The numerical analysis of the impact of CASTOR-1500 cask model simplifications on temperature distribution in the cask

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Abstract

Nuclear fuel is the most important component in a nuclear reactor that has a limited service life and then needs to be either reprocessed or carefully handled before the geological disposal which would be the final step in its management. In order that the spent fuel could be disposed of in a geological repository, spent nuclear fuel activity and decay heat should be reduced. For this purpose, it is stored in water pools and interim storage facilities. In interim storage facilities, spent nuclear fuel very often is placed in special casks. All storage casks must fulfil safety requirements. The main thermal parameter for cask safety is fuel load temperature which must not exceed the maximum defined value. In this paper, thermal processes in the CASTOR RBMK-1500 storage cask are numerically analyzed using 2D and 3D models. Several simplifications were applied to the cask numerical models and the effects on the internal temperature distribution were analyzed.

Keywords
RBMK-1500 reactor, spent nuclear fuel, interim storage, thermal analysis, numerical modelling, 2D and 3D comparison

1. Introduction

At present, Europe is facing a crisis of energy resources and is increasingly turning to nuclear energy, because in order to reduce CO_2 emissions, this is one of the solutions before a full transition to renewable sources. Regardless of future solutions, the challenges of the near future that arise after the shutdown of nuclear power plants must be addressed. One of the most important issues is the safe management of spent nuclear fuel (SNF). During operation, nuclear power plants generate significant amounts of SNF and its proper management is a very important issue. It is recognized now that the geological disposal of SNF could be the final step in its management.

The spent nuclear fuel assemblies that were used in a reactor core and now have been retrieved emit a lot of heat and are highly radioactive and therefore must be stored in special pools until their heat and radioactivity reduce. Such a process should last at least 5 years. In Finland, Posiva Oy had already submitted the license application for the operation of an encapsulation plant and geological repository at the end of 2021, but it will take some time for such repositories to appear in other countries. In any case, SNF must be stored at interim storage facilities before disposal. Unlike in wet storage systems, which use water, the dry storage technology uses inert gas or air as a coolant with passive cooling to ensure normal operating conditions of such casks.

The Ignalina Nuclear Power Plant operated the RBMK-1500 water-cooled graphite-moderated channel-type power reactors that now are under decommissioning. There are two SNF interim storage facilities at the nuclear power plant site, where more than 21,000 fuel assemblies are stored. For that purpose, the SNF was loaded into three different types of non-ventilated casks.

In the world, there are currently two types of SNF storage casks used: ventilated and non-ventilated. There have been a wide range of investigations performed for SNF storage in ventilated casks with PWR and BWR fuel (Tseng et al., 2011; Li and Liu, 2016; Benavides et al., 2019), etc. and WWER fuel (Alyokhina et al., 2015) etc.

Special attention should be given to the (Wu et al., 2018) paper. The authors performed a detailed 3D thermal and fluid flow analysis of a vertical dry storage cask that contains PWR spent nuclear fuel (after a 5 year–storage period at the reactor). The accuracy in the modeling was preserved by not forgetting the filling gas inside the cask as well as the air acting as a cover of the cask. The simplification of the simulation was achieved by introducing an effective thermal conductivity method in the simulation of the fuel assembly's thermal conductivity. The results showed that the peak temperature in fuel assemblies was recorded higher in the assembly compared to previous assumptions. This happened because of a helium convective cycle driven by the buoyancy force in the container. The peak temperature was also of a lower value than in earlier calculations. The heat transfer within the fuel assemblies was enhanced and the peak temperature decreased within the system because of this naturally occurring convection.

