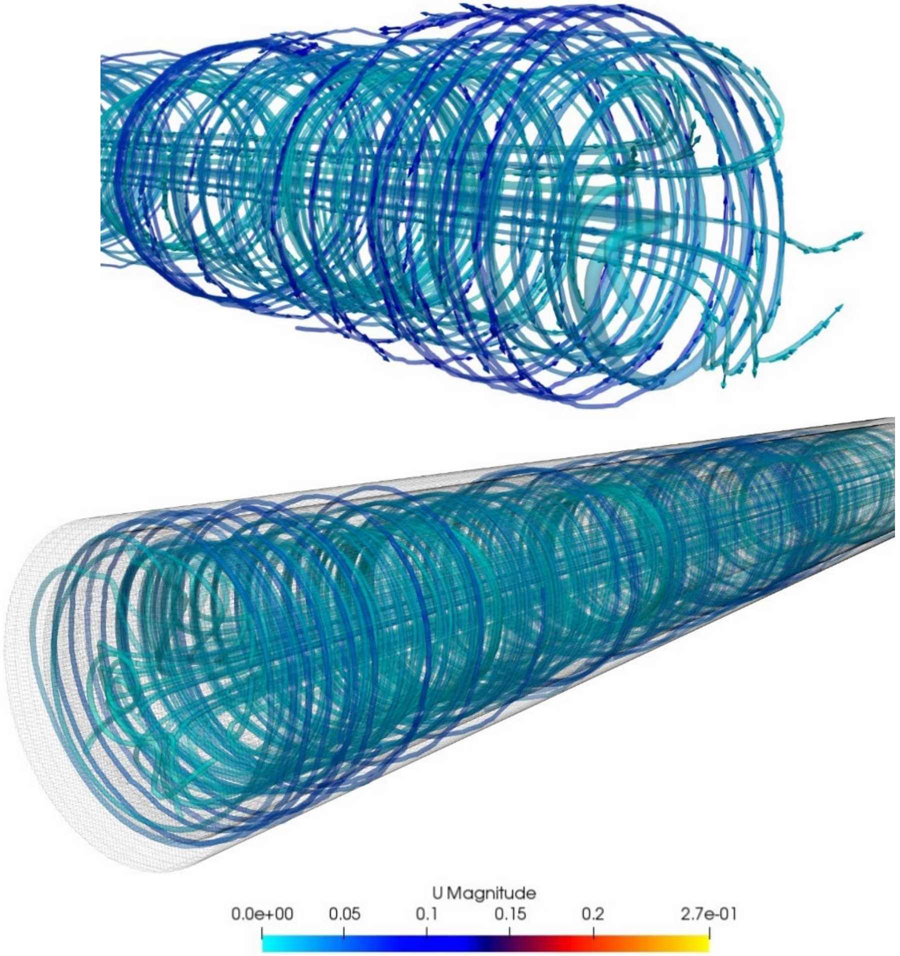




Thermodynamic results





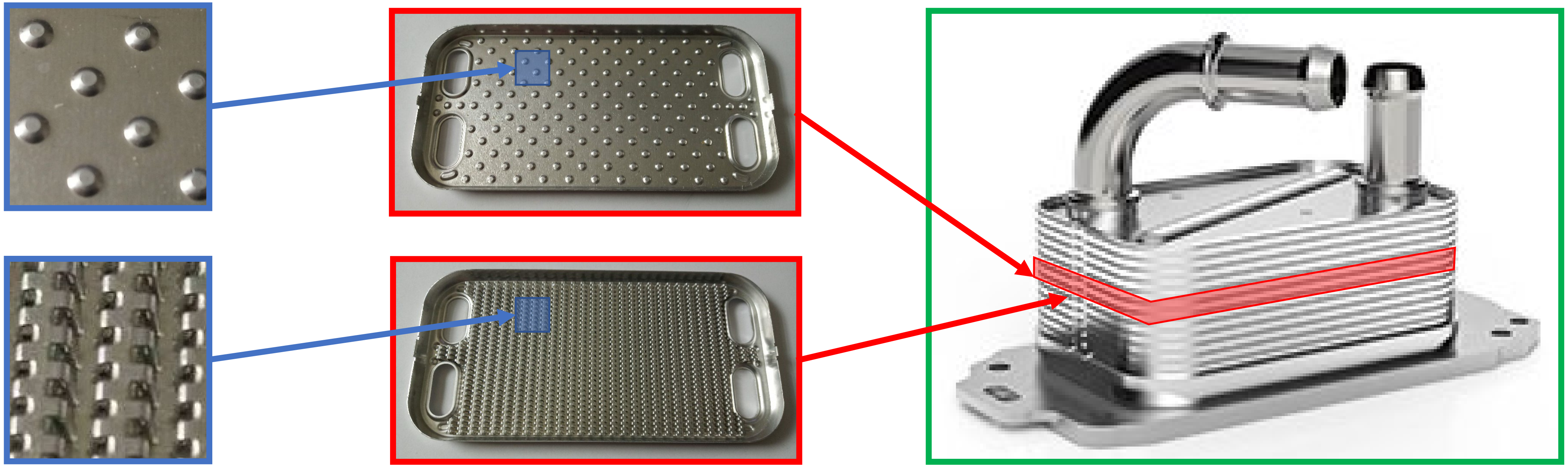


- Correspondence of regions with high loss concentration and high temperature
- Heat traversed by **conduction**
- Effect of rotation on water flowing in **shaft cooling channel**

Cooler Multi-scale CFD model

Design and optimization of oil-cooler is performed at different levels:

Micro-scale (µm – mm) | **Macro-scale (cm – dm)** | **Full-scale (cm – dm)**



Choice / optimization of the turbulator geometry

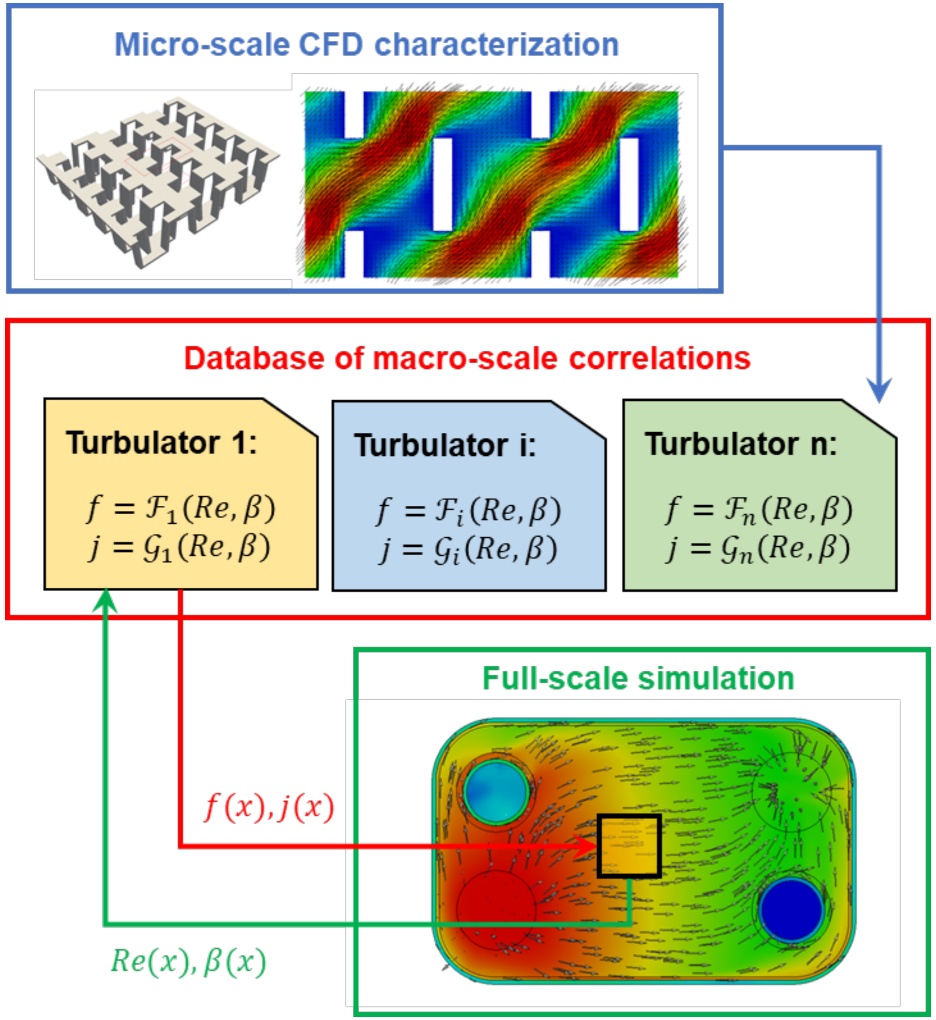
Design of the single heat exchanger layer

Design and optimization of the overall device

Methodology Multi-scale CFD model

Methodology consists of three main steps:

