A Novel 3D+1D coupled model for the thermal-hydraulic simulation of the gravity support of the DTT toroidal field coils

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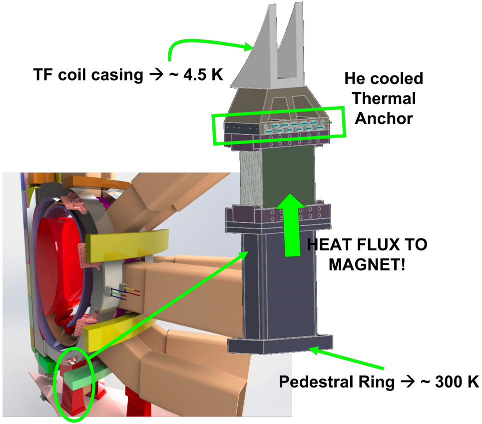
Necessity of an accurate TH model of the DTT TF GS

- The GS is a stainless steel structure which thermally connect the TF casing to the cryostat base $\rightarrow$ parasitic heat load to the magnet.
- This load is captured by means of an He cooled Thermal Anchor (TA).
- **The effectivness of the TA must be assessed and the parasitic heat load to the magnet must be evaluated.**



[A. Di Zenobio et al., FED 2017]

Necessity of reducing CPU cost, while preserving accuracy

- The DTT TF GS is a complex object and a 3D model seems to be required to accurately reproduce its behaviour.
- A full 3D model requires a massive amount of cells to properly describe the entire domain and must resolve heat diffusion equation in the solid domain and mass, momentun and energy conservation in the fluid one. $\rightarrow$ **Massive CPU cost.**
- On the contrary a simplified 1D model is not capable of accurately reproduce the thermal anchor and the temperature gradient along the TF casing connection.
- All of the above justify the development of a **coupled 3D+1D model for TH simulations**.

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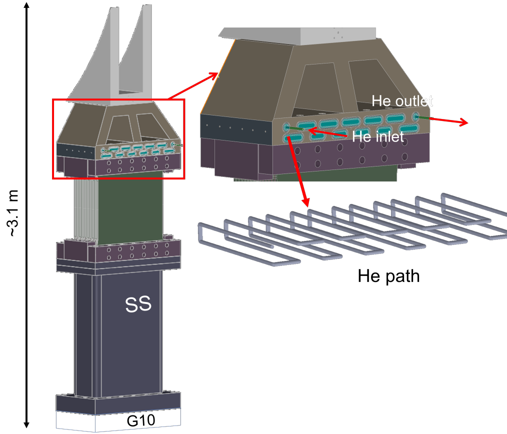
2 The DTT TF gravity support

Geometry and materials

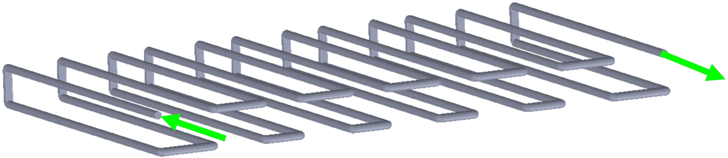
2 The DTT TF gravity support

- Coolant He path is drilled in the top part of the GS and the He flow is supposed to exhaust the largest possible fraction of the heat rising from the pedestral ring.
- The G10 support block is supposed to cooperate in the heat flux reduction due to its low thermal conductivity



Thermal Anchor detail

- Cooling pipe diameter $\rightarrow d_{in} = 1.0cm$
- Cooling pipe length $\rightarrow L \approx 11.4m$
- Helium is collected from the the TF CCCs outlet and directed to TA inlet $\rightarrow T_{in} \approx 6K$ and $\dot{m} \approx 10g/s$



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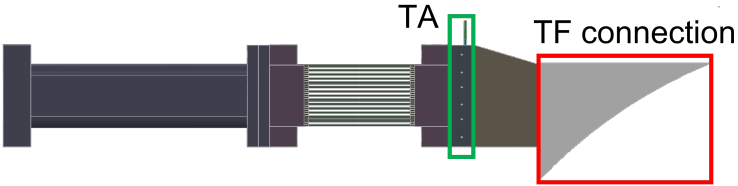
Simplified 1D model

As a first sight the entire GS can be considered as a 1D object in which the heat diffusion equation is solved along its axis. However this approach shows two **main weaknesses**:

- The thermal anchor (TA) must be approximated with an equivalent advective heat flux imposed on the external surfaces of the column.
- The TF connection must be approximated with an equivalent length which can not represent the real heat flux distribution on the TF connection surface.



