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PRELIMINARY CALCULATION FOR PARAFFIN COOLING SYSTEM OF FCC-EE INTERACTION REGION VACUUM CHAMBER

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1 Introduction

This note aims to present the first conceptual design of the cooling system of the central part of the beam vacuum pipe of Interaction Region of the Future Circular Collider. The calculations of the heat transfer and flow dynamics of the coolant are reported.

2 Cooling system

The cooling system is made of two concentrical cylinders creating a gap of 1 mm for the paraffin flow.

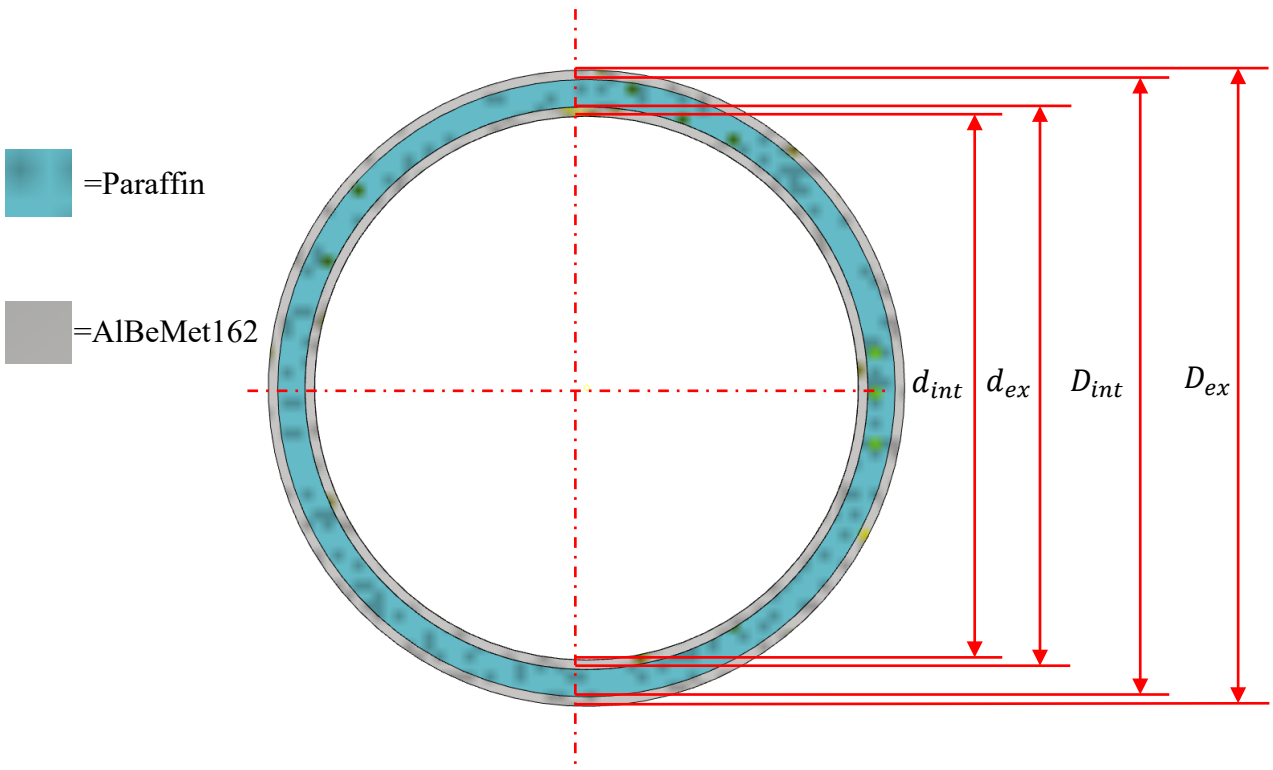


Figure 1-Cooling system (scale 10:1)

In the following table are reported the characteristic dimensions of the channel:

Symbol	Value	Unit of measurement	Description
$t_{paraffin}$	1	mm	Thickness of the gap, where paraffin flows
$t_{AlBeMet162}$	0.35	mm	Thickness of the AlBeMet162 wall
D_{ex}	22.4	mm	External diameter of the covering
D_{int}	21.7	mm	Internal diameter of the covering
d_{ex}	20.7	mm	External diameter of the beam pipe
d_{int}	20	mm	Internal diameter of the beam pipe
L	180	mm	Length of the exchanger

Table 1 - Main dimensions

The materials used in this system are the AlBeMet162, for the two cylinders, and the paraffin as coolant; the characteristics of each material adopted in the calculations are reported in the following tables [1] [2].

