CFD simulations of the Molten Salt Fast Reactor

DE LA RECHERCHE À L'INDUSTRIE

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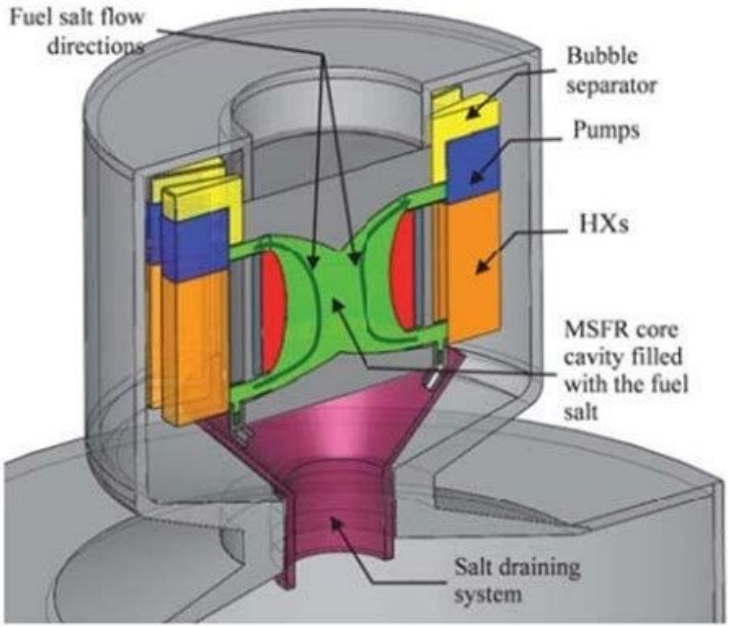
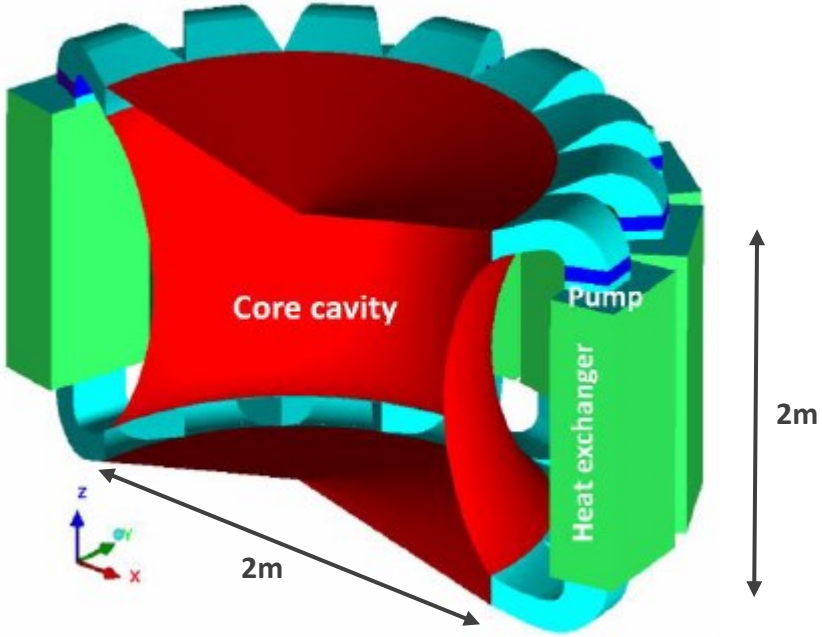
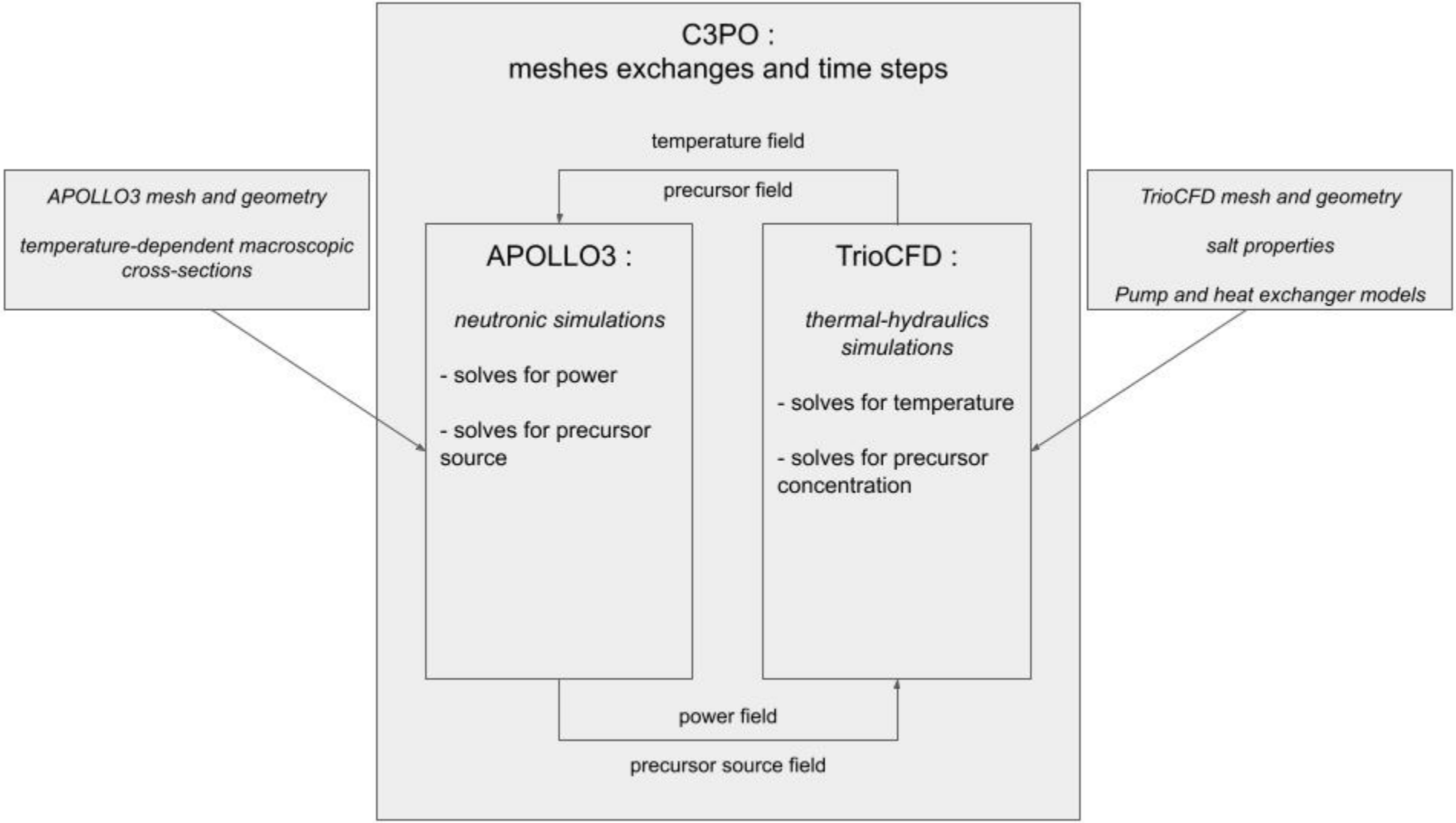
The Molten Salt Fast Reactor