Full 3D model

A detailed full 3D model has been developed here making use of the state-of-the-art CFD software **StarCCM+**. This model can overcome the weaknesses of the 1D model simulating in very detailed way both the thermal anchor and the TF connection.

To get such detailed results a price is paid $\rightarrow$ **very high computational cost given by**:

- Large number of cells required to mesh the entire domain
- Complexity of the equations to be solved within the liquid domain (**Mass, momentum and energy conservation**)

The full 3D model can be used as reference for the verification of the following model simplifications.

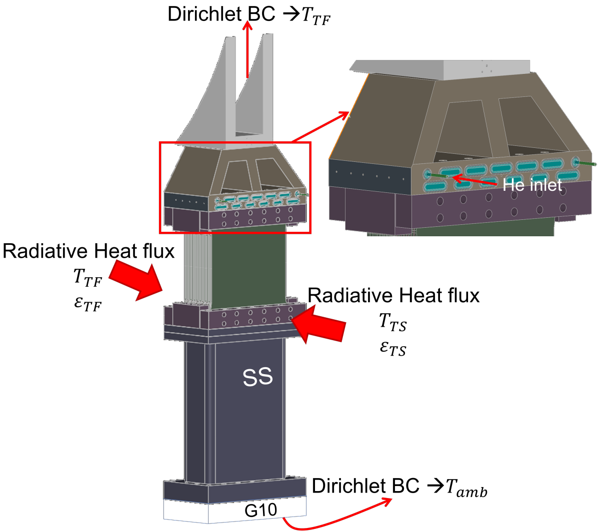
Full 3D model - Simulation setup

3 TH modelling of the DTT TF gravity support

Boundary conditions summary

Variable	Value	Unit
Inlet Temperature	6.0	K
Mass flow rate	10.0	g/s
Inlet pressure	6.0	bar
T_{TF}	4.5	K
T_{TS}	100.0	K
T_{amb}	300.0	K
ε_{TF}	1.0	-
ε_{TS}	0.05	-
ε_{GS}	0.15	-

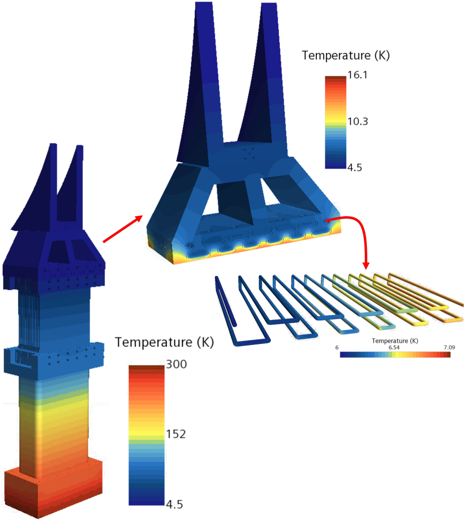
- All material properties have been considered **temperature dependent**
- Adopted turbulence model: $SST\ k-\omega$



Full 3D model - Results (I)

- The importance of the thermal anchor is highlighted by the very low power which is transmitted to the TF casing, compared to those directed to the cooling helium.
- Temperature increase of the helium and pressure losses are within the operating range of the cryoplant.