AlBeMet® is a family of metal matrix composites made up principally of beryllium and aluminum. The ratio of the two metals can be varied to alter the physical, thermal and mechanical properties.

AlBeMet162 contains 62 wt% commercially pure beryllium and 38 wt% commercially pure aluminum; it combines the high modulus and low-density characteristics of beryllium with the fabrication and mechanical property behavior of aluminum. These metal matrix composites are weldable, and can be formed, machined, and brazed like conventional aluminum metal matrix composites.

Properties	Values	Unit of measurement
Density	2.10	g/cm^3
Composition	Al-62 wt% Be	
Modulus	193	GPa
Poisson's Ratio	0.17	
CTE @ 25ºC	13.9	ppm/˚C
Thermal Conductivity	210	W/mK
Specific Heat @ 20˚C	1465	J/KgK
Electrical Conductivity @ 20˚C, % IACS	49	
Damping Capacity 25˚C, 500 HZ	1.5x10^{-3}	
Fracture Toughness K1c Ksi √in ()	11-23	MPa·√m

Table 2 - AlBeMet162 datasheet

Property	Value	Unit of measurement
Density @ 25ºC	0.734	g/cm^3
Specific Heat @ 20˚C	2.21	J/gK
Thermal conductivity	0.34	W/m°C
Kinematic viscosity @ 30˚C	1.1	mm^2/s
Dynamic viscosity @ 20˚C	0,92	mPa·s
Melting point	-27.9	˚C
Boiling point	174.1	˚C
Autoignition temperature	210	°C
Flash point	51	˚C

Table 3 - Paraffin (C10H22) datasheet

The central chamber has been drawn in Autodesk Inventor and it consists of the following part:

- Internal cylinder with a thickness of 0.35 mm
- External cylinder with a thickness of 0.35 mm
- 1 mm gap between the two cylinders
- Two manifolds, one per side, made in copper to create the inlet and outlet of the paraffin