- **Total volume of salt : 18m^3**
- **Power : 3 GWth ; Temperature : 600-750°C**
- **Salt : fluoride (LiF-ThF$_4$) ; Spectrum : fast ; Cycle : ^{233}U / ^{232}Th**
- **Turbulent flow (Re ≈ 1.10^6 , mean velocity ≈ 2 m.s^{-1})**





Scheme of the CEA coupled tool



TrioCFD modeling of the MSFR

APOLLO3-TrioCFD tool aims to be the reference CEA code :
→ The finest thermalhydraulics modeling is sought.

Different turbulence models were compared :
- RANS (classical and realizable k-ε).
- LES.

Different geometries were compared :
- One sector (1/16th) of the MSFR.
- A quarter of the MSFR.
- The full core.

Heat exchanger modeling :
- A reference heat exchanger is still to be defined for the MSFR.
- The impact of the meshing of the HX was studied.

Turbulence model : RANS

Navier Stokes equations :

It is the momentum conservation of a constant-properties, newtonian fluid :

$$\frac{D\mathbf{U}}{D\mathrm{t}} = -\frac{1}{\rho}\nabla \mathrm{p} + \nu\nabla^2\mathbf{U} \ (1)$$

For high Reynolds numbers, chaotic solutions → need to simplify the equation.

RANS modeling :

We split the velocity in two parts, a mean velocity and a random one.

$$\mathbf{U} = \langle\mathbf{U}\rangle + \mathbf{u}$$

We solve the Navier Stokes equations for the mean part only :

$$\left\langle\frac{D\mathrm{U_j}}{D\mathrm{t}}\right\rangle = \frac{\partial\langle\mathrm{U_j}\rangle}{\partial\mathrm{t}} + \frac{\partial\langle\mathrm{U_i}\mathrm{U_j}\rangle}{\partial x_i} = \frac{\partial\langle\mathrm{U_j}\rangle}{\partial\mathrm{t}} + \langle\mathrm{U_i}\rangle\frac{\partial\langle\mathrm{U_j}\rangle}{\partial x_i} + \frac{\partial\langle uiuj\rangle}{\partial x_i} \ (2)$$