Non-ventilated casks have been investigated in (Yoo et al., 2010; Creer et al., 1987; Brewster et al., 2012; Fort et al., 2019) etc. In (Yoo et al., 2010), the numerical analysis of a TN24P cask was performed using the FLUENT code. The cask model predictions were compared with the experimental data and COBRA-SFS code results. There was good agreement between the FLUENT predictions and the experimental data. FLUENT also showed similar temperature predictions to COBRA-SFS. The same cask was analysed in (Brewster et al., 2012). The STAR-CCM+ code was used for the thermal performance of this cask. A simplified method for such an analysis was suggested and comparison with the existing measured temperature data showed good agreement. In (Fort et al., 2019), experimental and numerical analyses (COBRA-SFS and STAR-CCM+ models) were performed with a storage cask Orano TN-32B High Burnup in the North Anna Nuclear Power Station's SNF storage installation. The fuel stored in the TN-32B cask was high burnup PWR fuel. The purpose of this work was to investigate the performance of high-burnup SNF (fuel temperatures as close as possible to the allowable peak cladding temperature) in dry storage. The results showed that both models produced equivalent trends of peak fuel cladding temperature with ambient temperature. However, comparison of the predictions with the experimental measurements showed that that the model predictions over-predicted the temperatures at the measurement locations by between 20 and 40 °C.

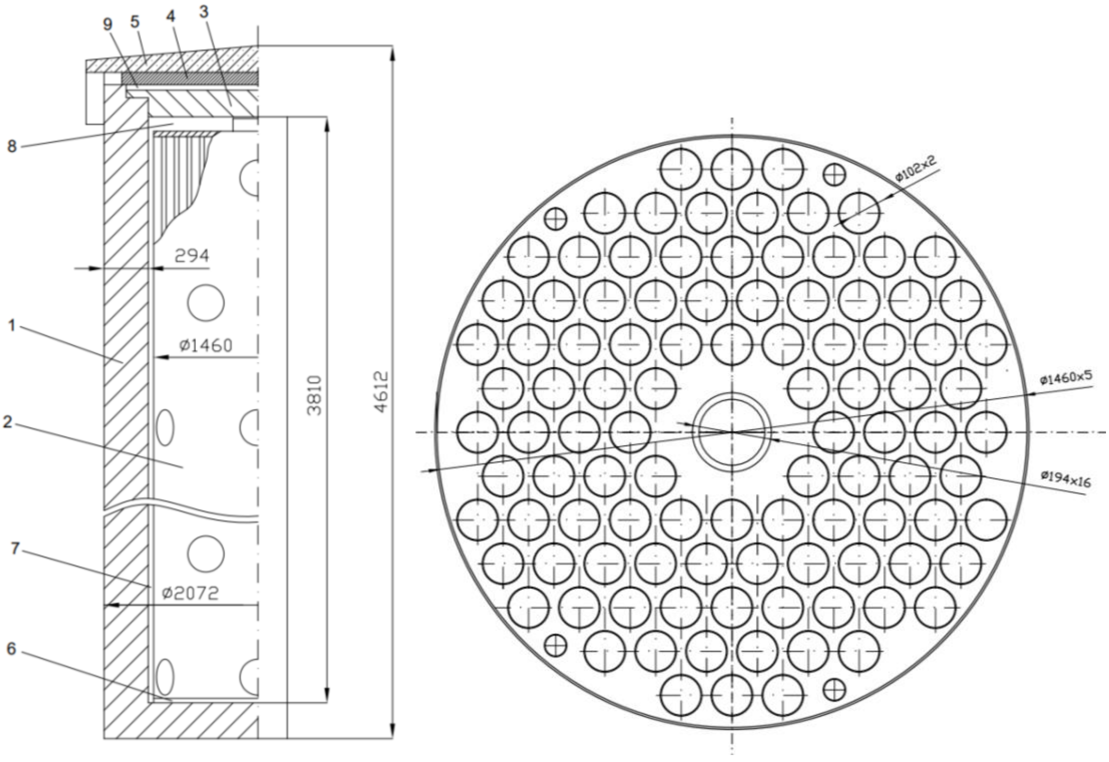
In (Poškas et al., 2006), the ALGOR code was used to obtain thermal data on CONSTOR as well as CASTOR non-ventilated containers in the case of RBMK-1500 SNF interim storage for 50 years. The model included the thermal regimes of both casks for various storage conditions and cases: a single cask and the a cask influenced by other casks in storage; a cask recently loaded with SNF (after being stored in water pools for 5 years) and being in storage for 50 years; in winter and summer conditions; with solar insolation taken into account and without it. R. Poškas et al. (Poškas et al., 2017) analyzed the thermal data of a non-ventilated cast iron CASTOR container loaded with SNF and stored for an extended up-to-300-years period at the Ignalina Nuclear Power Plant. The code used for the modelling was ALGOR. The container was modelled in open storage in summer and in winter conditions. The results of the investigation showed that the first 50 years was the period where the SNF temperature decreased the most. In (Poškas et al., 2019), the thermal analysis was performed for another type of CONSTOR cask (up to 300 years) also using the ANSYS Fluent code. It was concluded that the change in the temperatures of the outer surfaces of the casks is very insignificant after 50 years of dry storage. Hence, the cask fulfils the thermal requirements for dry storage of SNF for both storage periods.