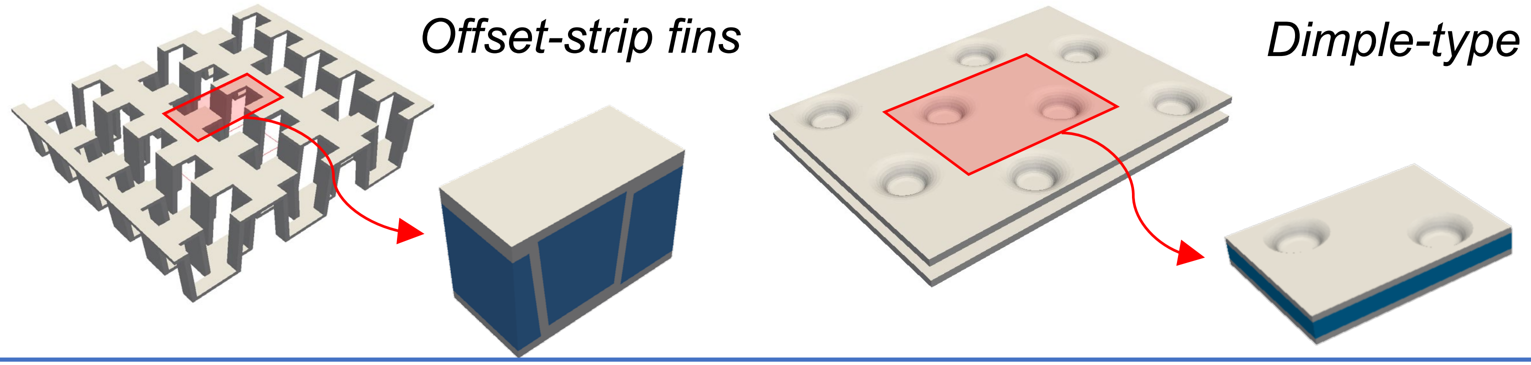
1. ***Micro-scale characterization of the REV of the offset-strip fins / dimple turbulator:***
   - Pressure drop
   - Heat transfer
2. ***Upscaling of micro-scale properties to derive macro scale correlations:***
   - Post-processing of micro-scale simulations
   - Creation of a database of correlations for different turbulators
3. ***Simulation of the full-scale heat exchanger:***
   - Turbolators are modelled by means of a porous media approach based on correlations
   - Possibility to include in the model every significant geometrical detail of the heat-exchanger



Methodology Micro-scale CFD characterization

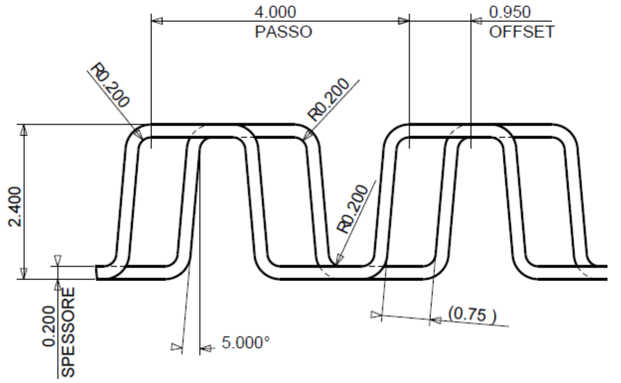
Computational domain

- One single representative elementary volume
- Two regions: fluid and solid



Geometry definition:

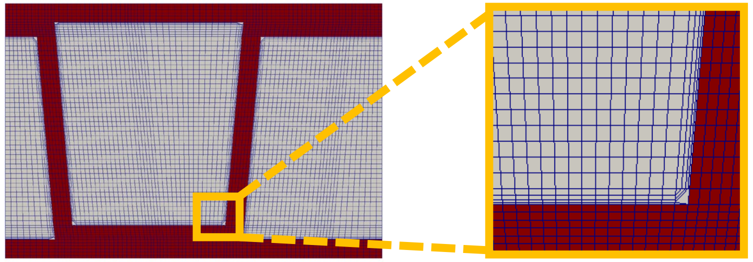
- Fully parametrized geometrical model



Fully automatic mesh generation

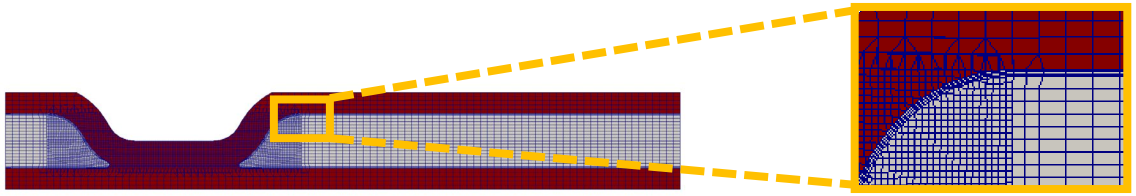
Offset-strip fins:

- block-structured hexaedral mesh
- addition of boundary layers



Dimples:

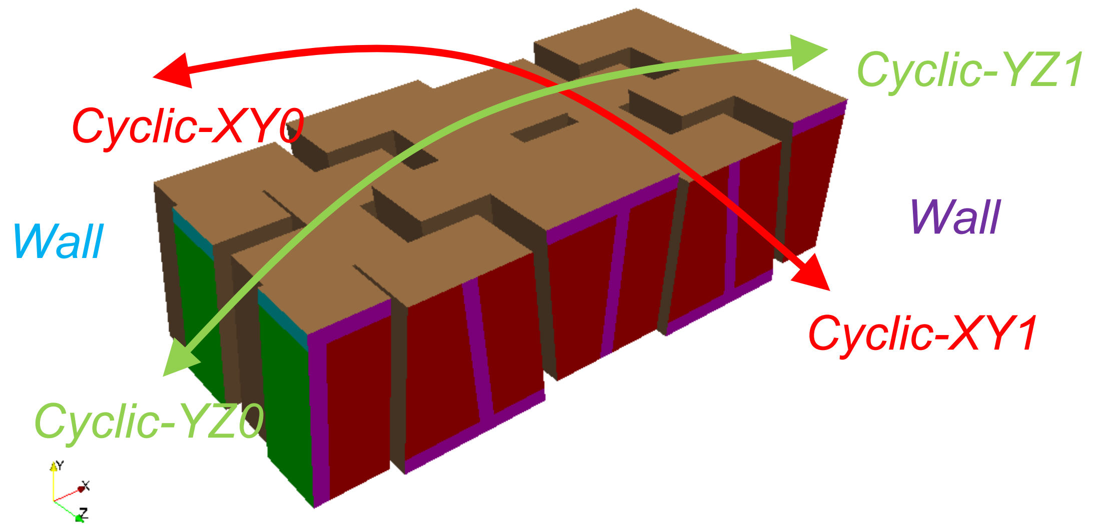
- predominately hexaedral mesh
- with boundary layers

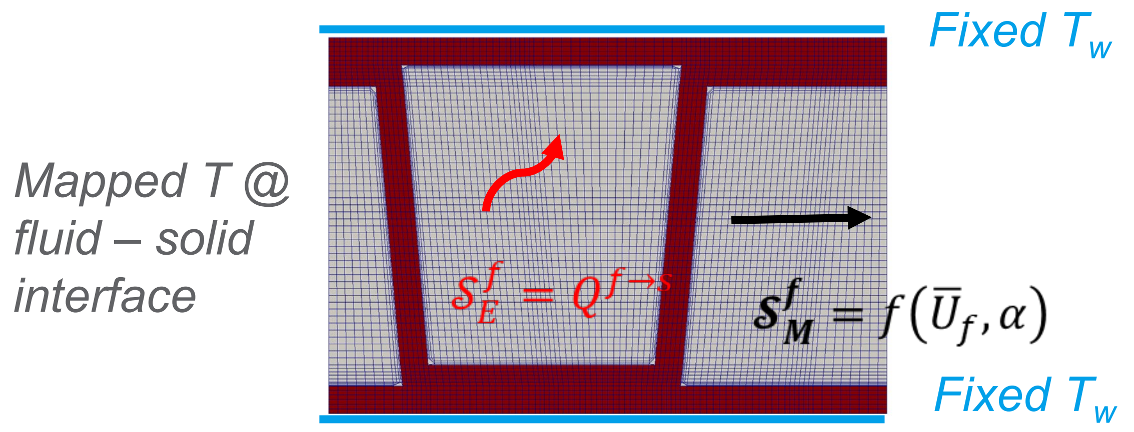


Methodology Micro-scale CFD characterization

Simulation setup

- **<u>Boundary conditions:</u>**
  - Cyclic boundary conditions for REV simulation
  - Mapped boundary conditions for conjugate heat-transfer between fluid and solid domain
  - Fixed temperature condition on top/bottom solid wall
- **<u>Source terms, on fluid domain</u>:**
  - Momentum source to establish (angled) flow
  - Heat source to establish heat flux from fluid to solid domain
- **<u>Thermophysical properties</u>:** to characterize fluid /solid properties
- **<u>Operating points:</u>** flow rate and flow angle



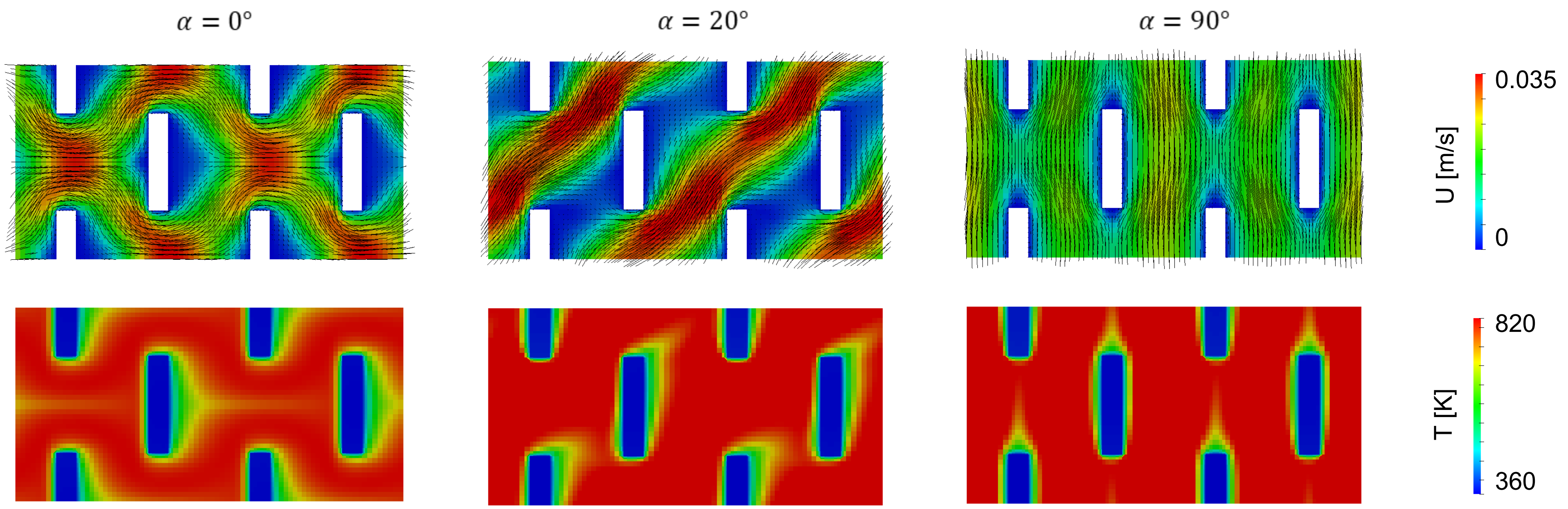


Methodology: Micro-scale CFD characterization

Simulation setup

- **<u>Operating conditions:</u>**
  - ➢ Different flow regimes: from laminar to turbulent
  - ➢ Different flow angles

