Natural Heat Transfer Performance of Helium Filled Spent Fuel Multi Purpose Container Calculated for Different Initial Pressures

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ABSTRACT

The simple model of helium filled Holtec's Multi Purpose Container (MPC) for 37 spent fuel assemblies was developed and the calculation was performed using the Ansys Fluent code in steady state. The flow and temperature distribution within the MPC was calculated for different initial helium pressures, and for limiting cask heat loading found in the NPP Krsko SFDS (Spent Fuel Dry Storage) campaign number 1. The determined relationship between helium top to bottom temperature increase and helium pressure decrease can be used as a measure of cask leakage. In addition, lateral temperature distribution in the top MPC plenum, influenced partially by different spent fuel assembly loading, should be checked as a cause for temperature variation at the MPC external top surface, where RTD (Resistance Temperature Detector) detectors are installed.

Keywords: *Spent fuel dry storage, MPC internal natural circulation, helium pressure, Fluent*

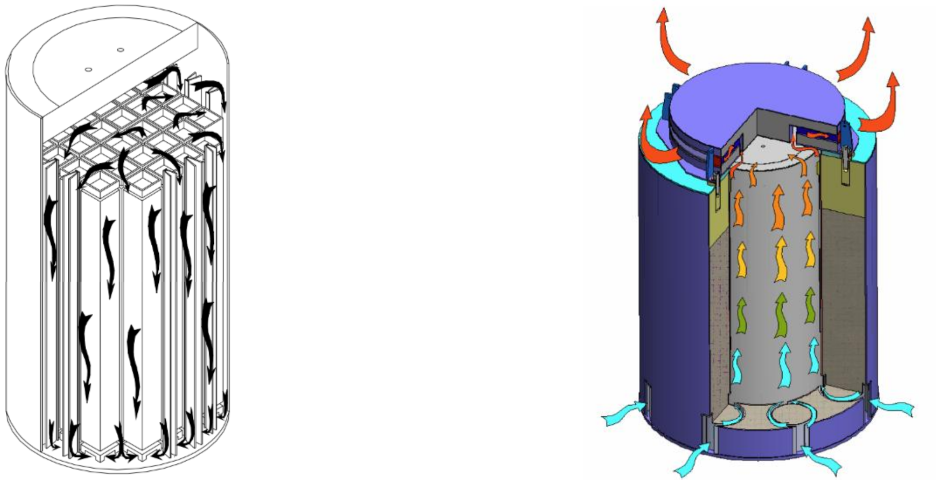
1 INTRODUCTION

Nuclear Power Plant Krško decided to store its spent fuel in the Spent Fuel Dry Storage (SFDS). The SFDS consists of a Dry storage building (DSB) which may house up to 70 HI-STORM storage casks and HI-TRAC transfer cask is used for transferring the spent fuel from the spent fuel pool to the DSB. The fuel is placed in an interchangeable Multi-Purpose Container (MPC) which can fit both HI-STORM and HI-TRAC. The spent fuel transfer to the DSB is divided into four loading campaigns. In the first loading campaign, which was in 2023, 592 spent fuel assemblies were transferred. The second loading campaign is expected to start in 2028 during which another 592 spent fuel assemblies will be transferred [1].

MPC is a stainless-steel structure which can house up to 37 spent fuel assemblies. The fuel is inserted into a METAMIC-HT basket supported by aluminium shims. After being filled with spent fuel and dried out, the MPC is sealed with a welded lid to form a confinement boundary and backfilled with helium to the design-basis pressures. The MPC basket has flow holes at the bottom to ensure helium circulation. Helium is an inert gas, so it provides stable environment for long-term storage of the spent fuel and it ensures passive heat transfer from the spent fuel to the MPC. The heat transfer within MPC and when canister is inserted in HI-STORM cask is shown in Figure 1. Heat generated within the spent fuel rods is transferred by conduction from the inner wall to the outer wall of the cladding. The outer wall of the cladding is in contact with helium, therefore natural convection occurs as helium heats up. The heated helium rises within square storage cells towards the top of the MPC, transfers part of the heat to the top of the MPC (top lid) and descends towards the bottom of the MPC through a downcomer formed by a basket outer surface and an MPC wall inner surface. The heat that reaches the inner side of the MPC wall is transferred by conduction to the outer surface of the MPC. The air removes heat from the MPC outer side by natural convection. Except for natural convection and conduction, radiation heat transfer also occurs, but to a lesser extent, therefore it is often neglected in normal operating conditions [2].

Since helium plays a vital role in the thermal performance of the MPC, it should be retained within the MPC and not diluted by the air ingress (air has lower thermal conductivity and it is not inert gas). Therefore, it is important to have a means to detect the situation caused by possible helium leakage [3].

In this paper, the simple model of helium filled Holtec's MPC for 37 spent fuel assemblies was developed and the calculation was performed using the Ansys Fluent code in steady state. The flow and temperature distribution within the MPC was calculated for different initial helium pressures, and for limiting cask heat loading found in the NPP Krsko SFDS campaign number 1. The obtained relationship between helium top to bottom temperature increase and helium pressure decrease could be used as a measure of cask leakage. In addition, lateral temperature distribution in the top MPC plenum, influenced partially by different spent fuel assembly (FA) heat loading, should be checked as a cause for temperature variation at the MPC external top lid surface, where upper RTD (Resistance Temperature Detector) detectors are installed.



MPC HI-STORM

Figure 1: Passive cooling of MPC and HI-STORM storage cask

2 METHODOLOGY DESCRIPTION

2.1 Ansys Fluent

Ansys Fluent is a general-purpose computational fluid dynamics (CFD) software used to model fluid flow, heat and mass transfer, chemical reactions, and similar processes. We used release 2020R2 of the code [4]. Fluent is known for its advanced physics modelling capabilities, which include turbulence modelling, single and multiphase flows, combustion, battery modelling, fluid-structure interaction, and much more. Also known for its efficient HPC (High Performance Computing) scaling, large models can easily be solved in Fluent on multiple processors on either CPU (Central Processing Unit) or GPU (Graphical Processing Unit). Multiple solver options are available, including pressure-based and density-based solvers to cover low-speed to hypersonic flows.

Ansys Fluent uses finite volume method (FVM) to solve complex engineering problems. The modeling method includes three phases

1. **Pre-process:** Define the physics and real-world conditions to be used in the model.
2. **Mesh and Solve:** Divide the object into finite volumes via meshing and apply the relevant physics representations and/or equations to each element. Then assemble the equations and solve them.
3. **Post-process:** Compute results to analyze and interpret implications for the whole domain.

2.2 MPC Modelling in Ansys Fluent

The model developed for the evaluation of the thermal performance of the MPC consists of the MPC body, basket, shims and spent fuel assemblies as shown in Figure 2. MPC is an empty cylinder with top and bottom lid. The outer diameter of the MPC is about 1.9 m and shell thickness is about 1.3 cm. Bottom and top lid thicknesses are about 7.6 cm and 22.9 cm, respectively. The basket is placed at the bottom of the MPC. It has 37 positions (square cells) for the spent fuel assemblies. Each location has flow holes at the bottom of the basket to ensure natural circulation of helium. The basket is supported at the periphery by aluminium shims, of the different shape, which increase the lateral thermal conduction transfer toward the MPC wall and ensure stability of the basket.