In (Poškas et al., 2021), the evaluation of CASTOR RBMK-1500 cask behavior in normal and accidental (fire) conditions using 2D geometry was performed with ANSYS Fluent. Here the heat transfer through the fuel load was evaluated using the effective axial and radial heat conductivity coefficients. The modeled cask was in an open storage facility in summer under normal conditions and was exposed to solar insolation and a 37 °C ambient temperature. To model heat transfer under steady-state conditions before fire, in helium and air gaps, the steady-state Navier-Stokes equations for laminar flow with variable physical properties were used. For fire and post-fire periods, transient equations were applied. It was demonstrated that during the fire, the fuel load maximum temperature was not really changing; however, it increased in the post-fire period and reached its maximum at day 7 after the end of the fire. During the fire, the cask body accumulated heat, which heated the fuel load and which was also dissipated to the ambient air during the post-fire period. During the 25 days after the end of the fire, the cask practically reached the steady-state condition.

In this paper, numerical simulations using the ANSYS Fluent code were performed to evaluate the impact of the model simplifications on the temperature distribution in a cast iron non-ventilated CASTOR RBMK-1500 cask stored in an open-type storage facility. The modeling results revealed that in the 2D model using the effective thermal conductivity of the fuel basket, the maximum fuel load temperature was the highest. However, it was close to the maximum basket tube temperature in most realistic 3D model with holes in the outer shell and horizontal partitions in the basket.

2. Methodology

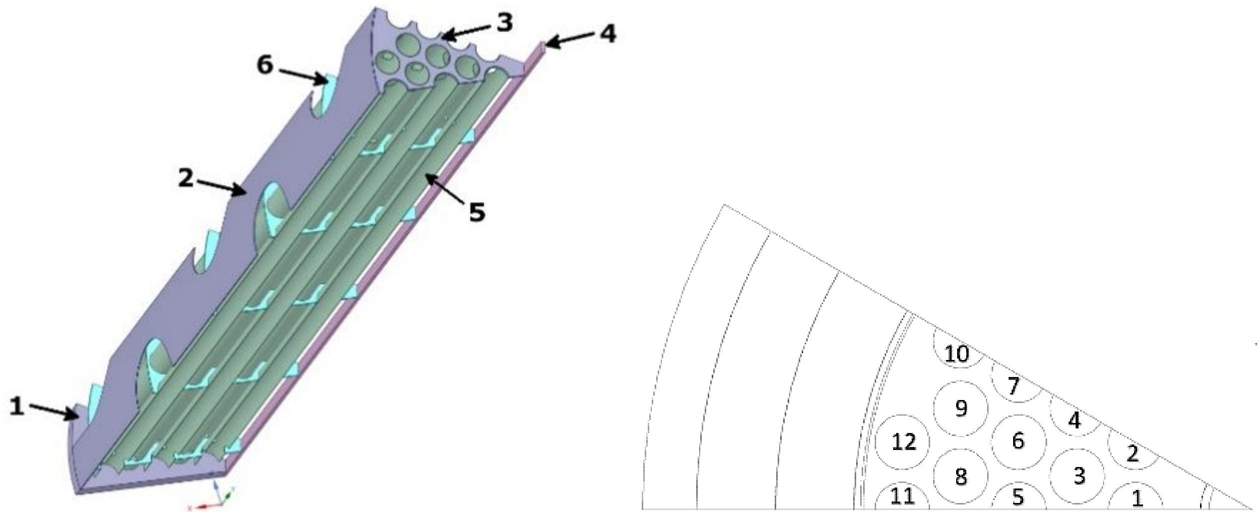
The main parts of the non-ventilated CASTOR RBMK-1500 storage cask are: the cast iron body, the fuel basket with loaded SNF and the lid system. More detailed information is presented in Fig. 1.