Around 100 simulations are needed to fully characterize the turbulator



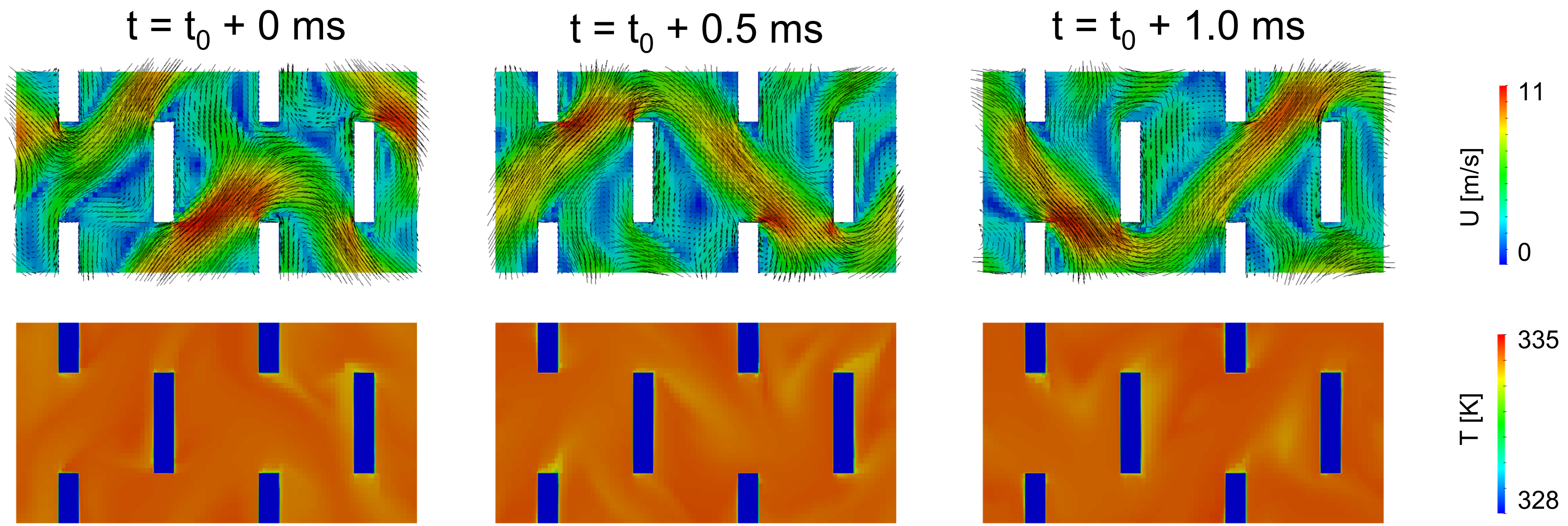
Offset-strip fins

Laminar regime

$U_{avg} = 0.01\ m/s$

Simulation setup

- **<u>Operating conditions:</u>**
  - Different flow regimes: from laminar to turbulent
  - Different flow angles
- **<u>Turbulence modeling</u>:**
  - iLES: for offset strip fins
  - RANS: for dimples



Offset-strip fins

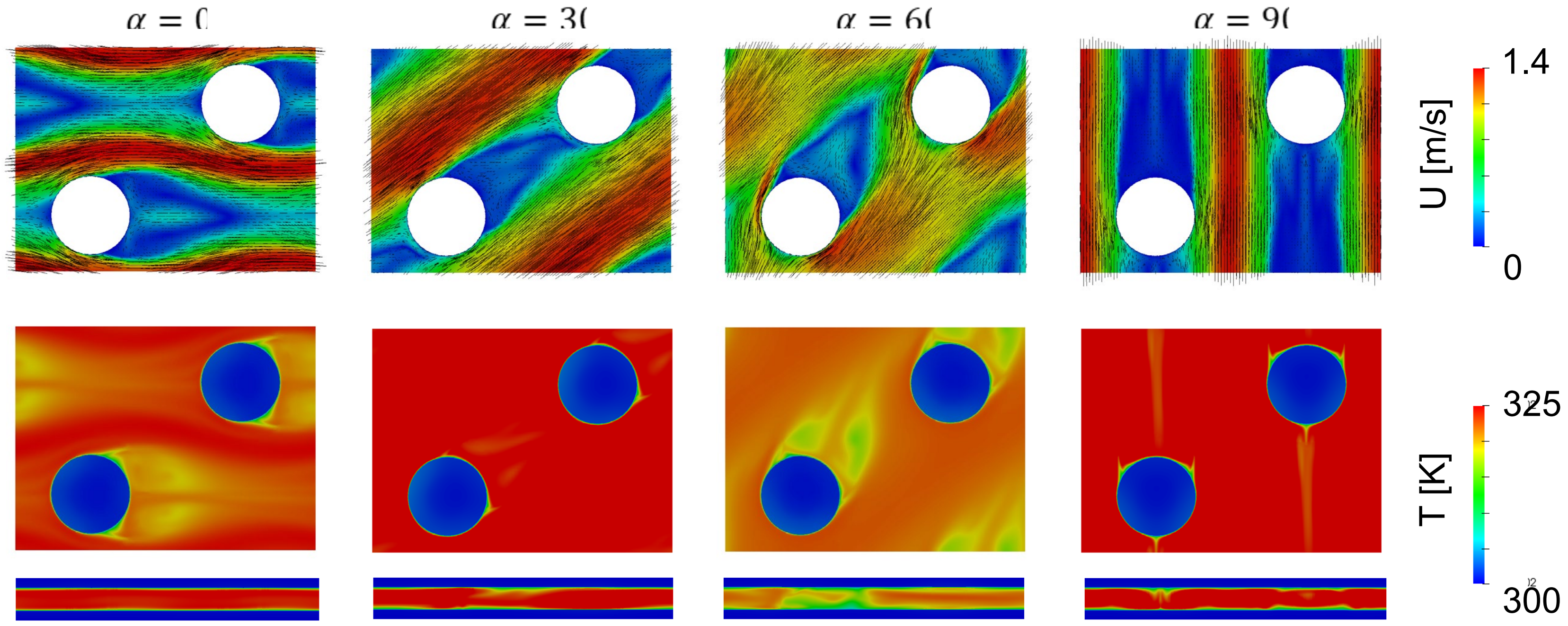
Turbulent regime

U_{avg} = 2 m/s

Flow direction α=0°

Simulation setup

- **Operating conditions:**
  - ➢ Different flow regimes: from laminar to turbulent
  - ➢ Different flow angles
- **Turbulence modeling:**
  - ➢ iLES: for offset strip fins
  - ➢ RANS: for dimples



Offset-strip fins

Turbulent regime

$U_{avg} = 0.5\ m/s$

A large number of simulations are run in parallel on the basis of the operating points to be simulated.

The cases are post-processed in order to obtain pressure drop & heat transfer characterization.

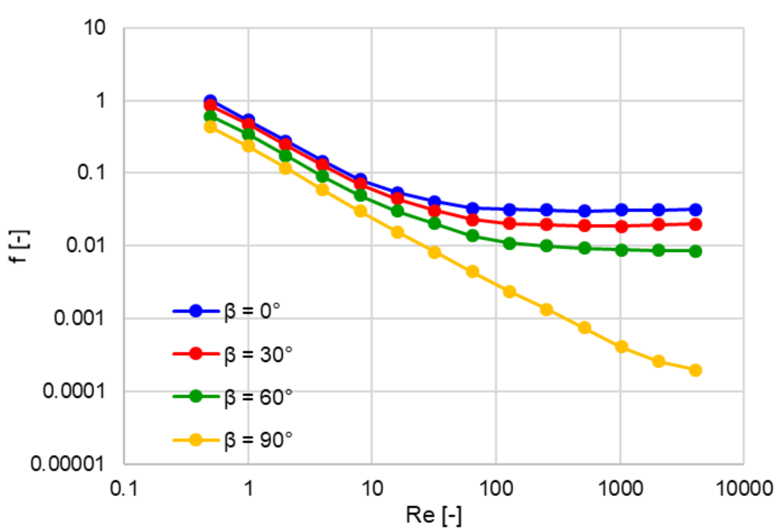
Non dimensional relationships:

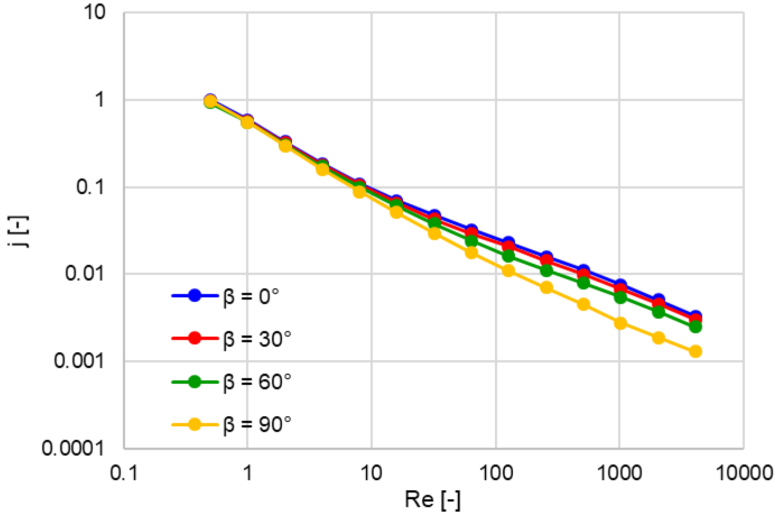
- Fanning factor:

$$\boldsymbol{f}(Re,\beta) = \frac{d_c}{4}\frac{\boldsymbol{\nabla p}}{\frac{1}{2}\rho\boldsymbol{\bar{U}}^2}$$

- Colburn factor:

$$j(Re,\beta) = \frac{Nu}{Pr^{\frac{1}{3}}\,Re}\,, \qquad \text{with} \quad Nu = \frac{h\,d_c}{k} = \frac{d_c}{k}\frac{Q^{f\to s}}{L_x L_z\,(T_f - T_w)}$$





Methodology: From micro-scale to macro-scale

Porous media approach is adopted to model the turbulator at the macro-scale.

Two dimensional grid is adopted, with just a single cell in the direction of the height.

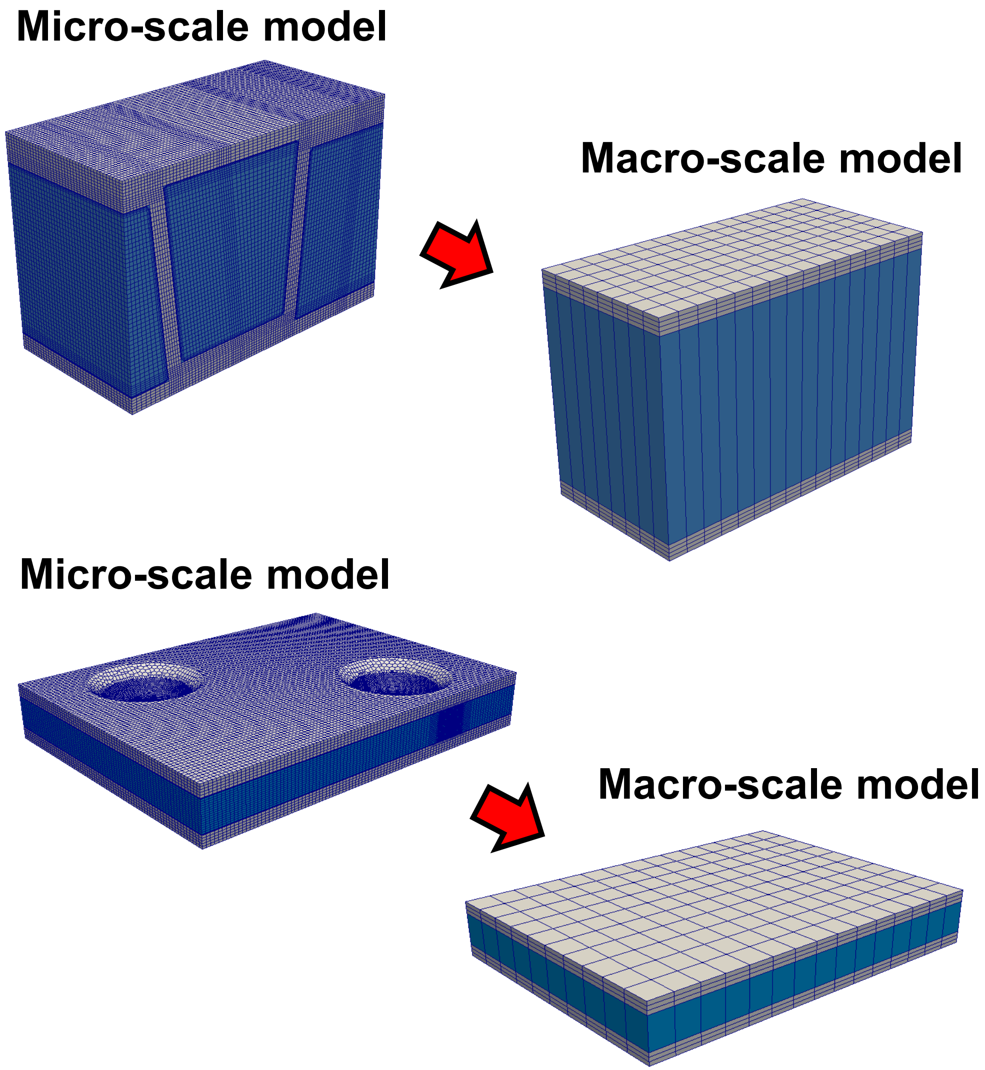
Macro scale model:

- Source term to describe flow resistivity:

$$\boldsymbol{S}_{\boldsymbol{M}}^{\boldsymbol{f}} = \boldsymbol{f}(Re,\beta)\frac{4}{d_c}\frac{1}{2}\rho \boldsymbol{U}_f^2$$

- Boundary treatment to describe heat transfer:

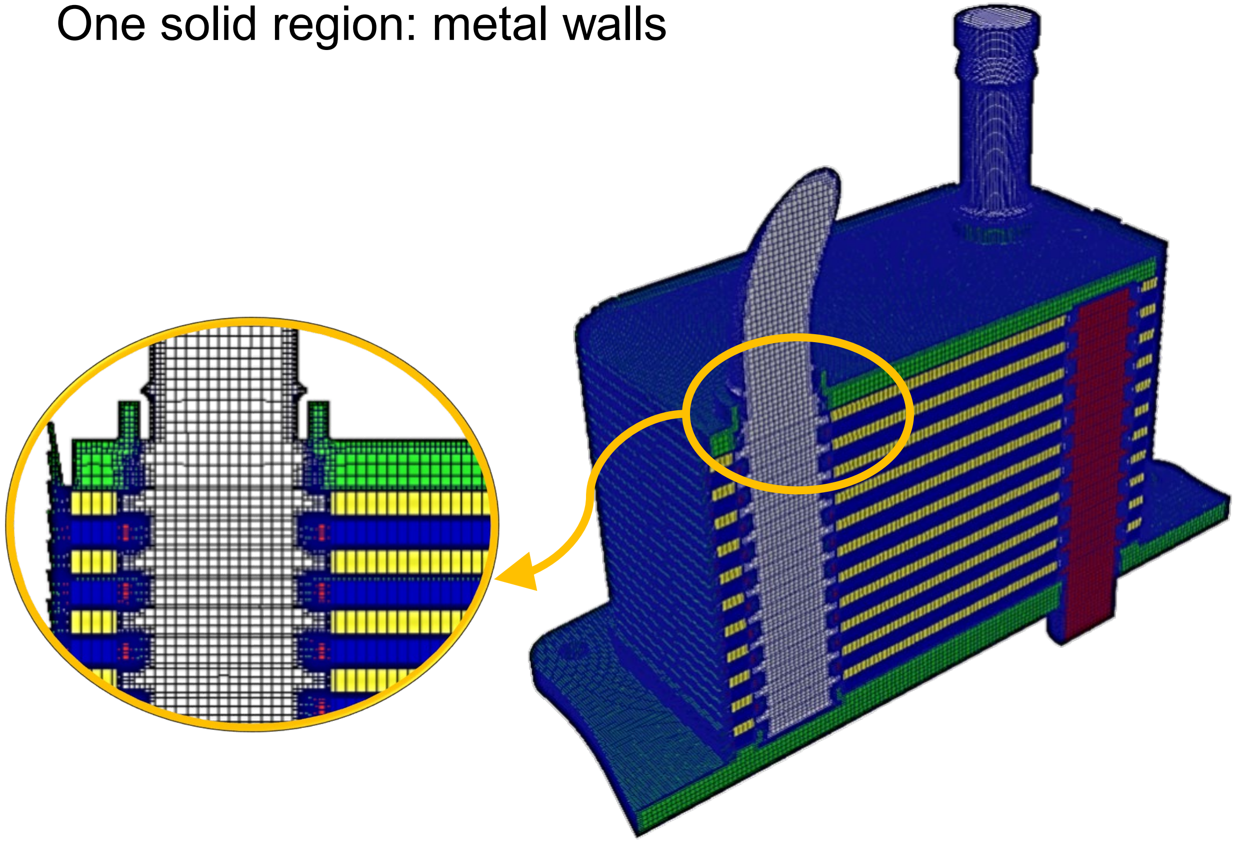
$$h_f(Re,\beta) = \frac{k_f}{d_c}\,\mathrm{j}(Re,\beta)\,\mathrm{Pr}^{1/3}\,Re$$