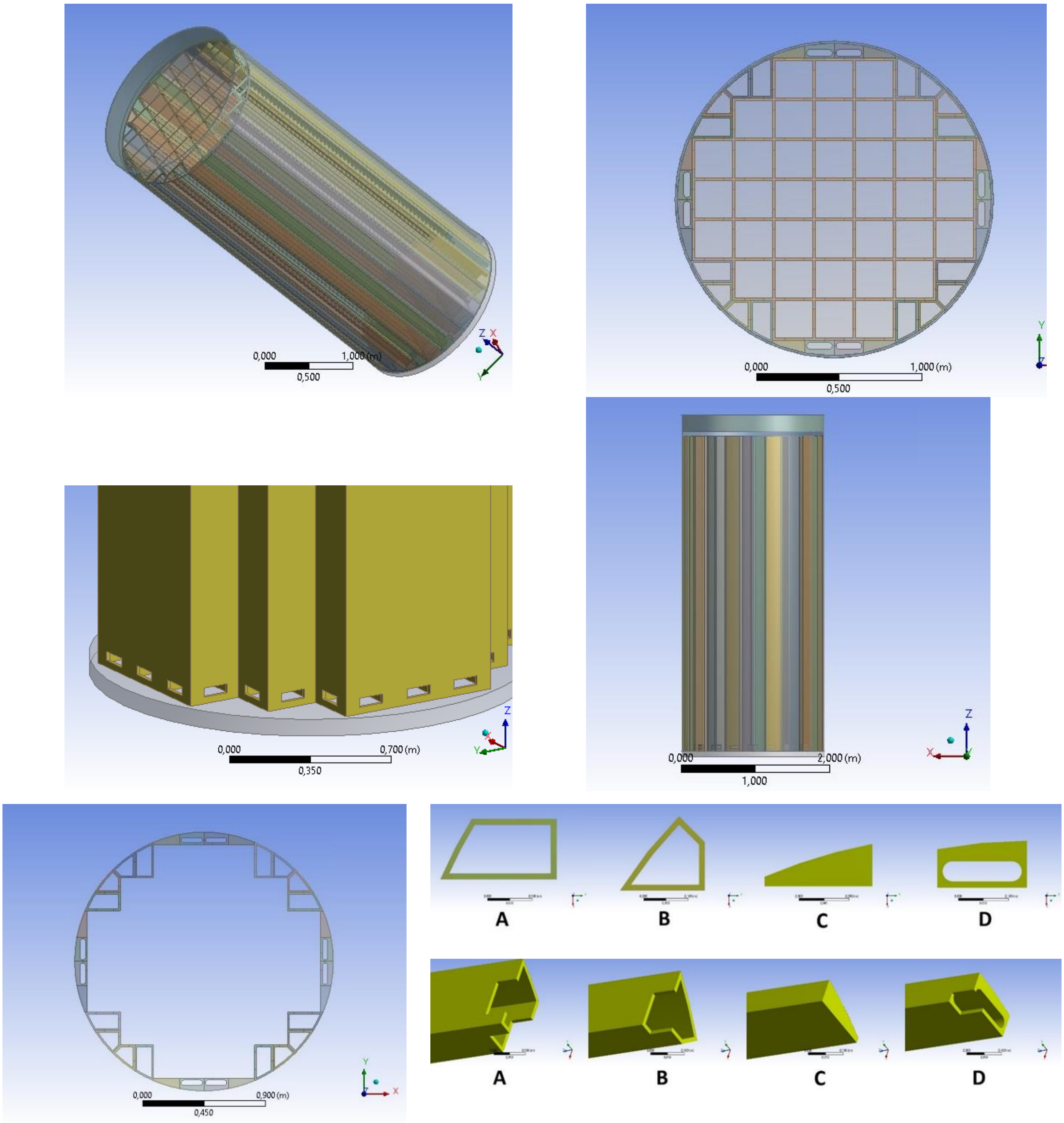


Figure 2: MPC model in Ansys

2.3 Assumptions and settings

Spent fuel assemblies that are placed in the MPC are the NPP Krško 16x16 fuel assemblies with 235 fuel rods, 20 guide tubes for control rods, and 1 instrumentation guide tube [5]. Two modelling approaches were used in this research study. The first one is an explicit model which is based on a model of each fuel rod in a fuel assembly (Figure 3). The rod diameter is 9.5 mm, height 3.66 m, and the distance between the fuel rod centres is 1.2 cm. In this model, guide tubes, distance lattice and upper and lower nozzle were neglected. This model is more complex, and calculations are computationally demanding. The other spent fuel assembly model is based on the thermal equivalent cylinder (Figure 4). This model is simplified in a way that instead of 235 fuel rods, one rod is modelled representing all 235 fuel rods (r_1), with the equivalent radius (r_{eq}) of 7.3 cm calculated using the Equation 1. That way flow cross section of the channel is preserved, but heat transfer surface area is underestimated (affects both pressure drop and temperature of the cylinder).

$$r_{eq} = \sqrt{r_1^2 \cdot n} \tag{1}$$

The following assumptions were made regarding material assignment. MPC bottom and top lid, and body were modelled as stainless steel, while basket, inserts and fuel rods were assumed to be made of aluminium. Although fuel rods are made of uranium and cladding is made of Zircaloy, the assumed aluminium, having good thermal conductivity, is used to compensate for the reduced heat transfer surface area in the equivalent model. The rest of the free space within the MPC is filled with helium. The material properties are standard material properties widely used in technical literature, provided in Table 1.