Figure 2 - Central chamber with inlet and outlet

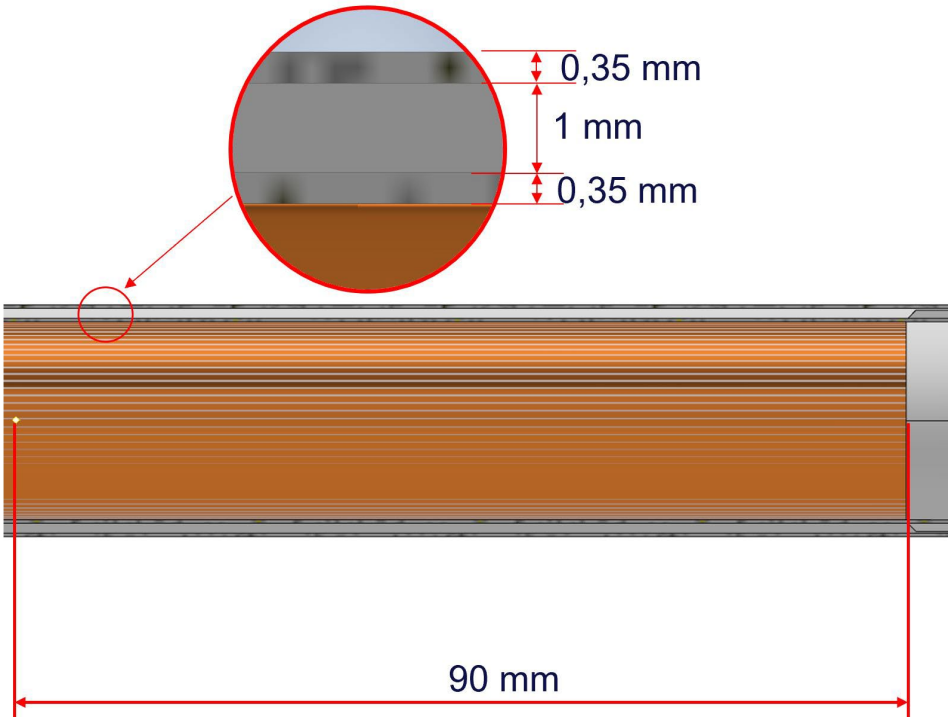
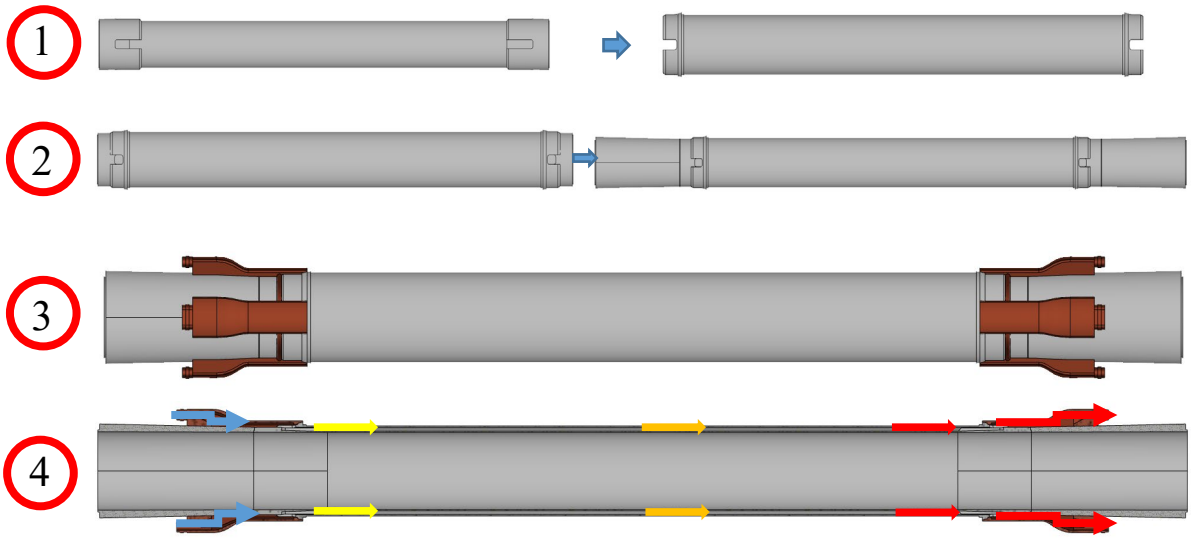


Figure 3-Central chamber layering

The manufacturing process follows these steps:

1. Insertion of the internal cylinder into the external one
2. Mounting and welding (EBW) the conical transition part
3. Creation of the inlet and outlet using the "*thick copper deposition*"

At point 4 the section explains the path of the paraffin flow.



3 Thermal calculation

The following schema shows the temperature distribution on a longitudinal section along the pipe's axis.