Methodology Full-scale model

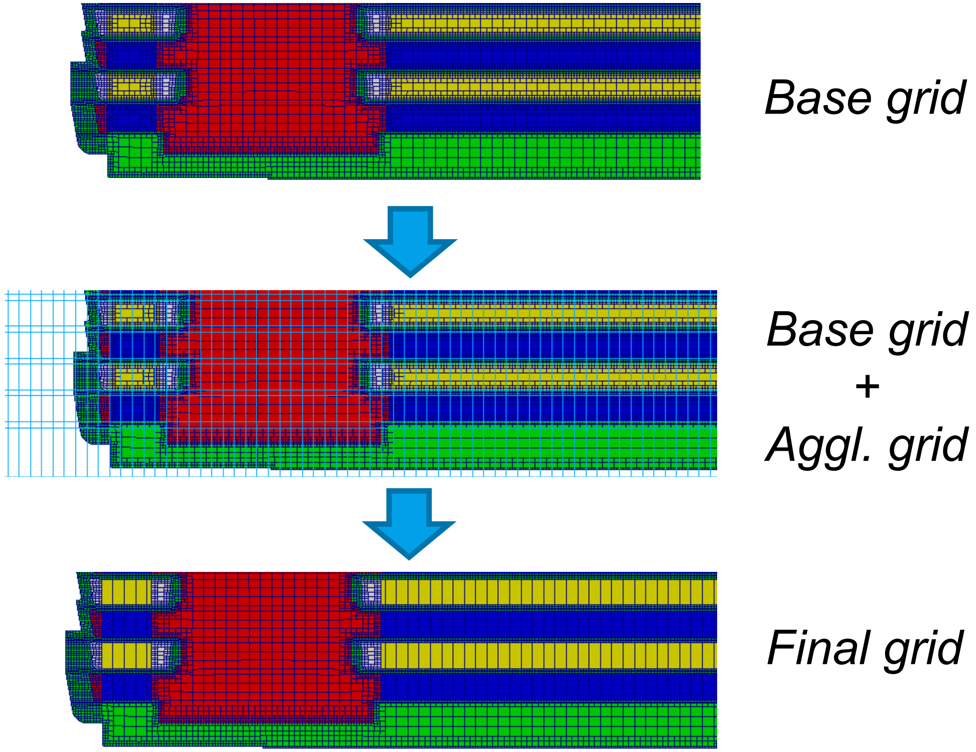
Full-scale model of the heat-exchanger consists of:

- Two fluid regions: oil and coolant
- One solid region: metal walls



Agglomeration procedure:

- generation of 2D mesh in turbulator zones



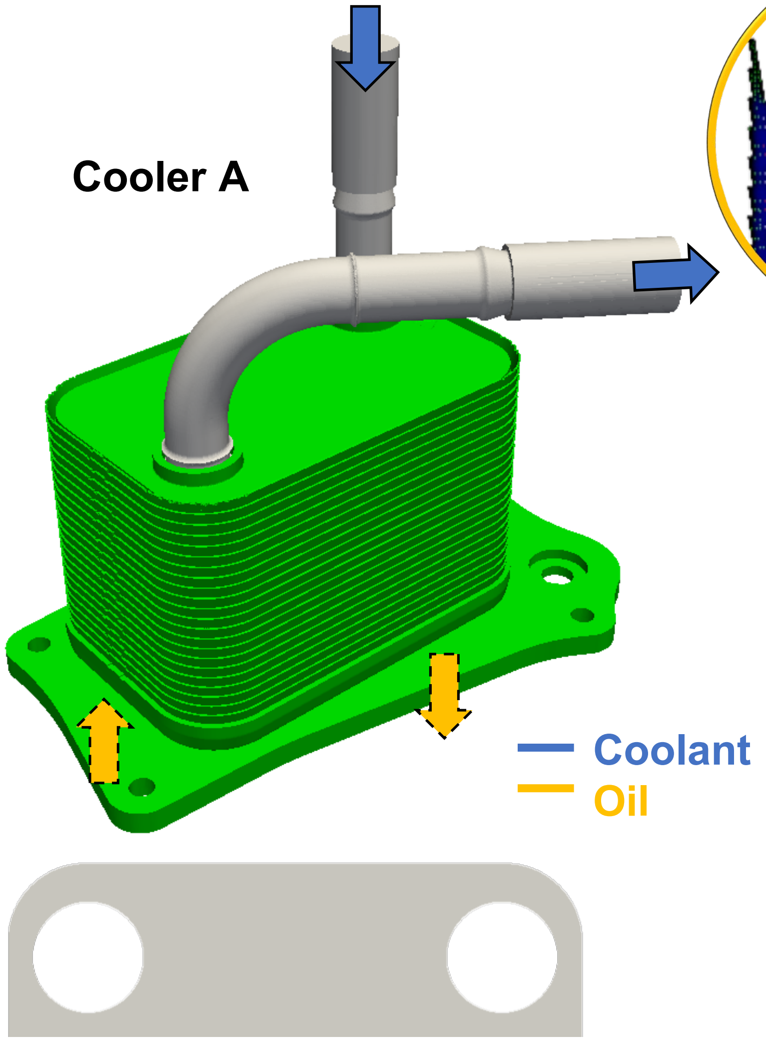
Application Cooler with offset-strip fins turbulators

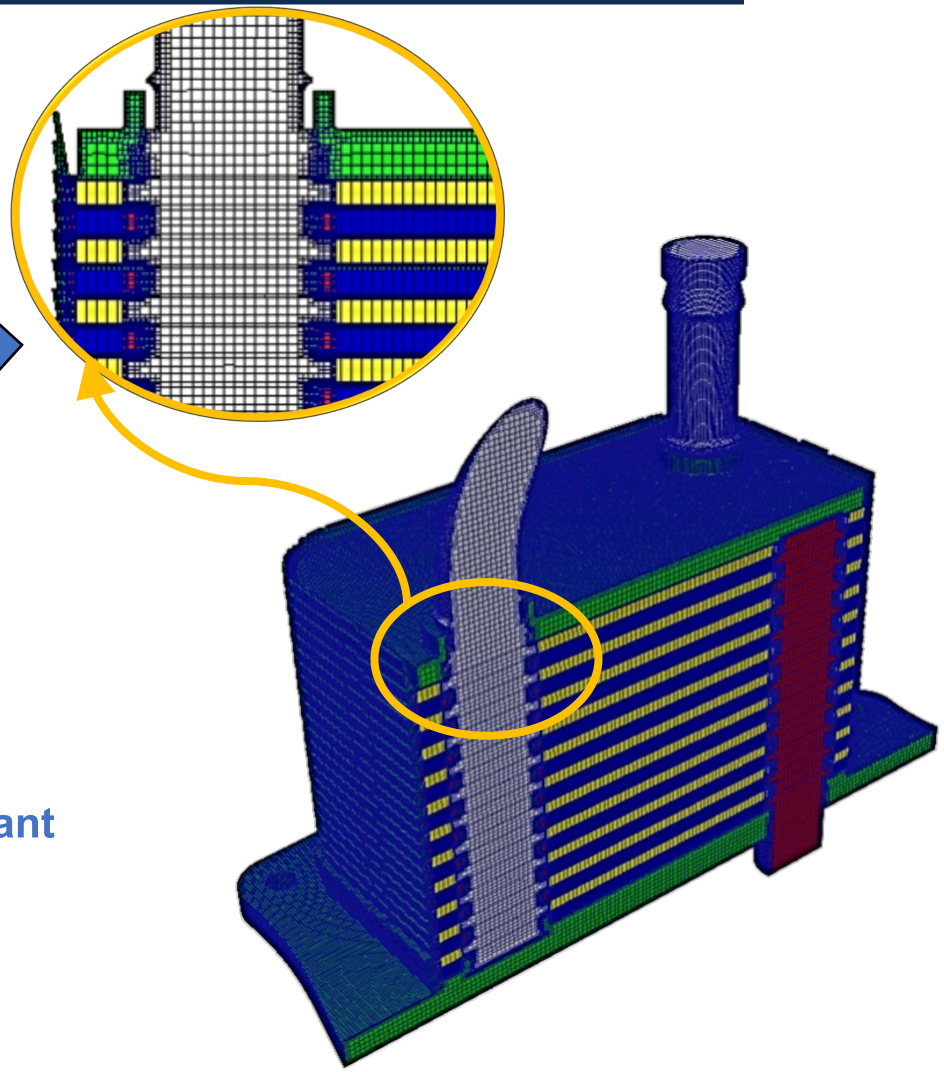
Oil-cooler offset-strip fins configurations:

- Cooler A: 11 oil + 11 coolant

Mesh cell count (base mesh)
- Coolant: 15.79 MLN
- Oil: 13.45 MLN
- Solid: 16.6 MLN