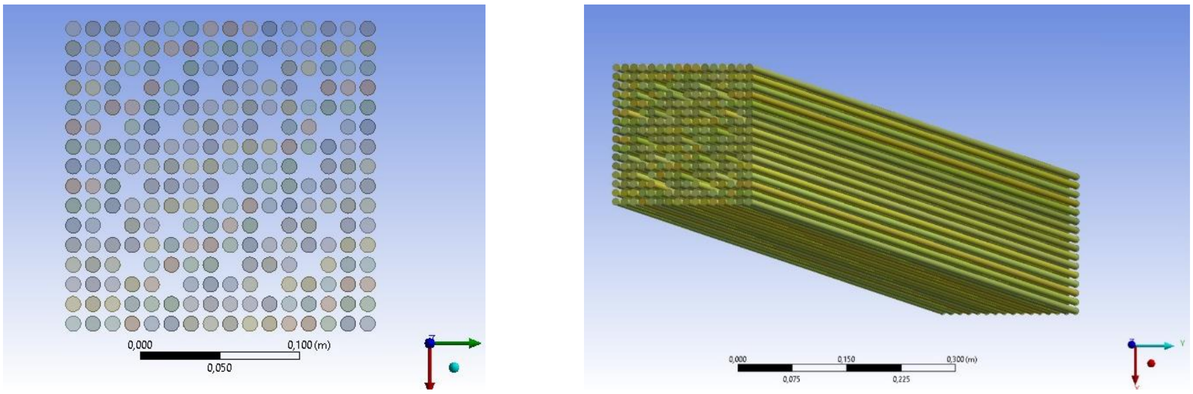


Figure 3: NPP Krško fuel assembly explicit model in Ansys

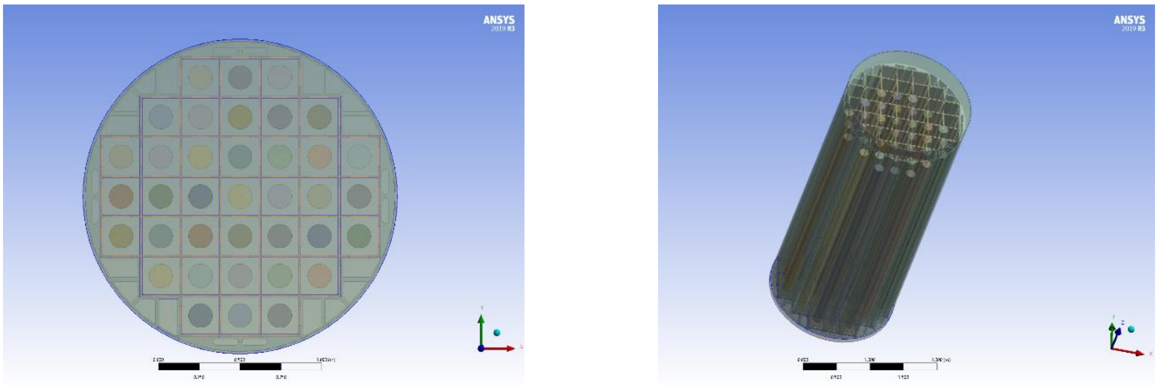


Figure 4: MPC geometry with fuel assembly equivalent model in Ansys

Table 1: Material properties

Material	Density $\left[\frac{kg}{m^3}\right]$	Thermal conductivity $\left[\frac{W}{mK}\right]$
Helium	Ideal gas	0.152
Aluminium	2719	202.4
Stainless steel	8030	16.27

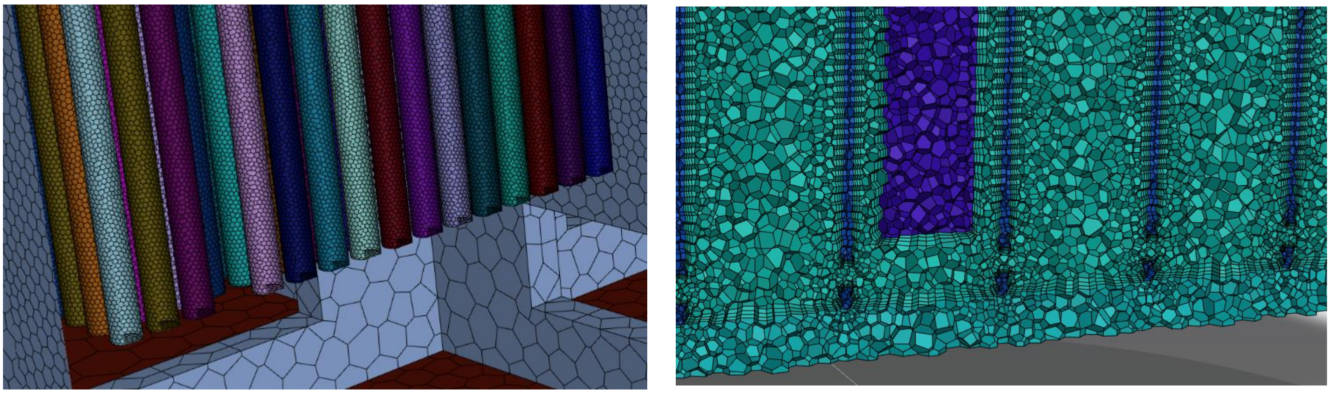
The following settings were used for the heat transfer simulation [6]:

- Steady state (pseudo transient) solver
- Gravity is taken into account
- Turbulent fluid flow (k-epsilon SST model)
- The initial temperature of helium is 293 K, and the initial pressure of helium is 4 bar, the properties are temperature dependent (full density model)
- Volumetric heat generated within fuel element is set to 11,287 kW/m^3 (one fuel element produces 687 W, for 37 fuel elements that is 25.4 kW)
- Fixed temperature of 293 K at the bottom of the MPC bottom lid
- Ambient temperature is 293 K
- Assumed convective heat transfer coefficient on the outer surface of the top lid 5 $\frac{W}{m^2K}$ and on the outer surface of the MPC body 10 $\frac{W}{m^2K}$.

3 RESULTS

3.1 Explicit and equivalent model

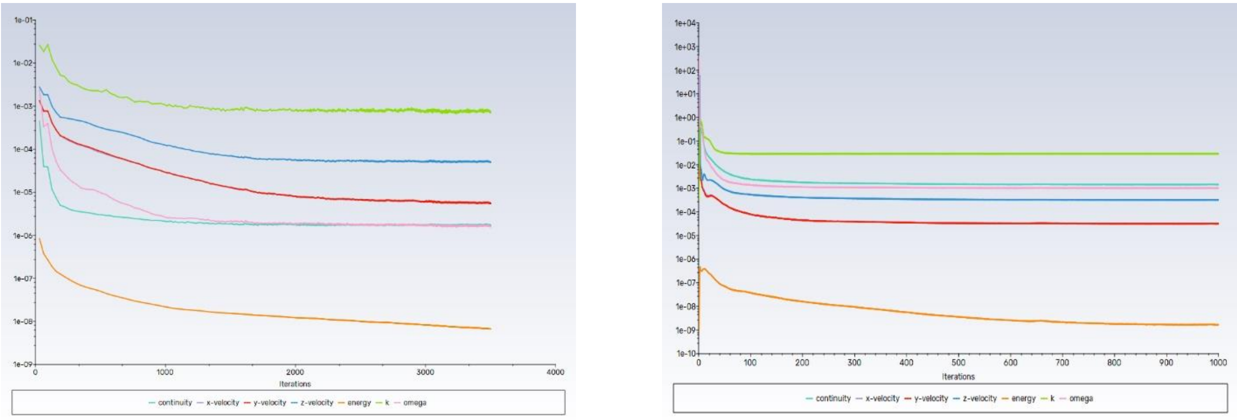
As already mentioned, Ansys Fluent is a FVM based code, therefore the selection of the mesh size is an important part of the calculation. The larger mesh size means more accurate results, but at the expense of longer CPU time and more computational resources. The surface and volume mesh for the lower part of the MPC with the explicit and with the equivalent fuel assembly model are shown in Figure 5. Comparing the sizes of the two models, for only one spent fuel assembly at the central position, about 3 times larger number of mesh elements was needed for the explicit model. The number of cells, faces and nodes for MPC with single equivalent fuel assembly are: 9816064, 63423309 and 51485378, respectively. The convergence of the calculation is shown in Figure 6 for the explicit and equivalent model. The number of iterations performed was 3500 for the explicit model and 1000 for the equivalent model. Due to the less complicated geometry, the solution of the equivalent model converges faster. Figure 7 shows axial temperature distribution for the explicit and equivalent model for the central vertical plane. The maximum temperature in the explicit model is 334 K, and in the equivalent model 329 K, for the same heat load. The smaller heat transfer area in the equivalent model is more than compensated by high thermal conductivity of the aluminium. That is the reason for higher gas temperatures in internal subchannels of the explicit model. The temperature distribution of the fuel assembly in the explicit case is closer to the real case. Local temperature distribution at the MPC top lid surface is shown in Figure 8. The maximum temperature is 302 K and the temperature distribution is almost equal in both cases. Therefore, the equivalent model is good enough for the calculation of temperatures on the outer surfaces of the MPC. Flow velocity distribution is shown in Figure 9. In the explicit model the highest velocities are in the guide tubes and in the equivalent model the highest velocities are around the fuel assembly simulator surface. Due to slightly lower pressure drop in case of the equivalent model, the maximum velocities are higher than in the explicit model.