Turbulence model : RANS

We define the mean particular derivative :

$$\frac{\overline{D}}{\overline{D}\mathrm{t}} = \frac{\partial}{\partial \mathrm{t}} + \langle \mathbf{U} \rangle . \nabla$$

We then rewrite (2) as :

$$\frac{\overline{D}\langle \mathrm{U_j} \rangle}{\overline{D}\mathrm{t}} = \left\langle \frac{D\mathrm{U_j}}{D\mathrm{t}} \right\rangle - \frac{\partial \langle uiuj \rangle}{\partial x_i}$$

By injecting the mean of (1), we obtain the Reynolds equations :

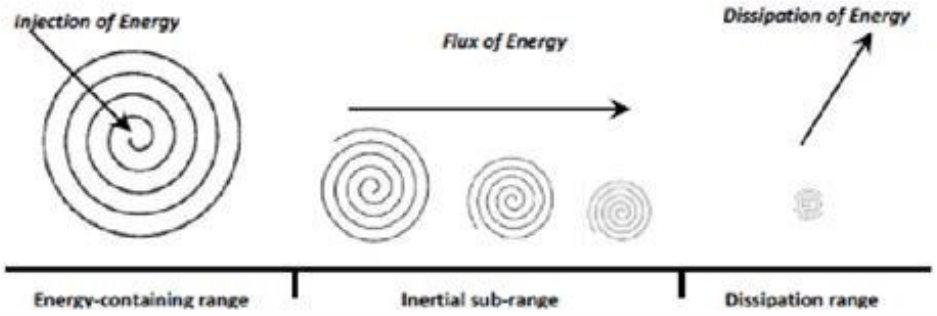
$$\frac{\overline{D}\langle \mathrm{U_j} \rangle}{\overline{D}\mathrm{t}} = -\frac{1}{\rho}\frac{\partial \langle p \rangle}{\partial x_j} + \nu \nabla^2 \langle \mathrm{U_j} \rangle - \boxed{\frac{\partial \langle uiuj \rangle}{\partial x_i}} \quad (3)$$

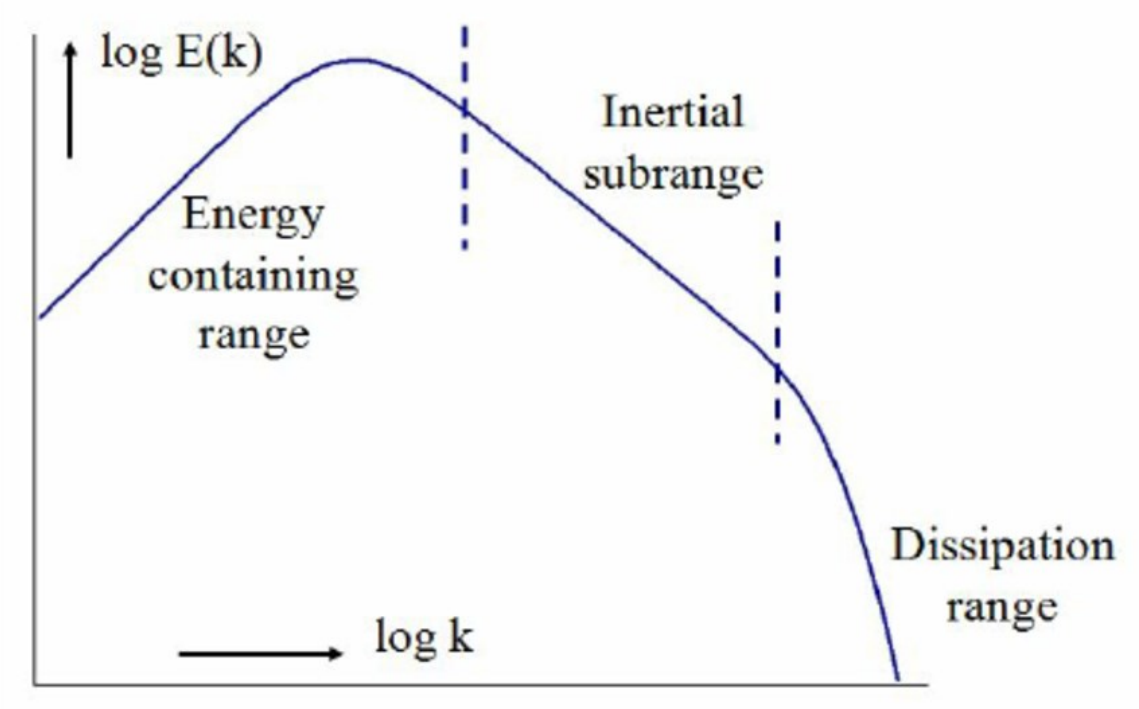
Closure problem with the Reynolds stress tensor : we need a closure relation.