a) b)

Fig. 1. Cast iron CASTOR RBMK-1500 storage cask (not to scale): 1 is the cask body; 2 is the basket; 3 is the cask lid; 4 is the guard plate; 5 is the concrete cover; 6 is the central basket tube; 7 are basket tubes; 8 are holes in the basket outer shell.

A fragment of the fuel basket (Fig. 2) provides details in the fuel basket and numbering of the basket tubes to be used in the analysis below. There are wide holes in the outer shell of the basket and several thin horizontal partitions.



a) b)

Fig. 2. Fragment of the fuel basket (a): 1is the bottom; 2 is the outer shell; 3 is the top; 4 is the basket central tube; 5 are basket tubes; 6 are horizontal partitions; and numbering of the basket tubes (b).

The heat source is 51 RBMK SNF assemblies cut in halves (102 fuel rod bundles) with a burnup of 22.2 MWd/kgHM and a cooling period of 5 years. The total decay heat load from 102 RBMK bundles is 7.14 kW (Poškas et al., 2017). The fuel rod bundles are placed into the basket's tubes (Fig. 1). The heat is transferred through the cylindrical wall of the storage cask by conduction and through helium and air gaps by convection and radiation. The heat is removed from the outer surface of the storage cask to the surroundings by thermal radiation and by convection due to the buoyancy-induced air flow. A more detailed description of the cask is presented in (Poškas et al., 2021).

From the point of view of thermal effect when assessing SNF storage in casks, the most critical conditions are summertime and maximum solar irradiation during daylight. In this modeling, the cask was in an open storage facility in summer conditions. Under normal conditions (steady state conditions in modeling), the cask was exposed to solar insolation and a 37 ^{o}C ambient air temperature. The average temperature in Lithuania in summer was selected to be the ambient temperature plus 10 °C to consider the impact from the adjacent containers. As it was a conservative approach, the decrease in temperature at night was not taken into account. According to IAEA recommendations (IAEA, 2018), the following values concerning the heat flux from solar insolation during daylight (12 hours a day) should be used: for the vertical surface of the cask 200 W/m^2, and for the horizontal surface 800 W/m^2.

But in this modeling, due to the massive heat-accumulating cask body, the heat flux from solar insolation was distributed through 24 hours, and therefore the heat flux values for the vertical surface of the cask is 100 W/m^2 and for the horizontal surface is 400 W/m^2.

In an actual storage facility, the heat flux value for the vertical surface is less because of the effect of the shading from the adjacent casks placed every 3 meters in the storage site. Solar flux is not taken into account for the outer bottom surface of the cask. Heat radiation from the outer vertical surface to the surroundings was not considered, because the wall temperatures of the adjacent casks are similar.

On the outer surface of the cask, the convective heat transfer coefficient of 5 W/m^{2}K was assumed. This value is reasonable because there is a laminar air flow developed due to the rather low temperature of the outer surface of the cask.

The CASTOR geometrical model simplification to the 2D model, as it was done in (Poškas et al., 2019), has a big advantage to computing power requirements, but in such a case, the effective conductivity of the fuel basket should be used. To model the flow structure in the fuel basket, the 3D model of the cask is required.