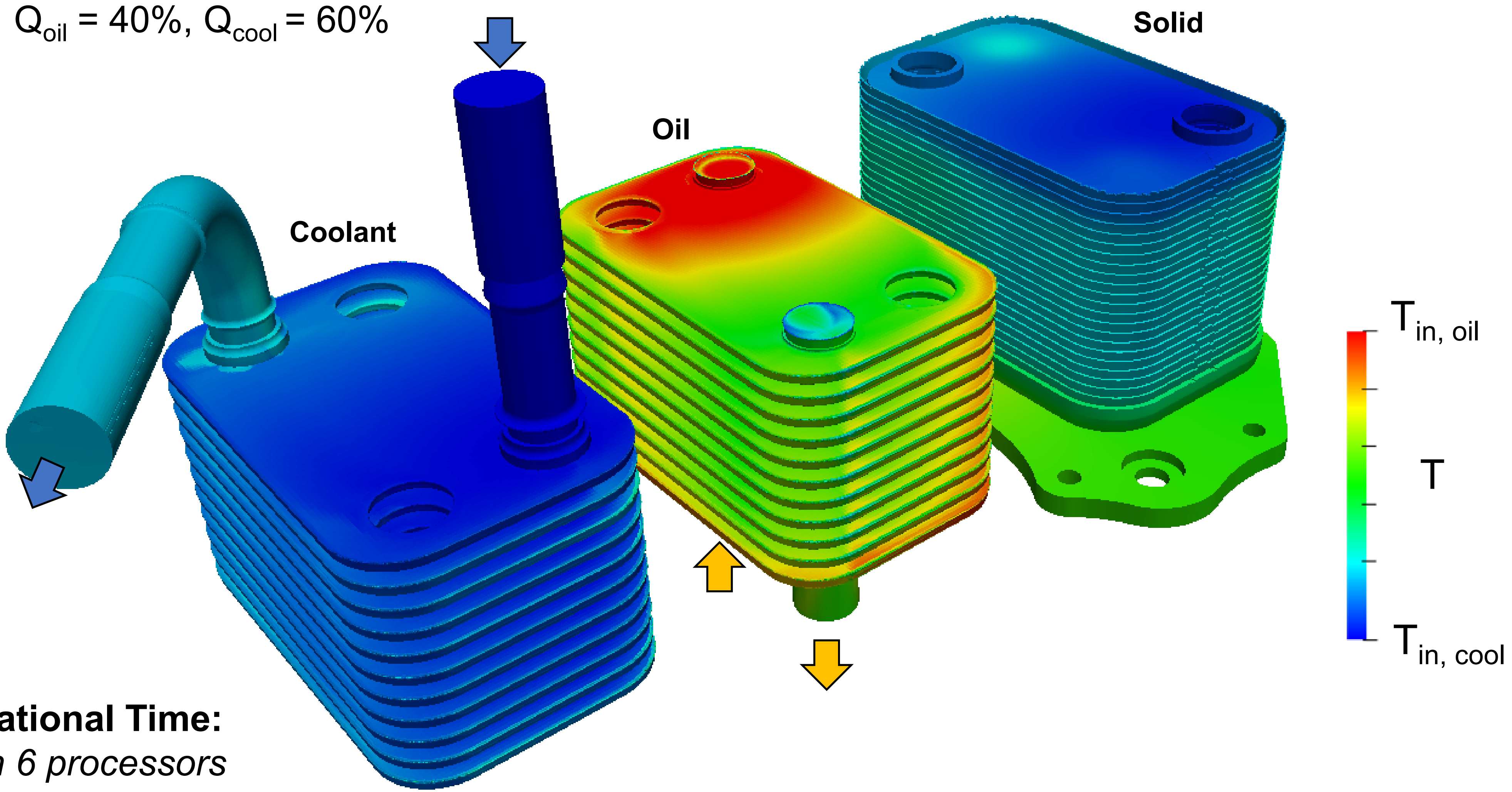
Mesh cell count (w agglomeration)
- Coolant: 1.79 MLN
- Oil: 1.45 MLN
- Solid: 16.6 MLN





Application Coolers with offset-strip fins turbulators

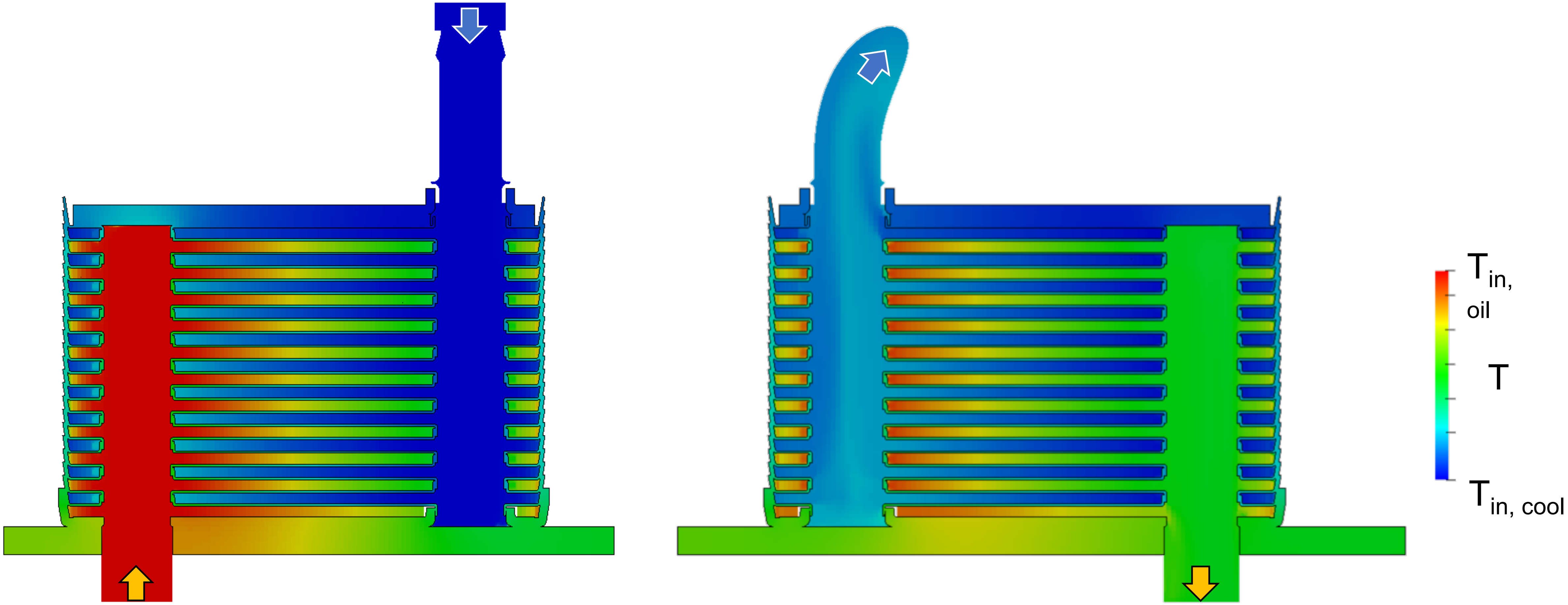
Cooler A: Q_{oil} = 40%, Q_{cool} = 60%



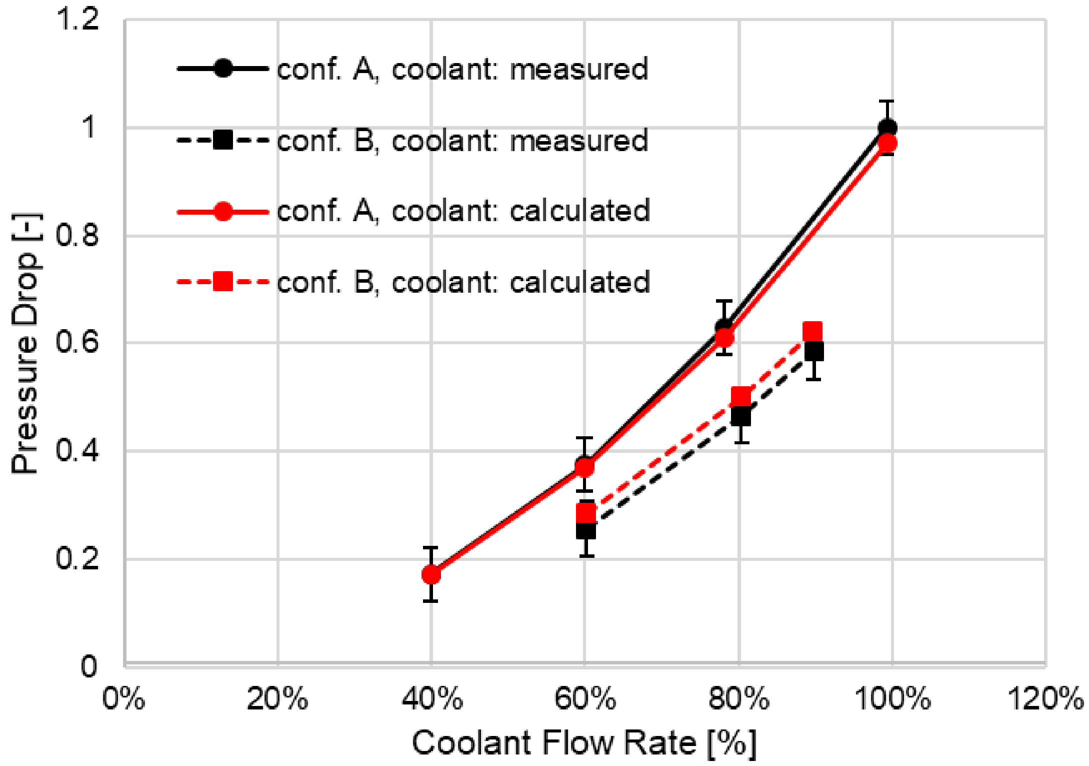
Computational Time:
- *6 h on 6 processors*