Many models exist : Reynolds stress models, k-ε, mixing length,…

Turbulence model : LES

Turbulent energy cascade :





Turbulence model : LES

LES modeling :

We split the velocity in two parts, a filtered velocity and a residual one.

$$\mathbf{U} = \overline{\mathbf{U}} + \mathbf{u}$$

The number of modes simulated (the filter width) depends on the mesh size.

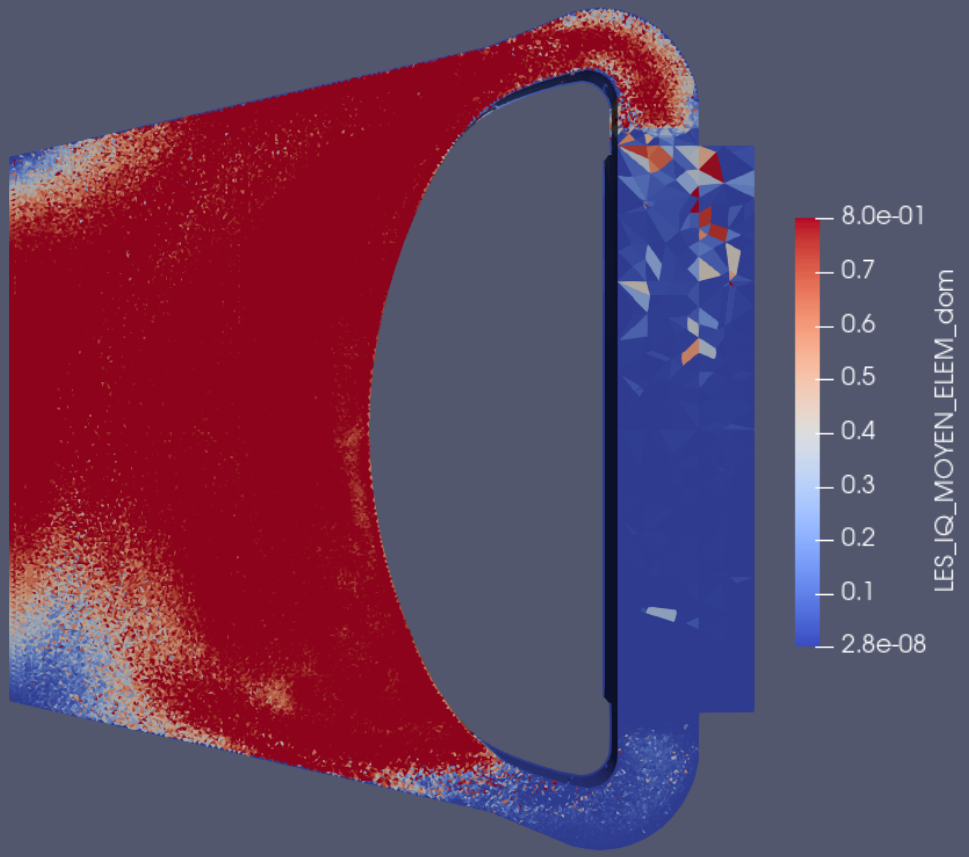
Momentum conservation for the filtered velocity :

$$\frac{\partial \overline{\mathrm{U}}_{\mathrm{j}}}{\partial t} + \boxed{\frac{\partial \overline{\mathrm{U}_{\mathrm{i}}\mathrm{U}_{\mathrm{j}}}}{\partial x_i}} = \nu \frac{\partial^2 \overline{\mathrm{U}}_{\mathrm{j}}}{\partial x_i \partial x_i} - \frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_{\mathrm{j}}}$$