This paper describes and compares the results of the four modeled cases for steady state conditions. Different levels of simplifications of the geometry of the fuel basket were selected with most detailed geometry in Case 4 (see Table 1).

Table 1
Conditions for four modeled cases.

	CASE 1	CASE 2	CASE 3	CASE 4
Model dimension	2D	3D	3D	3D
Processes in the fuel bundle	Not relevant	Effective thermal conductivity	Effective thermal conductivity	Effective thermal conductivity
Processes in the fuel basket	Effective thermal conductivity	Conduction, convection and radiation	Conduction, convection and radiation	Conduction, convection and radiation
Processes in the helium and air gaps	Conduction, convection and radiation	Conduction, convection and radiation	Conduction, convection and radiation	Conduction, convection and radiation
Processes in the central tube	-	Conduction, convection and radiation	Conduction, convection and radiation	Conduction, convection and radiation
Fuel basket side wall holes	Not relevant	Not modeled	Modeled	Modeled
Fuel basket partitioning	Not relevant	Not modeled	Not modeled	Modeled
Solid parts of the cask	Conduction	Conduction	Conduction	Conduction

The cask model was created with ANSYS SpaceClaim (2020 R2 package). The mesh was produced with the ANSYS Meshing tool (Release 19.0) and the calculations were performed using the ANSYS Fluent code (Release 19.0) (ANSYS Fluent, 2019).

The investigations were performed using 2D or 3D steady-state Navier-Stokes equations (accordingly to the case requirements) for a laminar flow with variable physical properties.

The radiation in helium/air gaps was solved using the Discrete Ordinates (DO) method (Murthy and Mathur, 1998) implemented in ANSYS Fluent, in which the radiative transport equations are discretized into a finite number of solid angles and solved on the same finite volume mesh as the flow and convective heat transfer equations, coupled through appropriate source terms.
Case 4 is the most complex one and was chosen for mesh validation. The results are presented in Table 2.

Table 2
Mesh testing results

Mesh elements	Active zone maximum temperature, °C	Outer surface maximum temperature, °C
20 516 000	204.53	103.12
34 084 000	204.09	102.70

As the results in Table 2 show, a negligible difference in temperatures was obtained for the two mesh testing cases, and therefore for the rest of the calculations, the denser mesh was used.

3. Results

The temperature distribution inside the cask at steady state conditions for all four cases is presented in Figure 3a. In the 2D case (Case 1), the temperature decreases with distance from the center in axial as well as radial directions. As it has already been indicated above, contrary to this case, all other cases were modeled in the 3D domain and have the basket inner structure where helium can circulate freely between the basket tubes. These attributes lead to the situation where the maximum temperature location moves toward the top of the fuel basket area (Cases 2–4).