a) Explicit FA model (surface mesh)

b) Equivalent FA model (volume mesh)

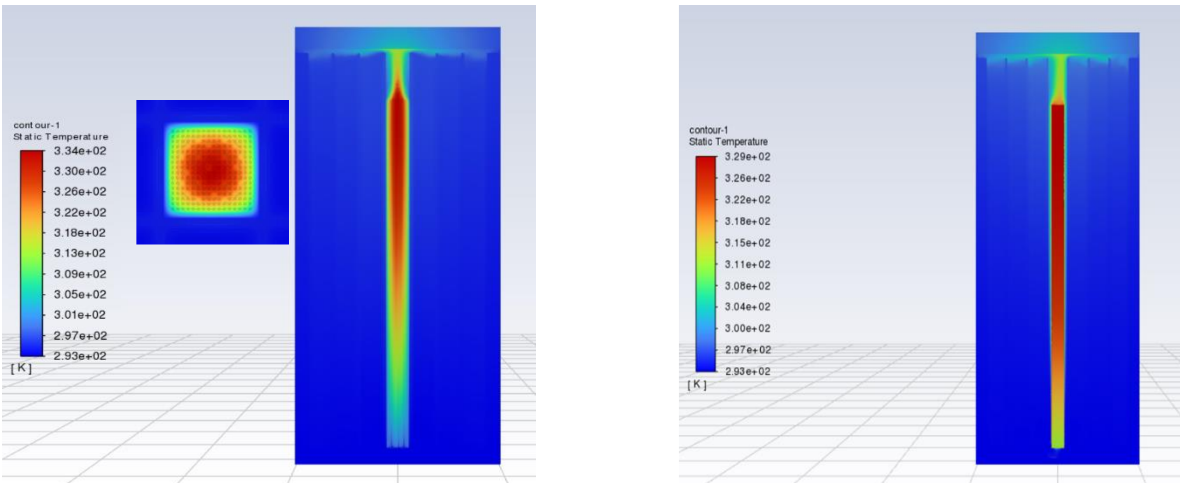
Figure 5: Surface and volume meshes of the MPC bottom



a) Explicit FA model

b) Equivalent FA model

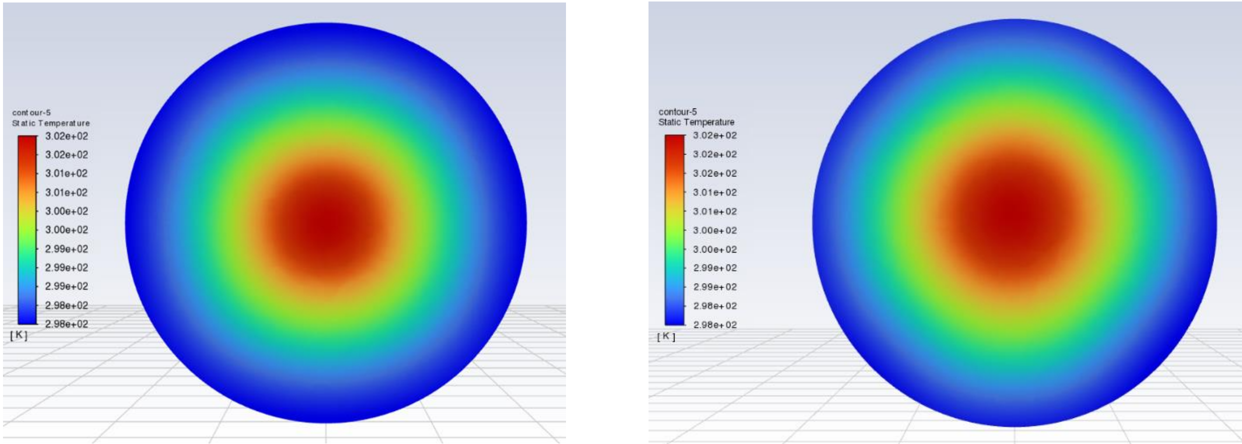
Figure 6: Convergence of the calculation



a) Explicit model

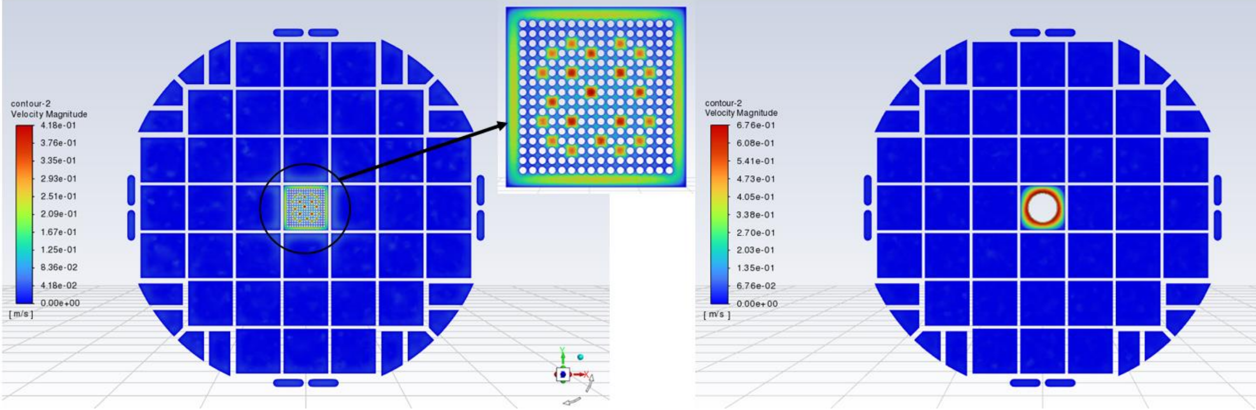
b) Equivalent model

Figure 7: Temperature distribution for a) explicit model, and b) equivalent model



a) Explicit model b) Equivalent model

Figure 8: Local temperature distribution at the MPC top lid surface a) explicit model, and b) equivalent model