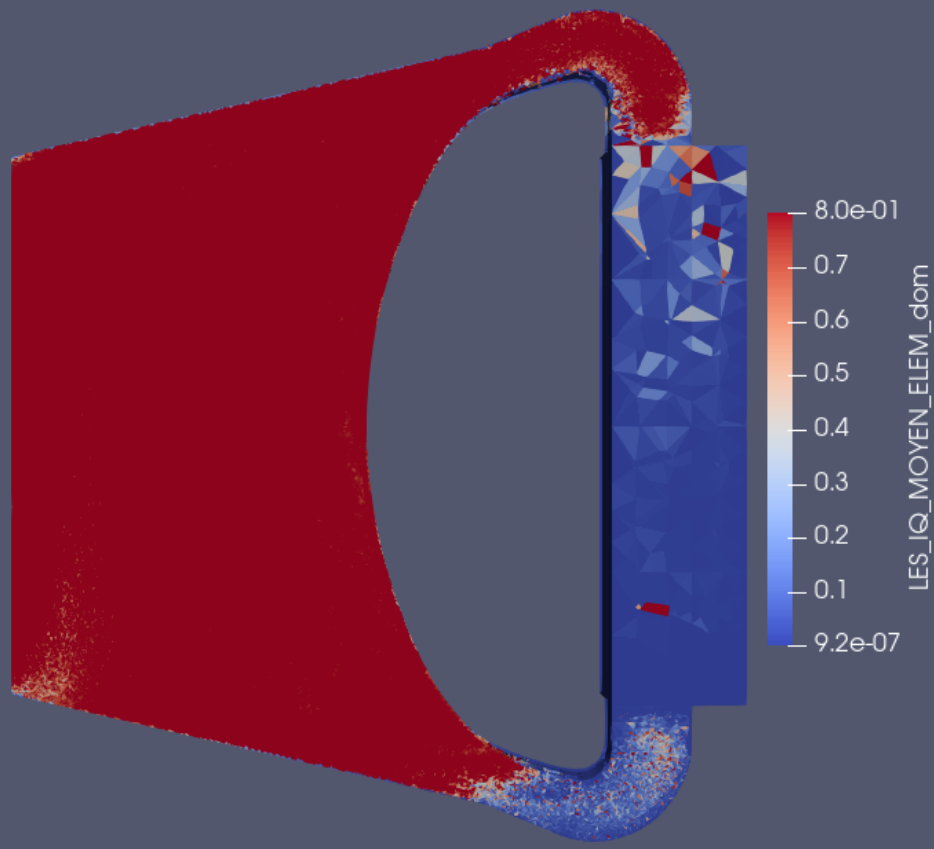
We have a closure problem with the residual stress tensor :

- Turbulent viscosity hypothesis.
- Different models for the turbulent viscosity (Smagorinsky, WALE).