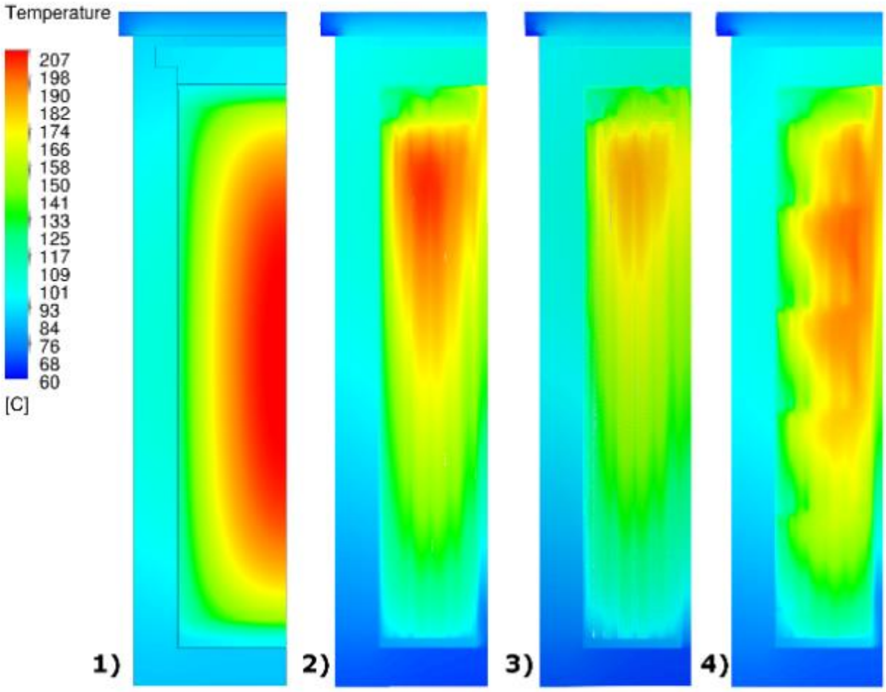


Fig. 3. Cask temperature distribution for modeled Cases 1–4.

The heat is transferred from the basket to the cask body through a narrow helium gap. Case 1, assuming an effective thermal conductivity of the basket, was thoroughly investigated in the previous work (Poškas et al., 2021).

Case 2 was the first when helium circulation between the basket tubes is modeled. As it has been indicated above, the modeling of the basket tubes is based on their effective thermal conductivity defined in advance based on detailed modeling of the fuel bundle in the basket tube. As a consequence, there are two separate helium zones: one inside the basket and the other outside of it. The latter zone is similar to the 2D (Case 1) narrow helium gap. In Case 2, the maximum temperature moved upwards due to free helium circulation inside the basket, and the maximum temperature was noticed near the top of the basket tube.

In reality, the basket outer shell has rather big holes (**Error! Reference source not found.**). These holes definitely have an impact on the helium flow structure in the basket and in the gap between the cask body and the basket. Modeling was performed in Case 3 for such conditions. As we can see from Fig. 3a, helium can freely circulate inside and outside the basket. As a result, this leads to a better heat removal from the basket tubes.

One more significant aspect is the necessity to evaluate the horizontal partitions in the basket as they have a significant impact on heat removal from the cask. These partitions complicate gas movement inside the basket. Therefore, the impact of the horizontal partitions was evaluated in Case 4. The resulting temperature field is presented in Figure 3a part 4. Due to limited helium movement between the horizontal partitions, the basket tubes in other sections also have quite high temperatures which leads to the more evenly distributed temperature inside the basket along the vertical axis. The circulation of the helium between the horizontal partitions is well expressed (Fig. 4), but due to the rather limited space between them, the velocities in Case 4 are lower than in Case 3.

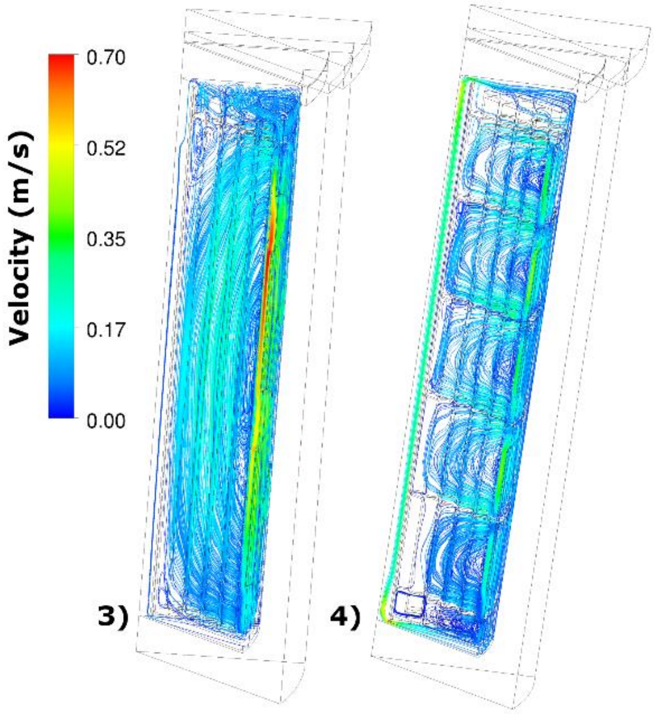


Fig. 4. Velocity streamlines for Cases 3 and 4.