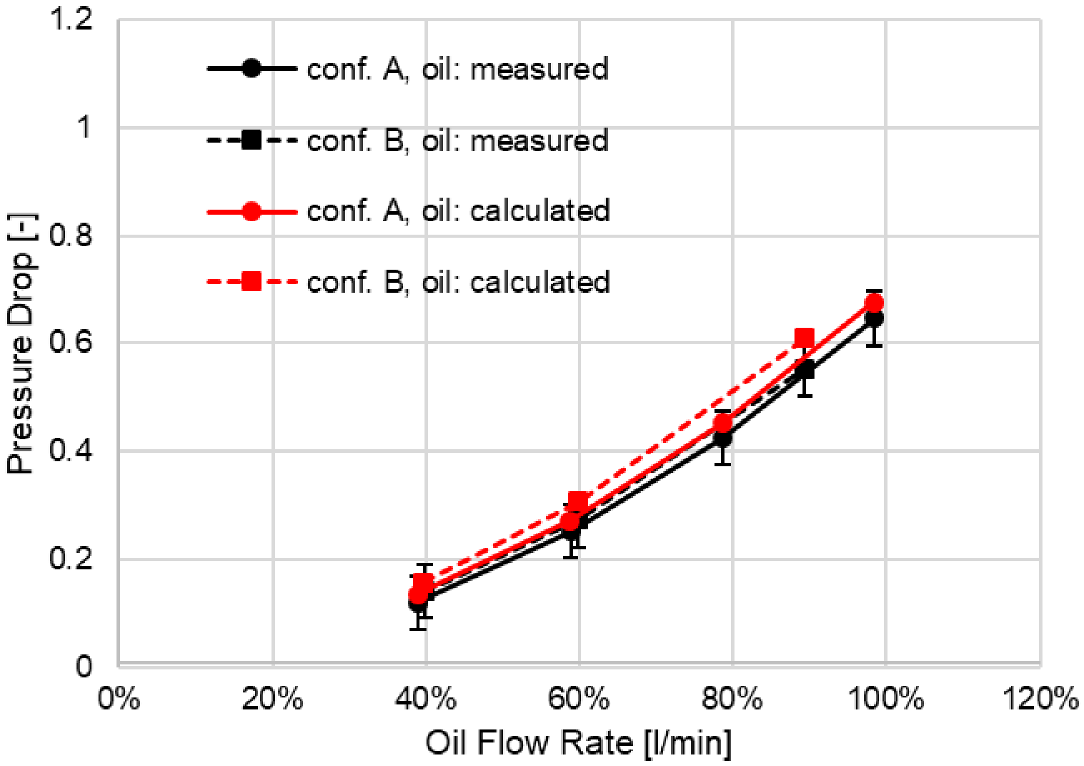
Application Coolers with offset-strip fins turbulators

Cooler A: Q_{oil} = 40%, Q_{cool} = 60%

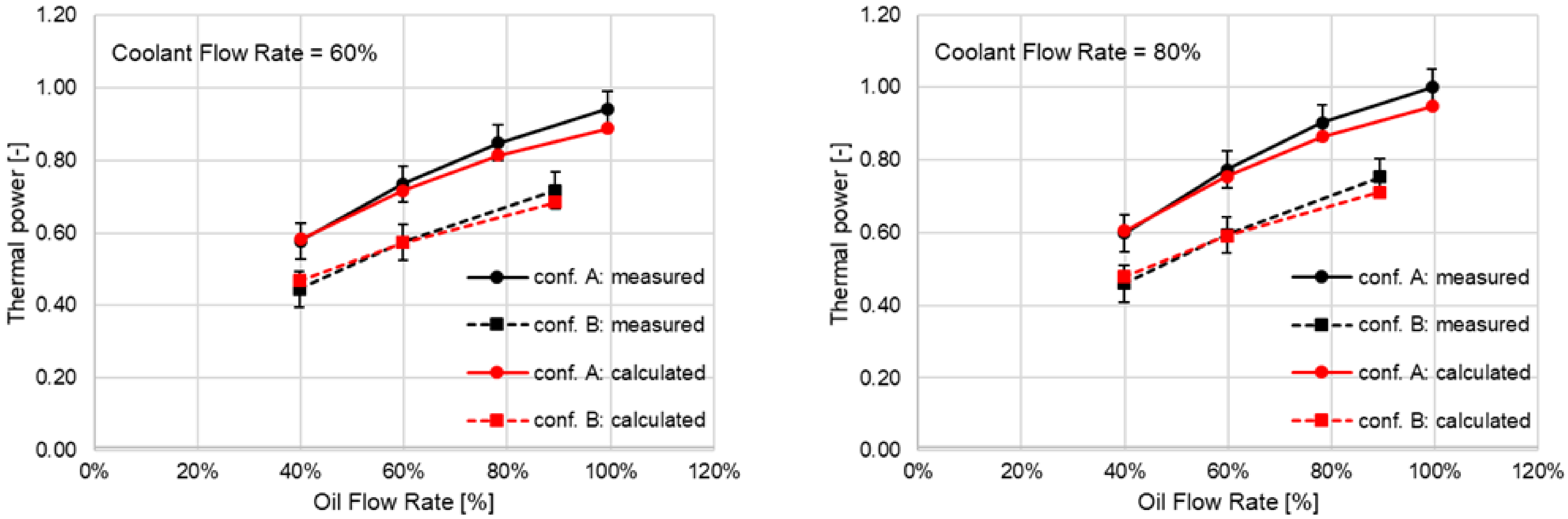


Pressure drop





Heat transfer



Conclusion and future developments

- Coupled thermodynamic and electromagnetic solver under the OpenFOAM
- Multiregion and CHT along with moving mesh architecture
- Evaluation of losses computed based on material behaviour and inclusion in energy equation
- Different machine configurations thanks to parametric mesh
- Multiscale CHT analysis for the optimization of the cooler

Future developments:

- **Electromagnetic phenomena** such as back EMF and skin effect
- **Discontinuity condition** introduced in boundary condition of $\boldsymbol{A}$
- Correct representation of **wires** system of stator windings

Acknowledgments

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CENTRO NAZIONALE PER LA MOBILITÀ SOSTENIBILE

Acknowledgments

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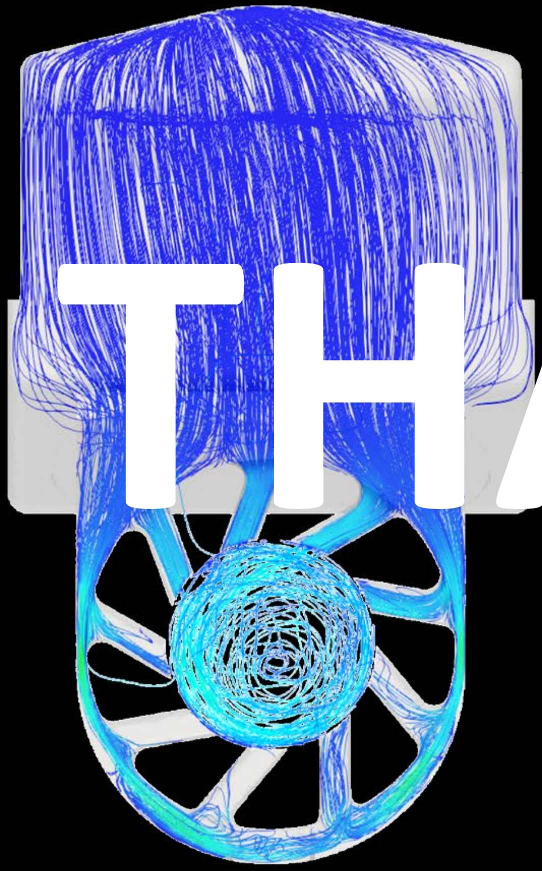

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THANK YOU

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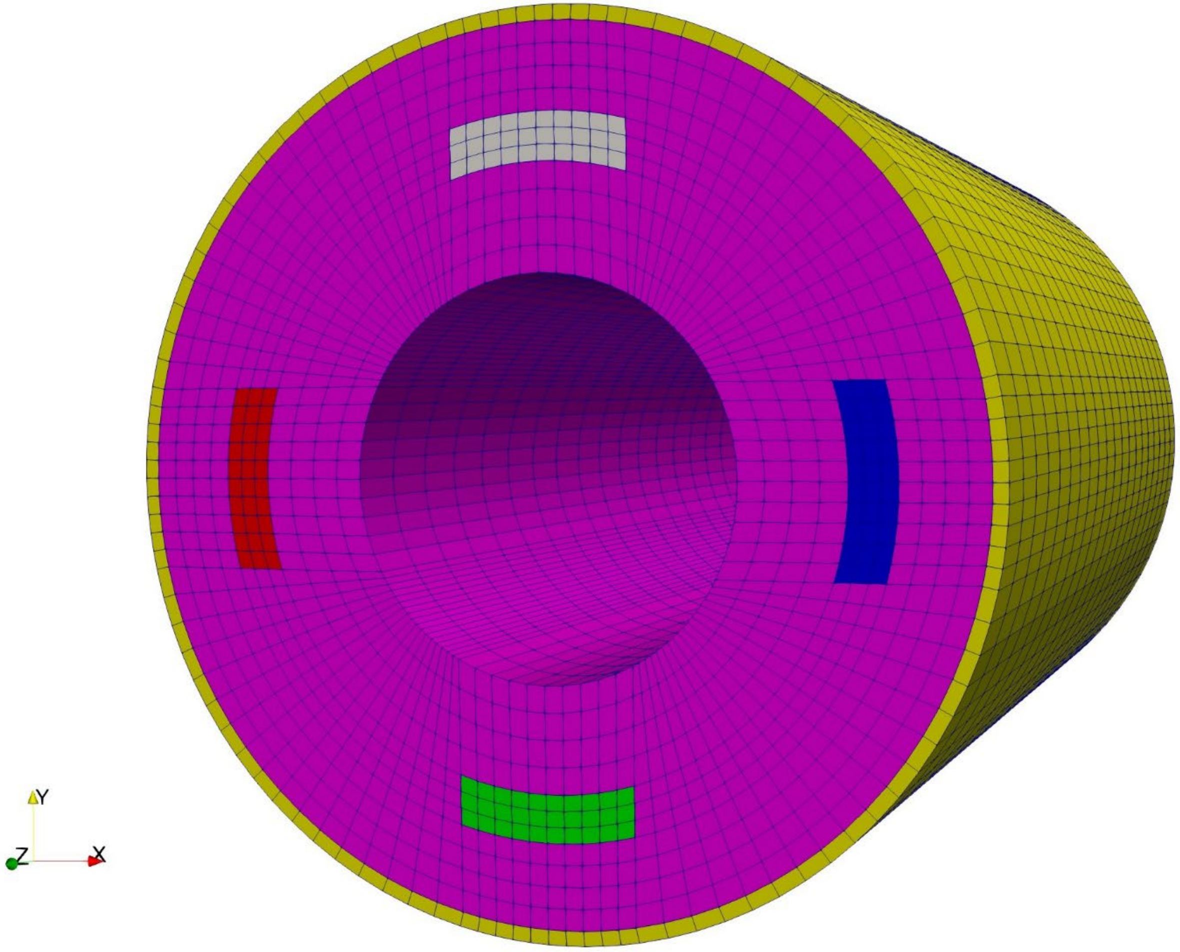