LES meshing resolution : LES Index of Quality



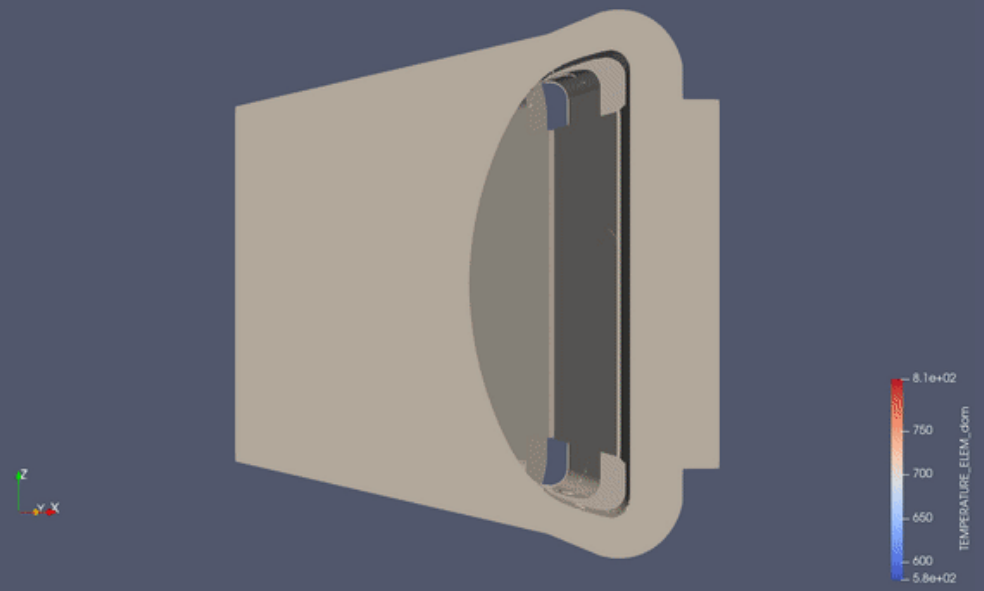
15mm mesh size



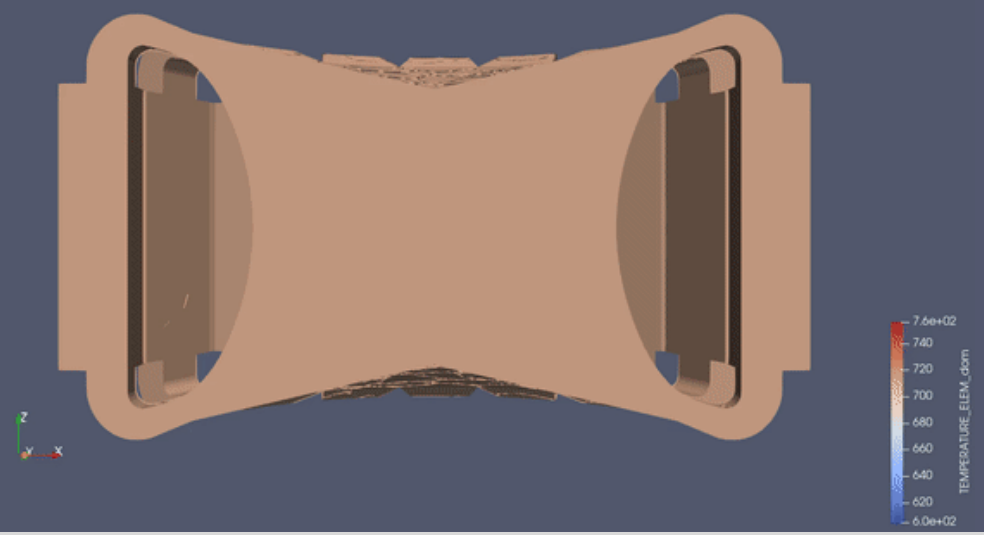
10mm mesh size

RANS vs LES simulations : instantaneous temperature