Fig. 5 presents temperature variations along the basket tube axis for Cases 2–4. It is a general tendency that the temperature of the basket tubes increases with the height. However, closer to the top, some decrease was noticed and it was different for separate Cases. As can be seen from Fig 5, the basket tubes No 4 and 5 have the maximum temperatures in Case 2. In Case 3, the basket tubes No 1 and 5 have the highest temperatures, and in Case 4 the basket tube No 1 has the highest temperature.

In all Cases the basket tubes with the highest temperatures are close to the central tube and the lowest ones are close to the basket wall.

The comparison of the temperatures in the hottest regions for Cases 1 to 4 is presented in Fig. 6. In Case 1, the hottest region is on the cask axis. For all other Cases, the central tube was modeled, and thus the hottest region does not coincide with the cask axis. For Cases 2–4, the temperature values on the hottest basket tube axis are plotted. For Case 1, the maximum temperature is in the middle of the cask, for Case 2 and 3 at about 3.4 m height and for Case 4 at about 3 m height.

It is evident From Fig. 6 that the highest temperature (213 °C) is obtained when the effective thermal conductivity of the basket is used. Cases 2 and 3 are not realistic, because the horizontal partitions are not taken into account and this creates conditions for an intensive circulation of helium in the fuel basket and effective removal of the heat from the cask. Case 4 represents the geometry of the fuel basket most realistically and gives the maximum temperature that is only10 °C smaller in comparison with Case 1. Thus, using the effective thermal conductivity of the fuel basket (Case 1), it is possible to model a realistic state of the fuel load temperature in the cask.