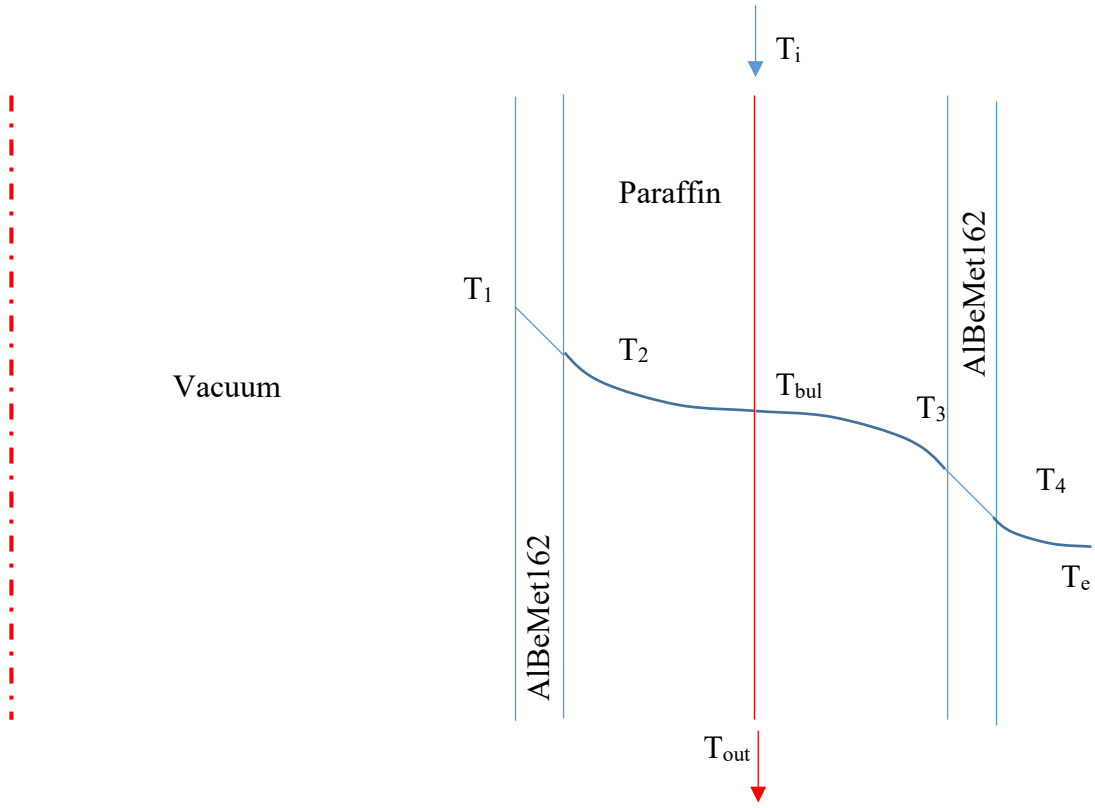


Figure 5 - Temperature diagram

To remove the heat produced by wake fields calculated using CST by Alexander Novokhatski [3], the paraffin flows into the annular gap of the beam pipe.

Considering CST calculation the heat load on the central chamber ($\dot{q}_{experiment}$) is 54W.

For a preliminary study, it is possible to make some hypotheses:

- Due to the small thickness of the AlBeMet162 and the high conduction of the material, it is possible to set the:

$$T_1 = T_2 \quad \text{(Eq.1)}$$

$$T_3 = T_4 \quad \text{(Eq.2)}$$

- It is possible to assume that:

$$T_{bulk} = \frac{T_{in} + T_{out}}{2} \quad \text{(Eq.3)}$$

- If the heat transfer with the external environment is neglected, it is possible to simplify the calculation considering the whole heat produced by the experiment received by the coolant.

In this study are used two values of the velocity of the fluid; the values are chosen to keep the pressure drop quite low and to be far from the turbulent condition.

The values of the velocity are:

Case	Velocity [m/s]	Reynolds number	Flow rate [kg/s]
A	0.3	545.2	0.015
B	0.5	909.1	0.025

Table 4-Velocity

The flow rate is calculated using the following equation:

$$\dot{m} = \rho v S \quad \text{(Eq.4)}$$

With:

- ρ: density of paraffin.
- v: velocity of paraffin.
- S: section of the gap, where paraffin flows

$$S = \pi \frac{D_{int}{}^2}{4} - \pi \frac{d_{ex}{}^2}{4} \quad \text{(Eq.5)}$$

The Reynolds number is calculated using the following equation:

$$Re = \frac{v D_{eq}}{\nu} \quad \text{(Eq.6)}$$

With:

- v: velocity
- D_{eq} : equivalent diameter
- ν: kinematic viscosity

For D_{eq} it is possible to use the following relation:

$$D_{eq} = 4\frac{A_{flow}}{p_{wet}} \quad \text{(Eq.7)}$$

Where:

- A_{flow} = area where the paraffin passes through
- p_{wet} = perimeter involved in the heat transfer with the paraffin

Developing the equation:

$$D_{eq} = 4\frac{\pi\frac{{D_{int}}^2}{4} - \pi\frac{{d_{ex}}^2}{4}}{\pi D_{int} + \pi d_{ex}} = \frac{{D_{int}}^2 - {d_{ex}}^2}{D_{int} + d_{ex}} = \frac{(D_{int} + d_{ex})(D_{int} - d_{ex})}{(D_{int} + d_{ex})} = D_{int} - d_{ex} = 2t_{paraffin}$$

It is possible to express the heat transfer from the paraffin side in terms of convection and temperature trend. The heat that the paraffin receives by convection is the cause of the temperature increase from the entry of the paraffin to its exit.

$$\dot{q}_{experiment} = hA(T_2 - T_{bulk}) \quad \text{(Eq.8)}$$

$$\dot{q}_{experiment} = \dot{m}c_p(T_{out} - T_{in}) \quad \text{(Eq.9)}$$

Where:

- h: convective heat transfer coefficient
- $A = 2\pi r_{ex}L$: convective area
- c_p: specific heat.
- $T_{in} = 18\ ℃$.

From equation 9, it is possible to calculate T_{out}:

$$T_{out} = T_{in} + \frac{\dot{q}_{experiment}}{\dot{m}c_p} \quad \text{(Eq.10)}$$

From T_{out} and T_{in} it is possible to calculate T_{bulk}using equation 3.

In the equation 8 the heat exchange coefficient h is derived by the following diagram [4] .

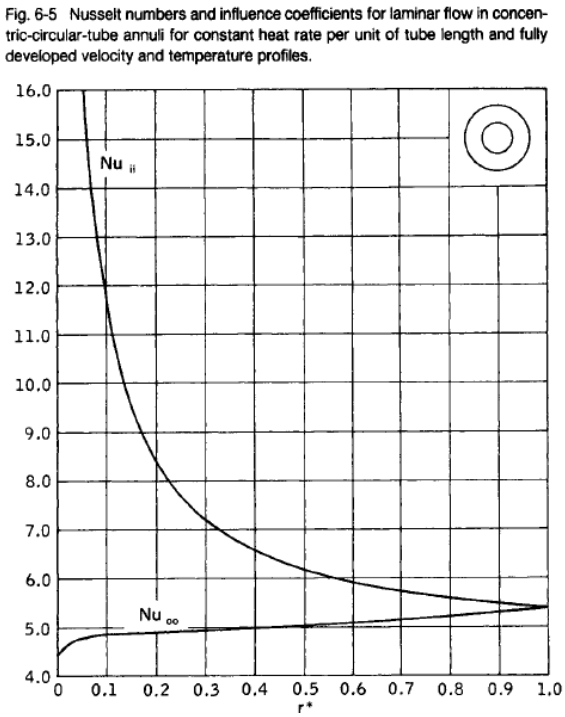


Figure 6 - Diagram from "Compact heat exchanger" written by W.M. Kays and A.L. London.

Entering with the radius ratio $r^* = \frac{r_{in}}{r_{out}}$ the Nusselt number is 5.45; using the following equation it is possible to calculate h:

$$h = \frac{Nu * k}{D_{eq}} = 903.9 \frac{W}{m^2 K} \quad \text{(Eq.11)}$$

Now it is possible to calculate T_2, using h, A and $\dot{q}_{experiment}$.
It is possible to calculate T_2:

$$T_2 = \frac{\dot{q}_{experiment}}{hA} + T_{bulk} \quad \text{(Eq.12)}$$

After the calculation, using the two different values of the velocity, there are different values for each temperature:

Case	A	B
Velocity	V=0.3 m/s	V=0.5 m/s
T_{out}[°C]	18.5	18.3
T_{bulk}[°C]	18.3	18.2
T_2[°C]	23.4	23.0

Table 5 - Temperature and velocity of paraffin

4 Pressure drop

For the calculation of the pressure drop, it's possible to use the following expression:

$$\Delta p = f \frac{L}{D_{eq}} \frac{v^2}{2} \rho \qquad \text{(Eq.13)}$$

It is necessary the friction factor (f); using another diagram [4] and entering with the radius ratio, it is possible to deduce the friction factor.

Fig. 6-4 Friction factors for fully developed laminar flow in concentric-circular-tube annuli.

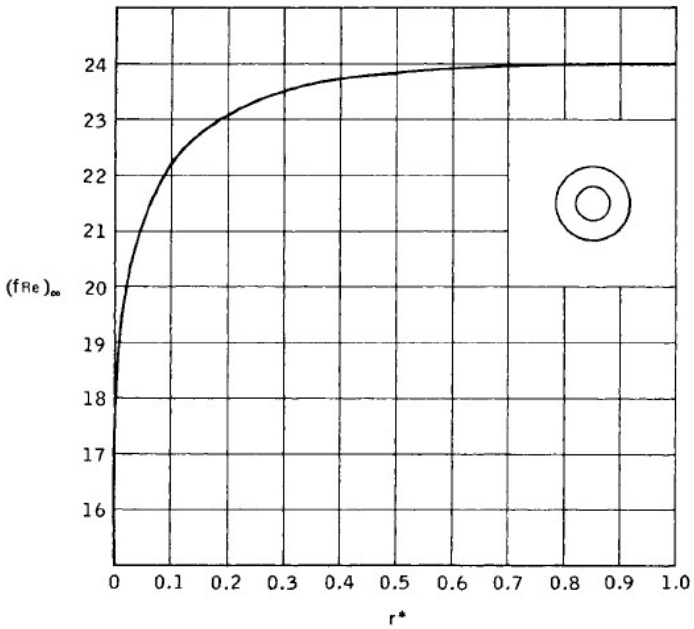


Figure 7 - Friction factor (f)

Using a $r^* = \frac{r_e}{R_i} = 0.954$ the friction factor is 24; now it is possible to calculate the pressure drop using the two velocities:

$$\Delta p_{v=0.3} = f \frac{L}{D_{eq}} \frac{v^2}{2} \rho = 24 \frac{0.180}{2 * 10^{-3}} \frac{0.3^2}{2} 734\ Pa = 71.34\ kPa$$

$$\Delta p_{v=0.5} = f \frac{L}{D_{eq}} \frac{v^2}{2} \rho = 24 \frac{0.180}{2 * 10^{-3}} \frac{0.5^2}{2} 734\ Pa = 192\ kPa$$

The case A pressure drop has been used for a structural simulation in Ansys Mechanical to check the mechanical resistance of the central chamber under this supplementary load. It has to be considered the extra-pressure needed for the circulation of the fluid into the circuit. In a future Technical Note this aspect will be deeply described.

5 Finite Element Analysis

In order to check the analytical calculation has been performed a thermal analysis using Ansys Mechanical.

5.1 Model

The model has been created importing into Space Claim the CAD file.

The solid has been meshed using shell element and the analysis performed is the "*Steady-State Thermal*".

The paraffin as "*thermal fluid"* has been created using a beam with the cross section given by the geometry of the channel. The mass flow has been assigned using the "*Mass Flow Rate"* block and the initial temperature of the paraffin imposed using the *"Temperature"* block.

In the same way of the analytical calculations, the heat transfer with the external environment is neglected and have been considered the same parameters used previously in the case A (v=0.3 m/s).