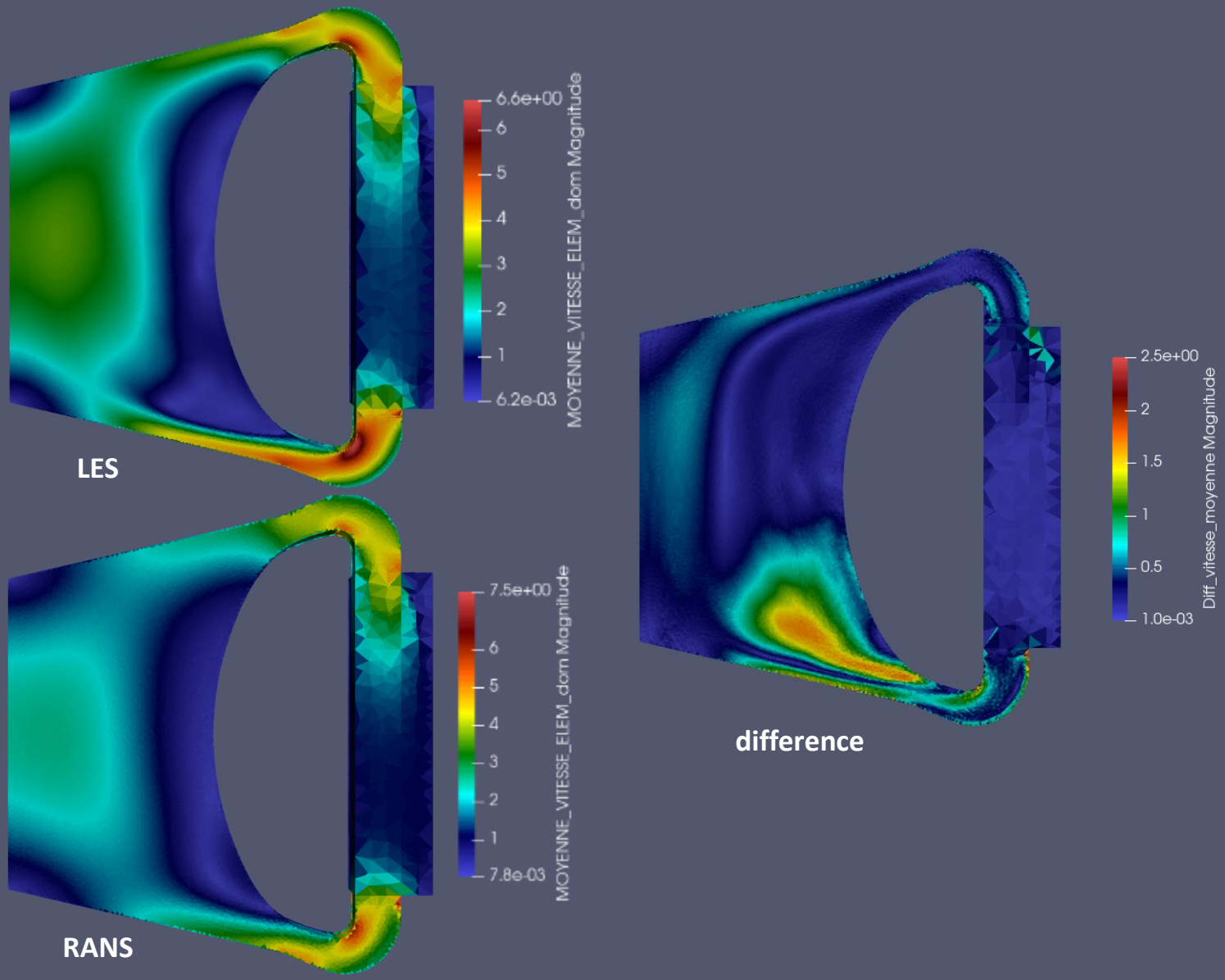
LES



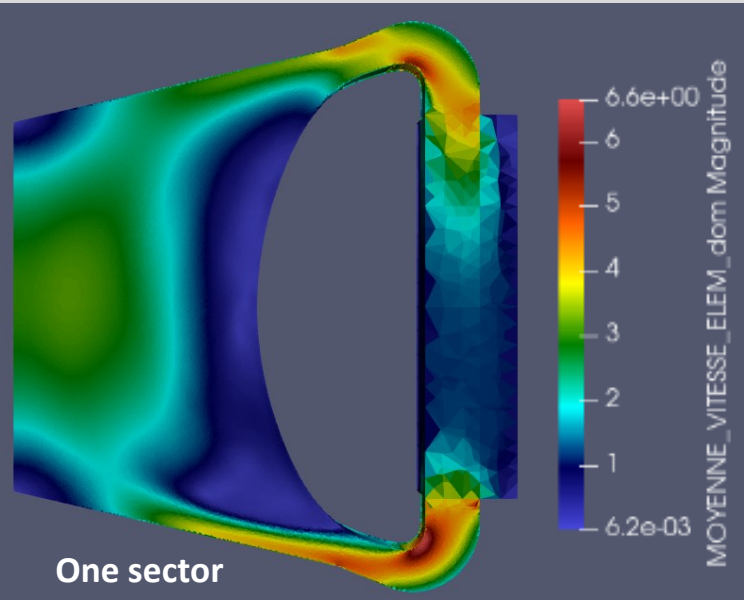
RANS

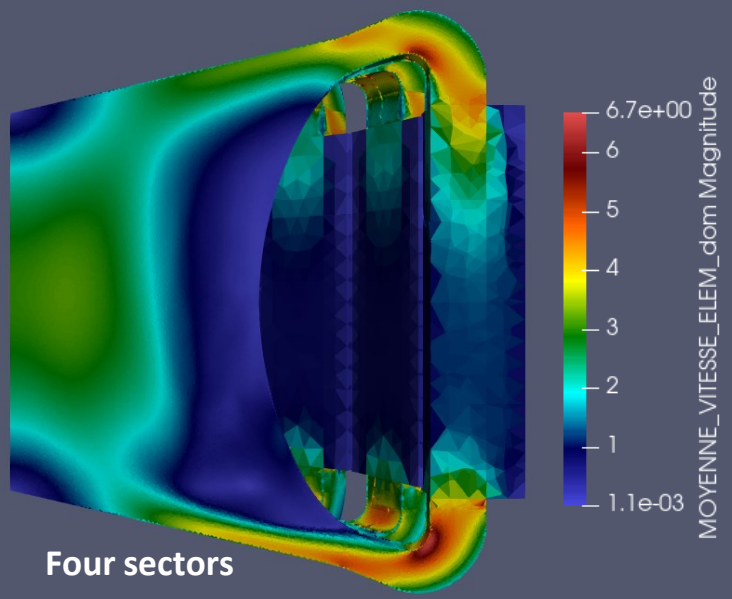


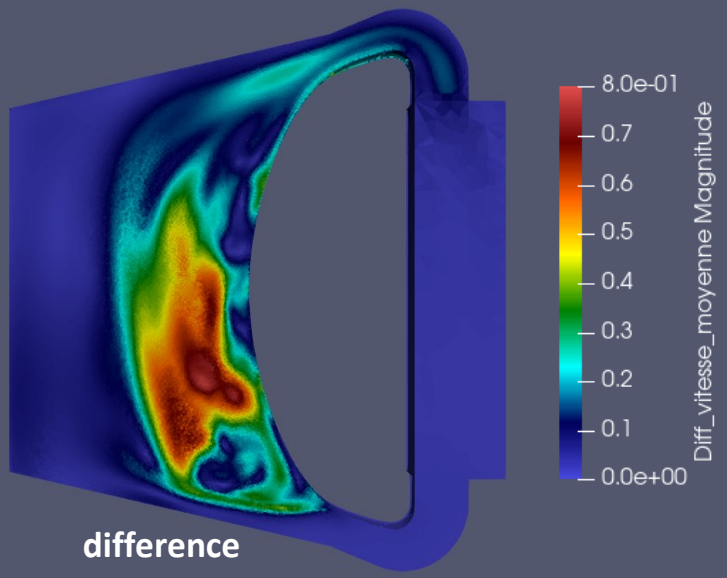
RANS vs LES simulations : mean velocity field