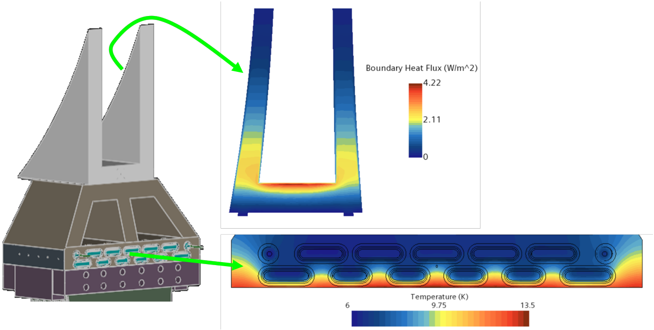
Variable	Value
P_{TF}	0.213 [W]
$T_{He,out}$	6.71 [K]
Δp	4.76 [kPa]
P_{He}	65.5 [W]



Full 3D model - Results (II)

Full 3D modeling allows to properly detect details not possible to be evaluated with simplified 1D models:

- Temperature non-uniformities in the thermal anchor region
- Heat flux non-uniformities on the TF casing connection



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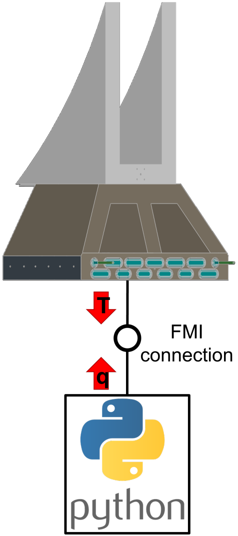
FMI standard: the base of the model

- The Functional Mock-up Interface (FMI) is a free standard which allows the communication between different tools dynamically exchanging simulation data. In this work FMI 2.0 standard has been used.
- This standard has been used to make **StarCCM+** communicate with another tool in which a simplified 1D model is developed.
- The 1D models have been developed in **python** making use of the pythonfmu library which has been used to built the communication with StarCCM+.

3D+1D solid model

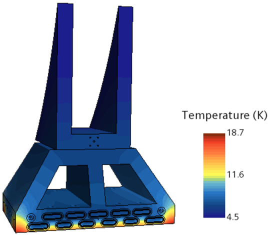
- The thermal anchor block and the connection with the TF casing are still modelled in **StarCCM+** $\longrightarrow$ allows to reproduce properly the non-1D nature of the TF connection and to consider carefully the heat removal by the thermal anchor.
- The remaining part of the GS is simulated by means of a simplified 1D model developed in **python** and based on **scipy** and **numpy** libraries.
- The 1D model solves the steady heat equation discretized with a **central finite difference scheme**, while the 3D one solves heat diffusion in solid and mass, momentum and energy conservation in the fluid.

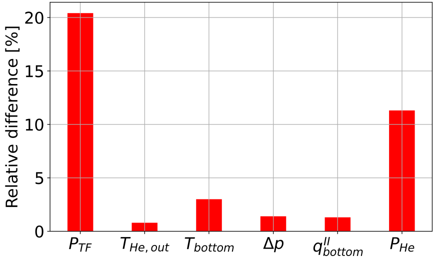


3D+1D solid model - Results (I)

The results obtained with the simplified 3D+1D model reproduce with good level of accuracy the reference one while reducing the computational cost!

Model	$P_{TF}\,[W]$	$T_{He,out}\,[K]$	$T_{bottom}\,[K]$	$\Delta p\,[kPa]$	$q^{II}_{bottom}\,\left[\frac{W}{m^2}\right]$	$P_{He}\,[W]$
Full 3D	0.214	6.71	13.9	4.76	195.0	65.5
3D+1D	0.257	6.76	14.3	4.83	197.6	72.9
Difference	$+20.4\%$	$+0.8\%$	$+3.0\%$	$+1.4\%$	$+1.3\%$	$+11.3\%$