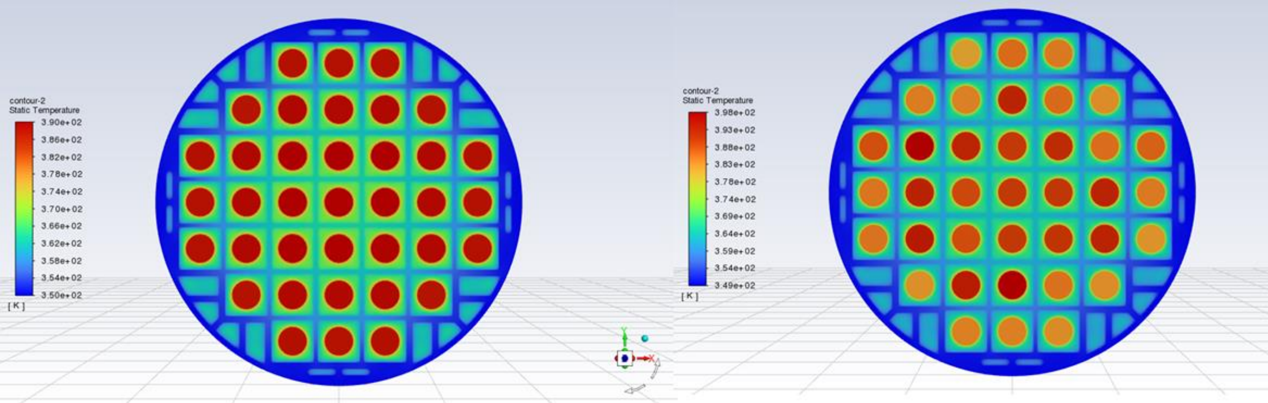
a) Explicit model b) Equivalent model

Figure 9: Flow velocity distribution at height of 2 m for a) explicit model, and b) equivalent model

3.2 Different heat source distribution

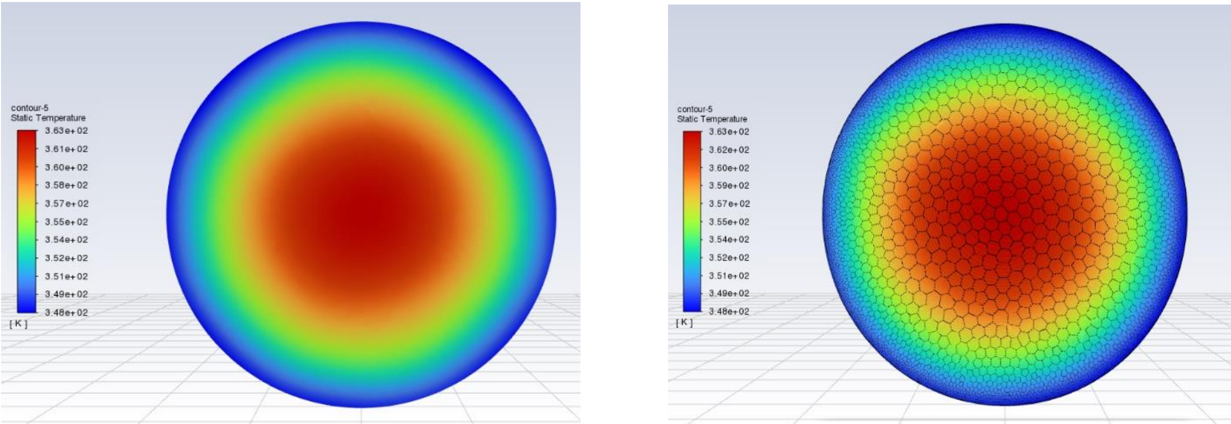
In this section, we compare results for different heat source distributions and all storage cells populated with equivalent FAs. Uniform and non-uniform power distributions are considered. Uniform distribution means that fuel assemblies have equal heat source intensity. Non-uniform distribution means that each fuel assemblies has its own (real) heat source intensity. In both cases the total heat source is 22.17 kW. For the uniform distribution it means that each fuel assembly releases 599 W of thermal power.

Figure 10 and Figure 11 show radial temperature distribution (local scaling) at height of 2 m and at the top of the MPC. Non-uniform temperature distribution is clearly indicated on the former, however from the latter it is obvious that the temperature distribution at the top of the MPC is almost equal in both cases. Therefore, non-uniform source distribution has no significant influence on the temperature distribution at the top of the MPC and simplified averaged heat source distribution can be used.



a) Uniform b) Non-uniform

Figure 10: Radial temperature distribution at 2 m a) uniform, and b) non-uniform FA powers

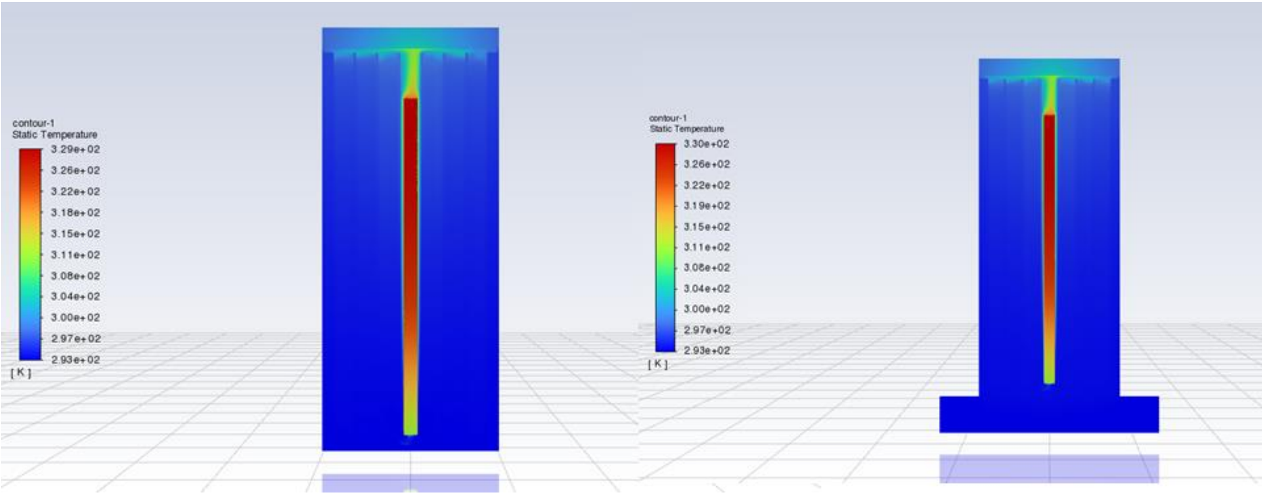


a) Uniform b) Non-uniform

Figure 11: Local temperature distribution at the MPC top lid a) uniform, and b) non-uniform FA powers

3.3 Influence of concrete base

When placed in a cask, MPC will be at the HI-STORM concrete base. Therefore, a model with concrete base was developed to investigate its influence (reduced bottom heat transfer) on the temperature distribution. The base is 0.5 m thick, and the bottom is fixed at 293 K, while the side is insulated. Convective heat transfer coefficient of 10 $\frac{W}{m^2K}$ is assumed for the side of the MPC and of 5 $\frac{W}{m^2K}$ for the top of MPC and the concrete base. The simulation is done for a single equivalent fuel assembly. Temperature distribution is shown in Figure 12. The maximum temperature without a base is 329 K, and with a concrete base it is 330 K. The temperature distribution is equal and there is no influence on the maximum FA temperature, but there are differences in the transferred heat in the upper and lower part (lower transfer in lower part when temperature is specified at concrete base bottom).