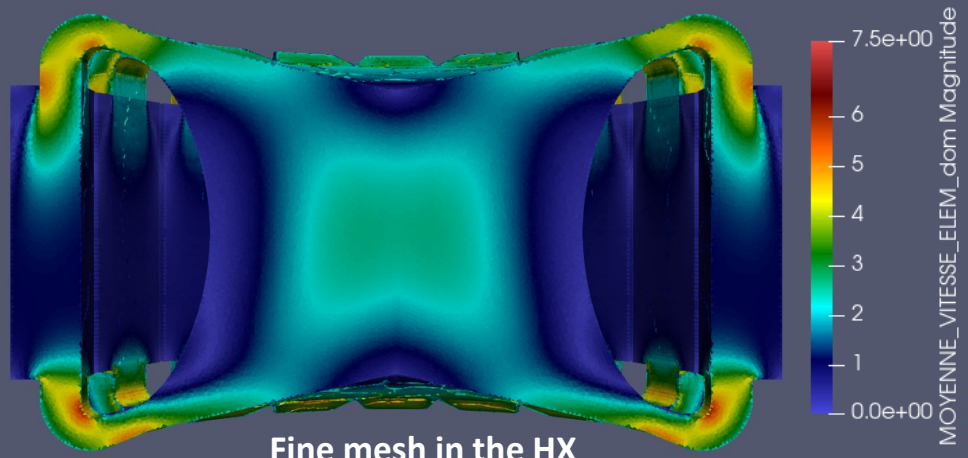
Geometry considered : LES mean velocity



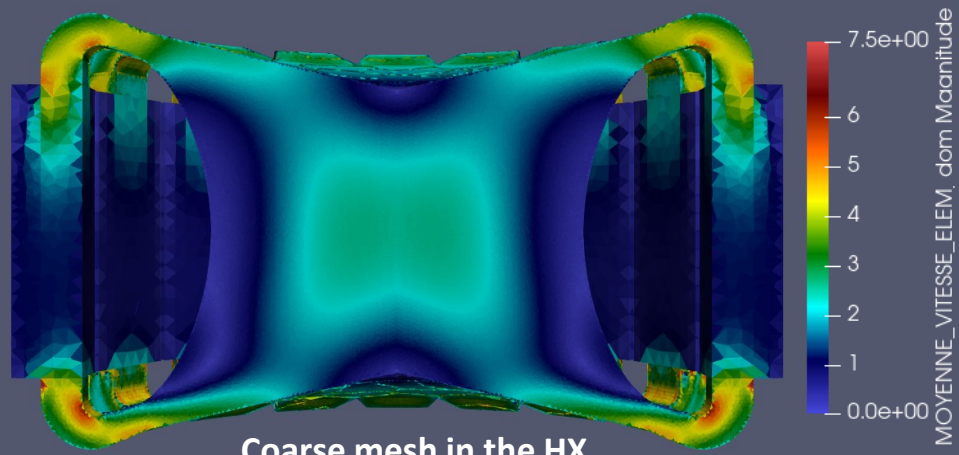




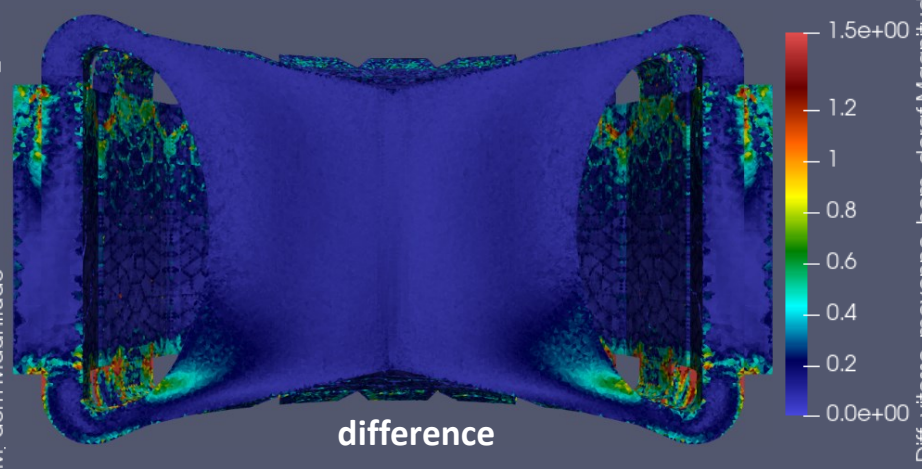
Heat exchanger modeling : RANS mean velocity



Fine mesh in the HX



Coarse mesh in the HX



difference

Conclusion and future work

MSFR design :

- The MSFR geometry was optimised with RANS simulations.

- Big discrepencies between the RANS and LES velocity fields.

→ Need to re-optimize the geometry with LES simulations ?

→ The heat exchanger design will impact the injection zone.

Future work :

- wall-resolved LES : implicit or hybrid time schemes.

- Coupling : impact on the mean temperature and the temperature fluctuations.

- Coupled RANS simulations : comparison with SAMOSAFER partners.

Thank you very much !

Meshing and computational cost

Our meshes :

25mm (RANS) :

Sector : 428 000 tetras ; Full core : 6.85 e6 tetras

10mm (LES) :

Sector : 5.25 e6 tetras ; Quarter : 21 e6 tetras ; Full core : 84 e6 tetras

Computational cost :

RANS : implicit time scheme, 48h on 300 threads.

LES : quarter core, 10 seconds of simulation → 48h on 2000 threads (TOPAZE cluster).