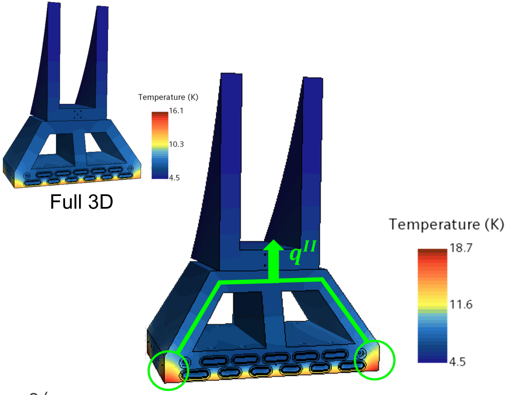


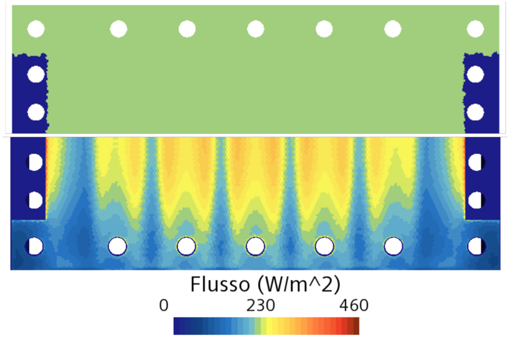


3D+1D solid model - Results (II)

4 Development of novel 3D+1D solid model

The slightly bigger discrepancy obtained on the power transmitted to TF casing is given by the hotter spots at block corner obtained with the 3D+1D model. This is due to the impossibility of such a model to impose an heat flux distribution on the block base.





3D+1D solid model - CPU time saving

Once demonstrated that the simplified model is capable of reproducing the reference results it is relevant to verify the CPU time saving obtained. The comparison has been done running the simulation on an *Intel® Xeon® Platinum 8160 CPU @ 2.10 GHz* using 48 cores.

Model	Number of cells	CPU time/iteration [s]
Full 3D	$11.6 \cdot 10^6$	3.9
3D+1D	$9.4 \cdot 10^6$	3.2
Saving	-19%	-17%

The CPU time reduction is almost proportional to the reduction of the number of cells, demonstrating the **effectiveness of the method**. By the way the saving is limited by the large amount of cells which are required to be used within the fluid domain $(6.3 \cdot 10^6\ cells)$. $\rightarrow$ **Interesting to develop simplified models for the fluid domain** (e.g. 3D+1D fluid model).

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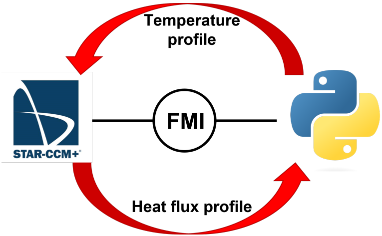
3D+1D fluid model - Required communication strategy updates

5 (Preliminar) Development of novel 3D+1D fluid model

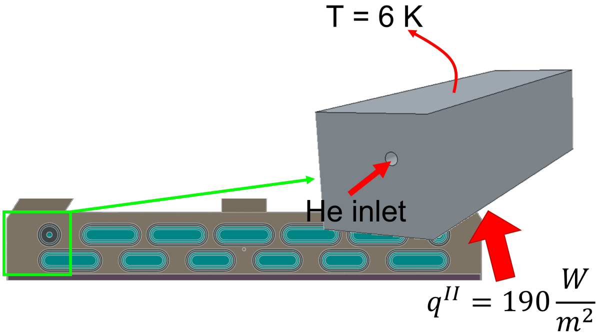
- The 3D+1D fluid model requires the exchange of quantities which are spatially distributed.
- From the numerical point of view this translates in the necessity of exchanging arrays, which is not possible with FMI 2.0 standard.
- For this reason the FMI link is used to develop a **file exchange logic**.



- Both Temperature profile and Heat flux profile are exchanged by means of a .csv file.
- Interpolation strategies are required in the 1D model to produce a 1D profile starting from 3D data coming from StarCCM+.

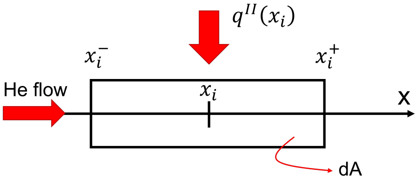
To assess the functionality of the developed model a preliminary test case has been extracted from the full problem.