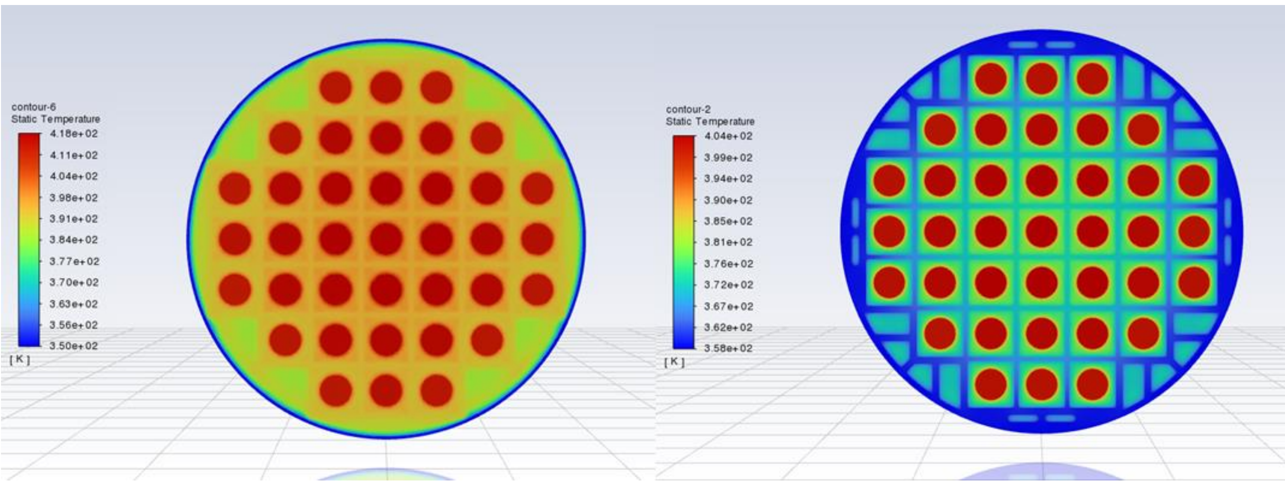


a) without a base b) with a concrete base

Figure 12: Temperature distribution a) without a base, and b) with a concrete base

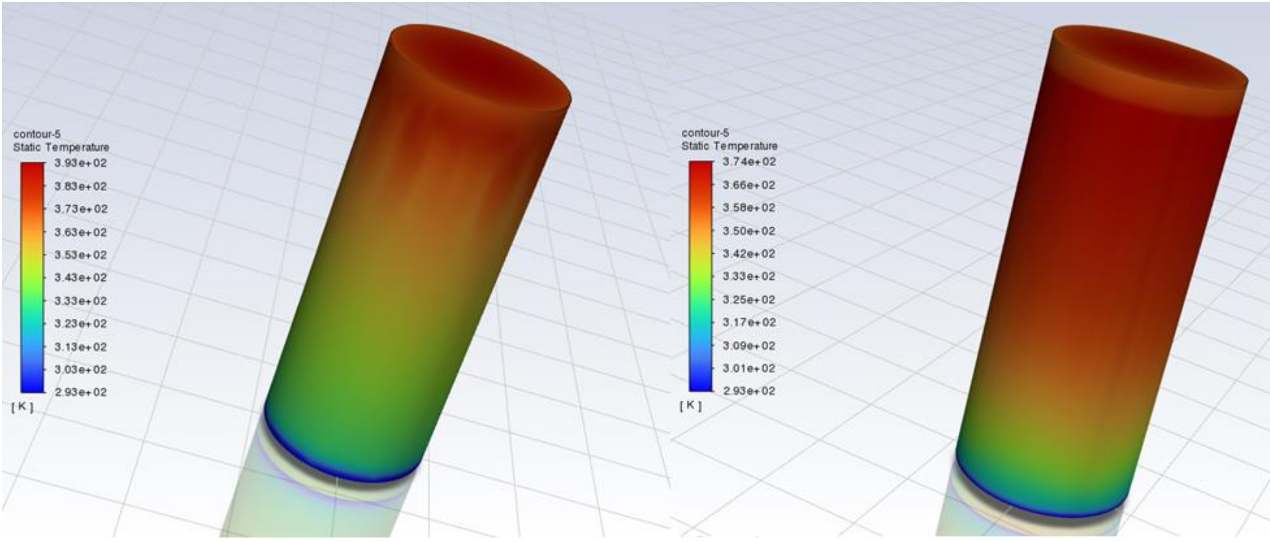
3.4 Influence of aluminium inserts

The basket is supported against MPC wall with aluminium inserts. Their influence on the temperature distribution is presented in this section. Radial temperature distribution (local scaling) at a height of 2 m is shown in Figure 13. The maximum temperature without inserts is 418 K, and with inserts 404 K. Lower helium temperature is observed for the model with inserts because more heat is removed by conduction through the inserts. Due to the higher thermal conductivity of aluminium than helium, the maximum temperature is lower in the model with inserts. Figure 14 shows the temperature distribution on the MPC surface. The maximum temperature is reached at the top of the MPC and it is 393 K when there are no inserts and 374 K with inserts. It can be observed that a larger area of high temperatures on the MPC mantle is observed in the case with inserts due to the high thermal conductivity of aluminium inserts. Helium flow velocity is shown in Figure 15. A larger region of higher peripheral flow velocities is observed in the case without inserts because more heat is removed by convection. The maximum absolute gas velocity is obtained in case with inserts due to smaller flow cross section area.