Y
Z
X

Materials characterization for thermal analysis

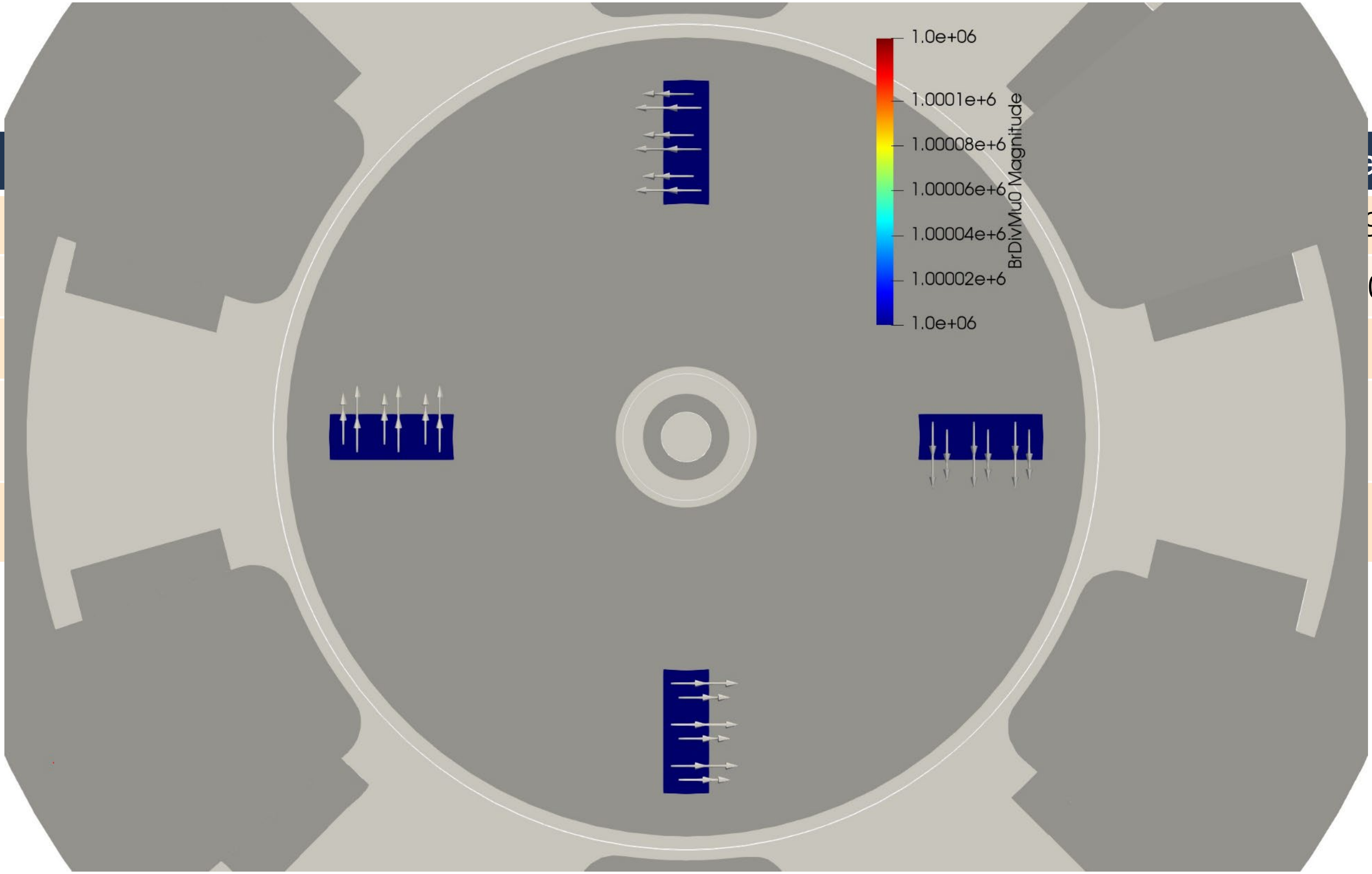
Solids

	rotor core	magnets	stator core	windings	shaft
material	*steel*	*NdFeB*	*steel*	*copper*	*aluminium*
$\boldsymbol{\rho}\ \frac{kg}{m^3}$	7800	7500	7800	8900	2700
$\boldsymbol{k}\ \frac{W}{mK}$	25	12	25	350	237
$\boldsymbol{c}\ \frac{J}{kg\ K}$	445	400	445	380	900

Fluids

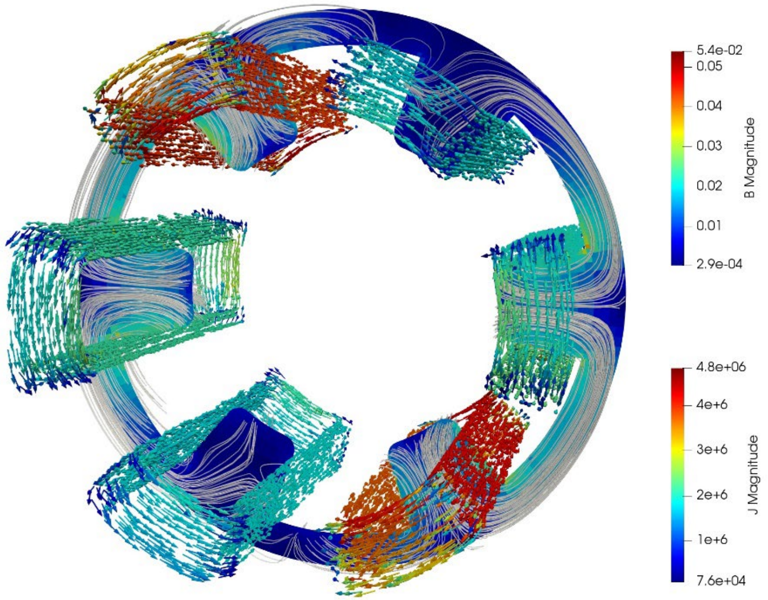
Characterized by **thermophysical models** used and physical properties.
Solved with a RAS methodology and $k\varepsilon$ turbulent model.

Materials characterization for electromagnetic analysis



	ater
μ_r	999
B_r	0
α	-
ρ / γ	-
σ	-

Stator and windings



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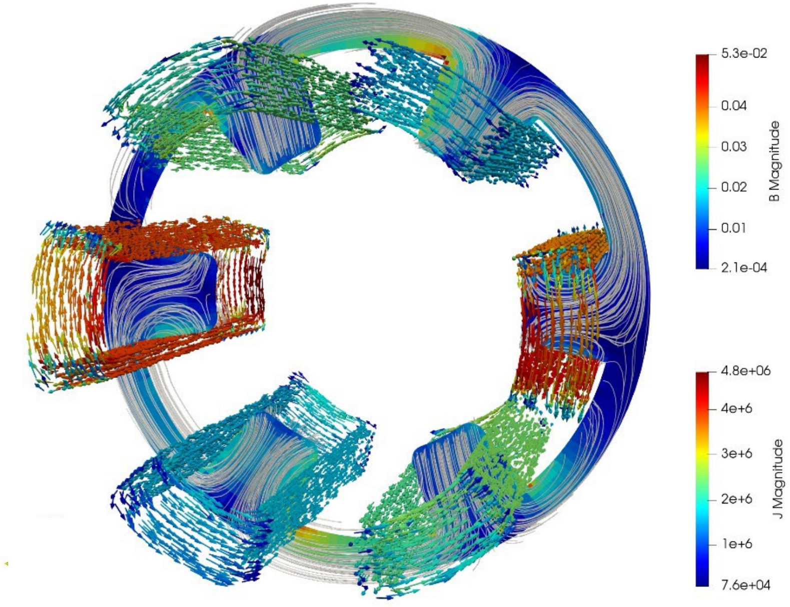

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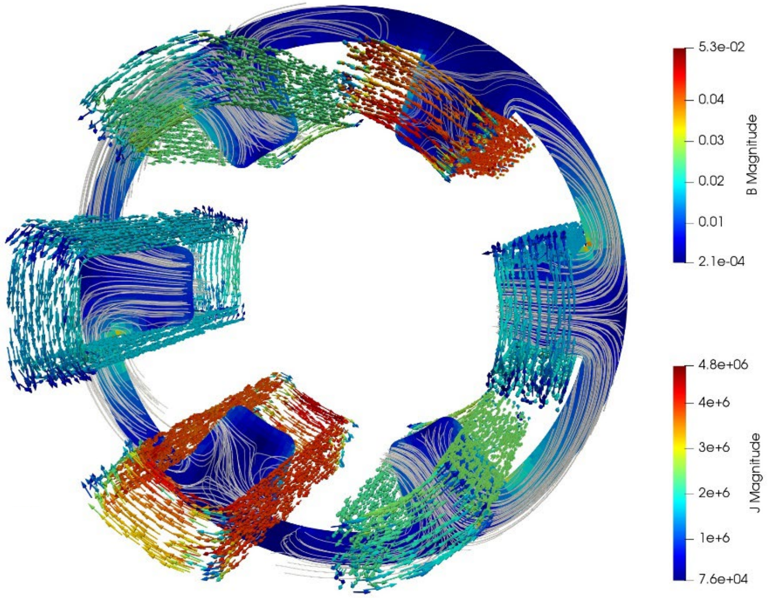

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