- $T_{He,in} = 6.0\,K$
- $p_{He,in} = 6.0\,bar$
- Solid is modelled as a stainless steel block



Simplified fluid model

1. Reconstruction of the equivalent 1D heat flux profile along the pipe centerline (retrieved automatically from input geometry using **Slicer3D + VMTK**) through suitable interpolation of the local heat flux map computed in **StarCCM+**.
2. Evaluation of He bulk temperature profile $\rightarrow T(x_i^+) = T(x_I^-) + \frac{\int q^{II}(x_i)dA}{\dot{m} \cdot c_p}$

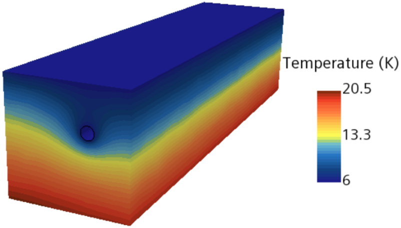


3. Evaluation of pipe surface temperature using HTC (from **Dittus-Boelter** correlation).
4. Mapping of the 1D surface temperature profile on the 3D domain

3D+1D fluid model - Results and Benchmark

The described simplified geometry has been simulated with this novel approach and results have been compared with those of a full 3D model used as a reference.

Variable	3D+1D fluid	full 3D	Difference
ΔT_{He}	$7.5 \cdot 10^{-2}\,K$	$7.8 \cdot 10^{-2}\,K$	$-3.8\,\%$
$q^{II}_{avg,up}$	$71.0\,W$	$71.5\,W$	$-0.7\,\%$
$T_{avg,down}$	$20.2\,K$	$20.2\,K$	$-0.1\,\%$



The selected test case is VERY simple, but results are very promising!

3D+1D fluid model - CPU time saving

Once demonstrated that the simplified model is capable of reproducing the reference results it is relevant to verify the CPU time saving obtained. The comparison has been done running the simulation on an *Intel® CORE(TM) i9-9900K CPU @ 3.60 GHz* using 1 cores.

Model	Number of cells	CPU time/iteration [s]	Total CPU time
Full 3D	$0.9 \cdot 10^6$	8.7	1535
3D+1D	$0.2 \cdot 10^6$	1.0	694
Saving	-78%	-87%	-55%

As expected the substitution of the fluid with a simplified model leads to impressive CPU time reduction

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6 Summary

Conclusions and perspective

Conclusions:

- Accurate TH modelling of DTT TF GS was required to evaluate the parasitic heat flux directed to the coil and to assess the effectiveness of the TA.
- This problem is, if solved with a full 3D model, very computational intensive, but there is space to reduce this cost!
- A methodology to develop a stable connection between **StarCCM+** and **python** via FMI 2.0 standard has been proposed here and applied to the analysis at hand.
- Both 3D+1D solid and 3D+1D fluid model have been developed and successfully tested.

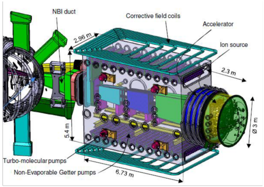
Perspective:

- Introduction of additional FMI links to furthermore reduce the requirements of cells in the 3D domain.
- Expand the 3D+1D fluid model to the real geometry.

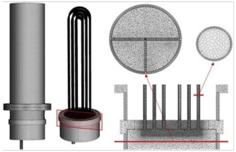
Some possible field of application in Nuclear Fusion

The developed model is generally applicable and it is not limited to the problem studied here. Here only few possible cases in which this model may be applied in the Nuclear Fusion field.

- DTT Neutral Beam Injection (NBI)
- Permeator Against Vacuum (PAV)
- DTT THermal Shield (TS)
- and many more



[R. Bonifetto et al.,Presented at SOFT 2022]



[E. Papa et al.,FED 2021]

Thank you for your kind attention!
Any questions?