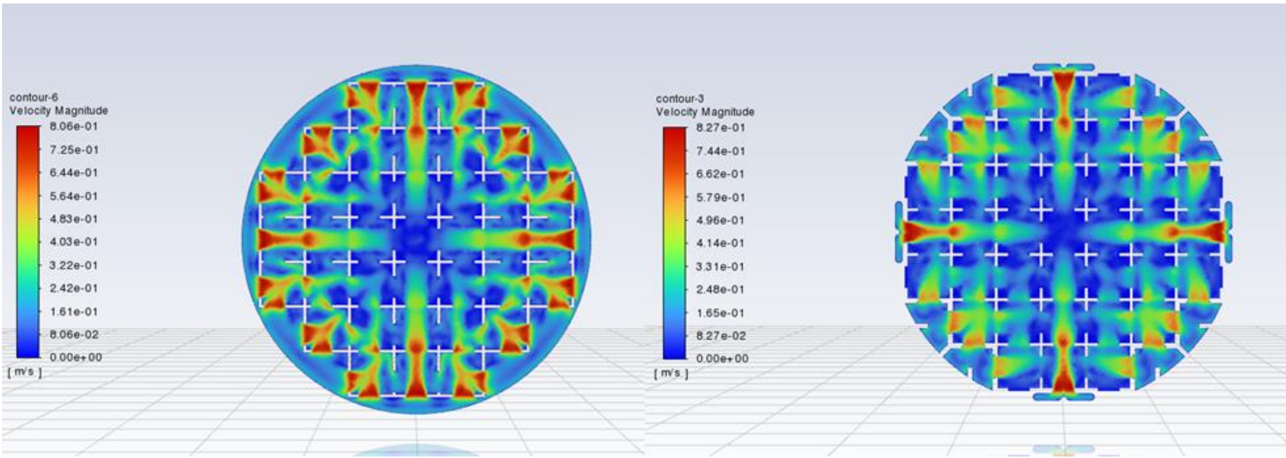
a) without inserts b) with inserts

Figure 13: Radial temperature distribution at height of 2 m a) without inserts, and b) with inserts



a) without inserts b) with inserts

Figure 14: Temperature distribution on the surface of the MPC a) without inserts, and b) with inserts

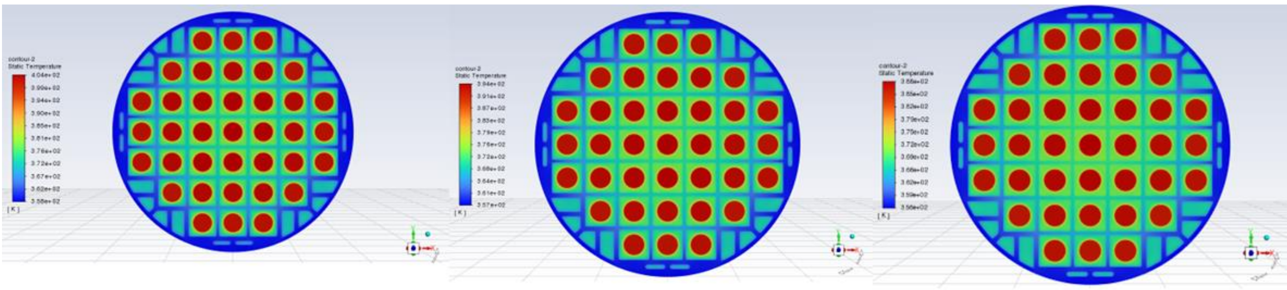


a) without inserts b) with inserts

Figure 15: Helium flow velocity at height of 0.05 m a) without inserts, and b) with inserts

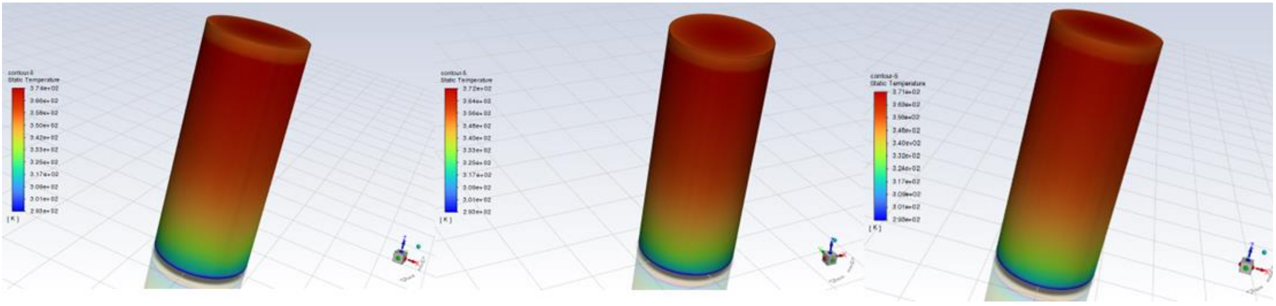
3.5 Different fill pressure

The reference pressure in MPC is 4 bars and the limiting pressure is 8 bars, therefore in this section we provide results for different helium fill pressures, ie. the reference pressure, the limiting pressure and one value in between the two (6 bars). Radial temperature distribution (local scaling) at height of 2 m for the pressure of 4, 6, and 8 bars is shown in Figure 16. The maximum temperatures at 4, 6 and 8 bars are 404 K, 394 K, and 386 K, respectively. It can be observed that the temperature distribution is similar in all cases. Figure 17 shows temperature distribution on the surface of the MPC. The maximum temperatures are 374 K for 4 bars, 372 K for 6 bars, and 371 for 8 bars. As the pressure increases, both the maximum fuel temperature (to a greater extent) and the maximum temperature on the outer surface of the MPC (to a lesser extent) decrease. The higher the pressure, the more efficient the cooling is. Helium velocity is shown in Figure 18. Lower maximum flow velocity is observed at higher pressure due to smaller temperature difference and larger density (mass) of helium present.



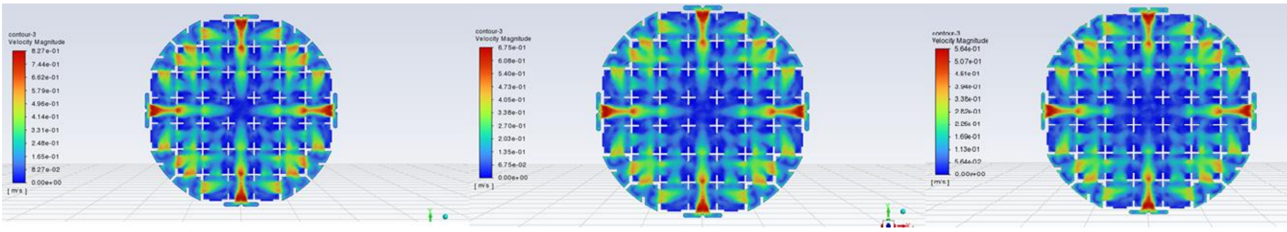
a) 4 bars b) 6 bars c) 8 bars

Figure 16: Radial temperature distribution at height of 2 m for the pressure of a) 4 bars, b) 6 bars, and c) 8 bars



a) 4 bars b) 6 bars c) 8 bars

Figure 17: Temperature distribution on the surface of the MPC a) 4 bars, b) 6 bars, and c) 8 bars