Parameter	Symbol	Value
Initial paraffin temperature	$T_{in\_paraffin}$	18 $°C$
Paraffin convective coefficient	$h_{paraffin}$	903.9 $\frac{W}{m^2K}$
Paraffin flow rate	ṁ	0.015 $\frac{kg}{s}$
Heat from wake field calculation	$\dot{q}_{experiment}$	54W

5.2 Results

Performing the Steady-State Thermal it is possible to calculate the temperature distribution of the central chamber.

The results are the following:

	Symbol	Value
Chamber maximum temperature	$T_{max-chamber}$	23.07 °C
Paraffin temperature at the exit	$T_{\text{out}-\text{paraffin}}$	18.76 °C
Chamber mean temperature	T_2	22.6 °C

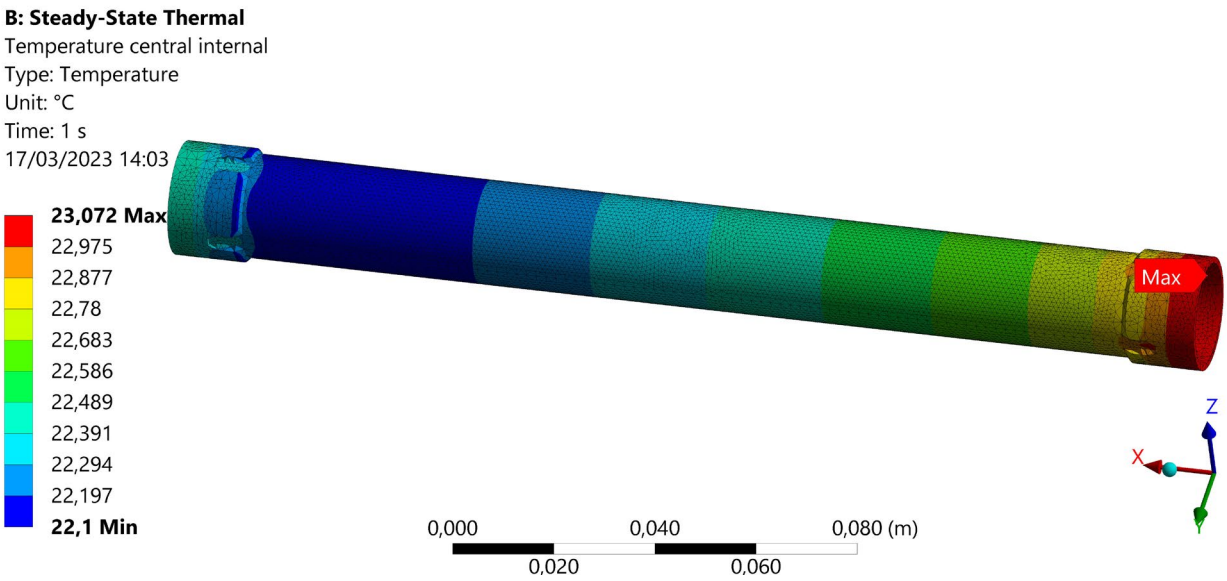


Figure 8-central chamber temperature distribution

6 Comparison and conclusion

It is possible to sum up the results obtained using the two different approaches. The analytical approach gives a mean value of the wall chamber temperature, therefore this value is compared with the mean value from the FEA.

	Symbol	Analytical result	FEA result	Difference
Chamber maximum temperature	$T_{max-chamber}$		23.07 °C	
Paraffin temperature at the exit	$T_{\text{out}-\text{paraffin}}$	18.5 °C	18.76 °C	0.26 °C
Chamber mean temperature	T_2	23.4 °C	22.6 °C	0.8 °C

The results obtained using two different approaches are concordant; the analytical approach overestimates the wall chamber temperature but the difference is not relevant.

A fluid dynamic simulation could increase the level of detail of the simulation as well as the validation of the system with a prototypes is necessary in the next future. The design of the pumping system for the paraffin have to be paired with the prototyping activity.

7 Bibliography

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[3] A. Novokhatski, «FCC-ee MDI: Trapped Modes and Other Power Losses,» *JACoW Publishing,* 2022.

[4] A. L. W.M. Kays, Compact heat exchanger.