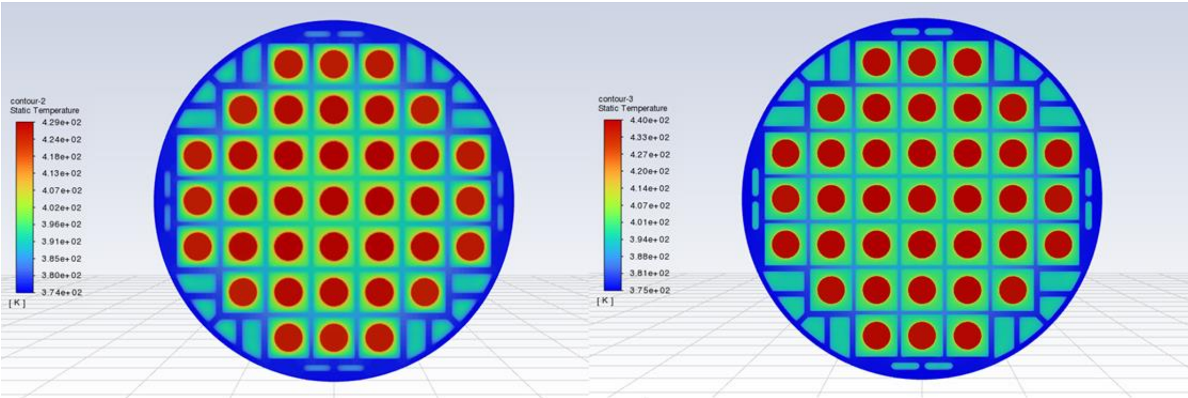


a) 4 bars b) 6 bars c) 8 bars

Figure 18: Helium flow velocity at height of 0.05 m for the pressure of a) 4 bars, b) 6 bars, and c) 8 bars

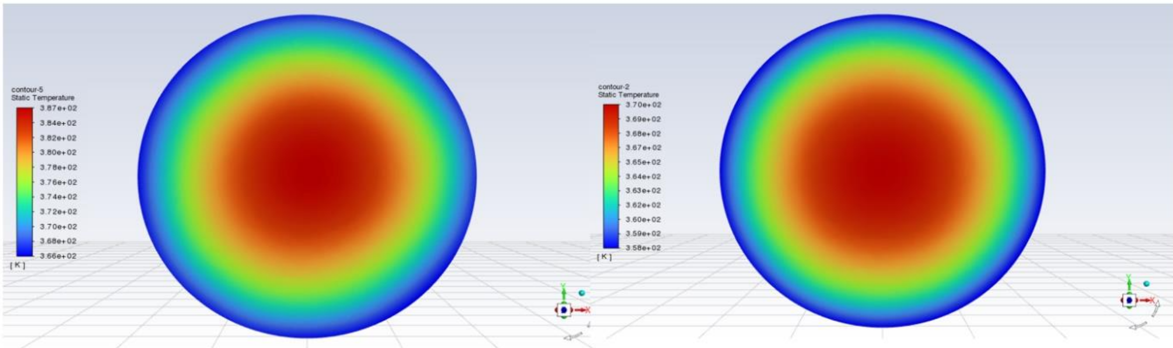
3.6 Different cooling medium

Lastly, we investigated the influence of the cooling medium heat transfer properties on the temperature distribution. In case of long-term helium leakage, air would partially fill the MPC. These two gases differ in thermal conductivity (0.0242 $\frac{W}{m\,K}$ for the air, and 0.152 $\frac{W}{m\,K}$ for helium). In this case, the model with concrete base and 37 equivalent fuel assemblies is used. Radial temperature distribution (local scaling) at height of 2 m for helium and air as a cooling medium is shown in Figure 19. The maximum temperature is 429 K for helium and 440 K for the air. Figure 20 shows the temperature distribution at the top of the MPC. The maximum temperature for helium case is 387 K, and for air 370 K. The average temperature for helium is 375.6 K, and for air 364.7 K. Fuel temperatures are higher with air as cooling medium, and the outer surface of the MPC is consequently at a lower temperature due to poorer thermal conductivity of the air than helium. That means that loosing helium means lower cooling efficiency of the fuel assemblies and their higher temperature. In the same time thermal connection between MPC basket and MPC surface is better with helium than with air. Flow velocity is shown in Figure 21. Higher velocities are observed in case of helium cooling.



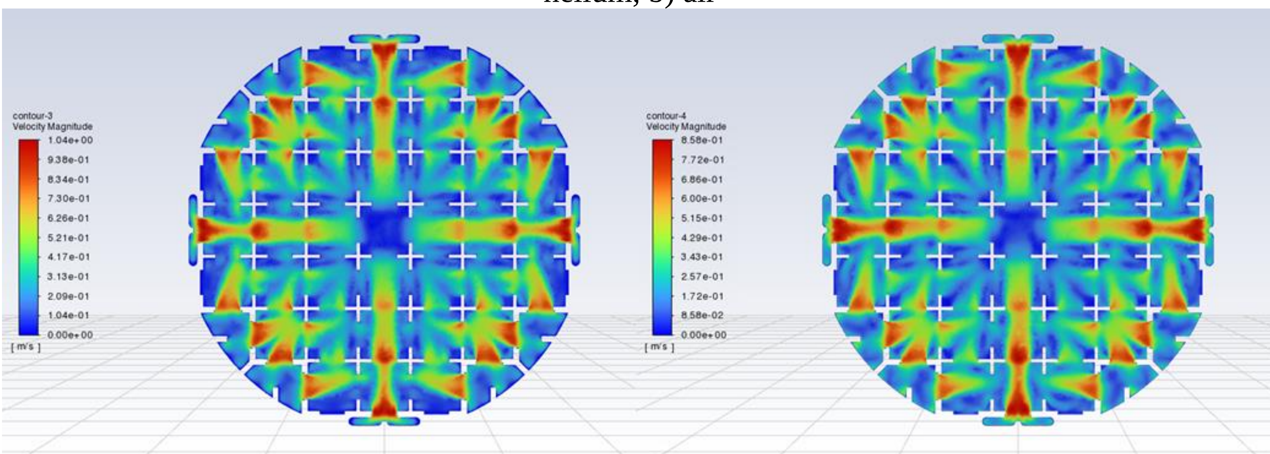
a) helium b) air

Figure 19: Radial temperature distribution at height of 2 m with a cooling medium a) helium, b) air



a) helium b) air

Figure 20: Temperature distribution at the MPC top lid surface with a cooling medium a) helium, b) air



a) helium b) air

Figure 21: Flow velocity at height of 0.05 with a cooling medium a) helium, b) air

4 CONCLUSION

This work presents a thermal analysis of simple model of helium filled Holtec's MPC with 37 spent fuel assemblies. The calculations were performed using the Ansys Fluent code in steady state. The explicit and equivalent modes are developed. The equivalent model of the fuel assembly has shown to be good enough if we are not interested in the temperature distribution of the fuel element itself. The uniform and non-uniform heat source distribution was also investigated. It was demonstrated that the non-uniform distribution of the heat source does not have a big impact on the temperature distribution on the outer surface of the MPC. Furthermore, a concrete base had no influence on the temperature distribution, but there were differences in heat transferred in the upper and lower part of the MPC. The influence of inserts on temperature distribution showed that more efficient cooling was achieved with inserts due to the higher thermal conductivity of aluminium than helium. The analysis of the influence of the initial fill pressure showed more efficient cooling at a higher pressure, as expected. Finally, the analysis of different cooling medium demonstrated more efficient cooling with helium compared to air. Additional analyses will be needed to determine the relation between the temperature difference and helium to air fraction in the MPC gas.

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