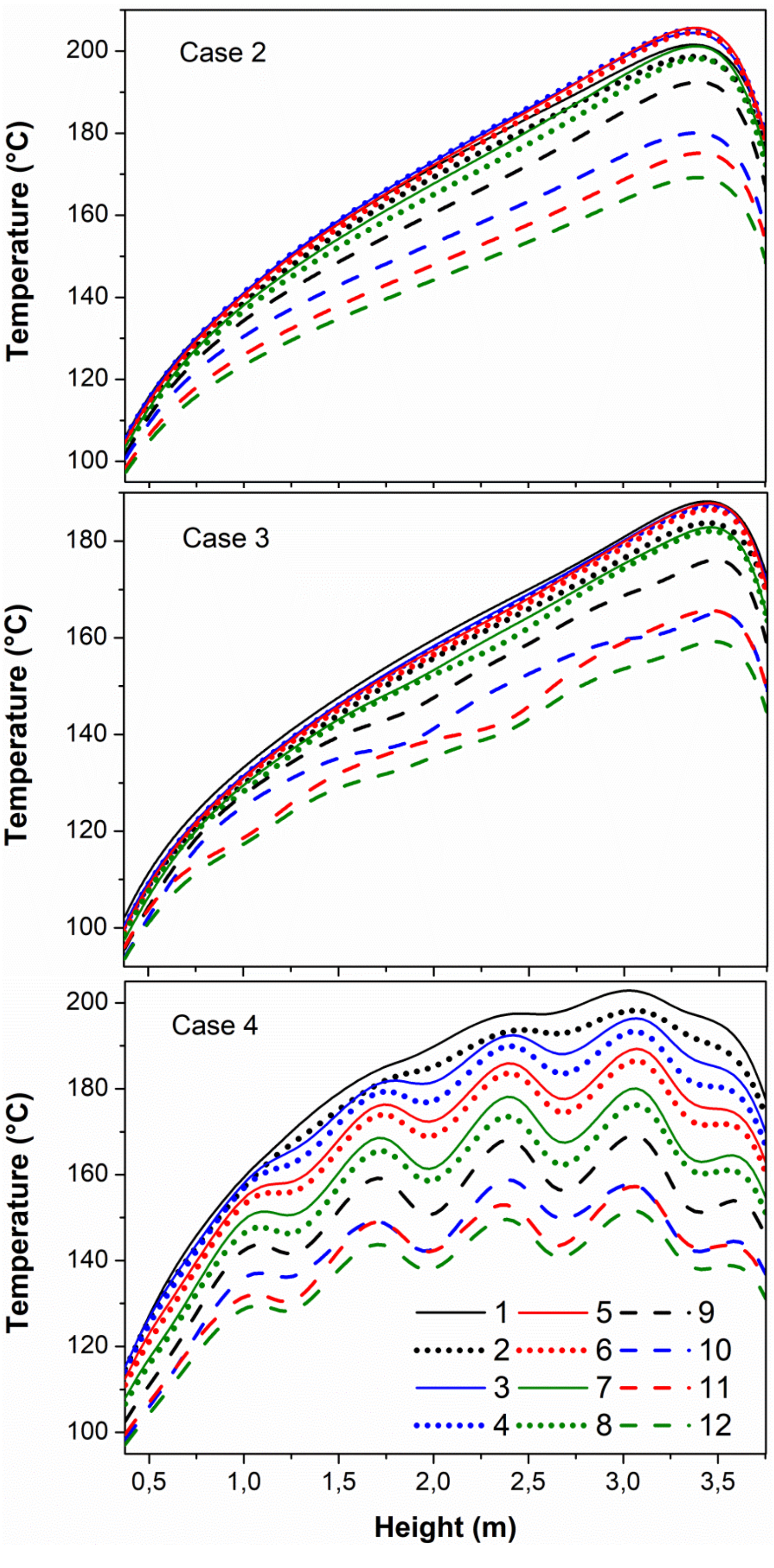


Fig. 5. Temperature variation along the basket tube axis for Cases 2–4. Basket tubes numbering is according to Fig. 2b.

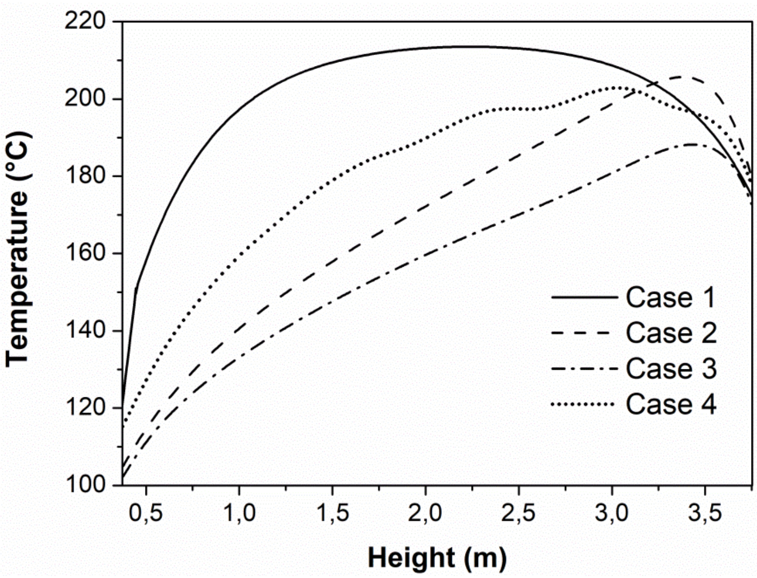


Fig. 6. The hottest temperature variation over the fuel basket height: for Case 1, the highest temperature is on the cask axis; for Cases 2–4, temperature variations on the axis of the hottest fuel basket tubes is provided.

Conclusions

After modeling the decay heat removal from the CASTOR RBMK-1500 cask using different simplifications in the fuel basket geometry (Cases 1-4), the following conclusions can be drawn:

1. 2D modeling using the effective conductivity of the fuel basket (Case 1) gives the highest maximum temperature of the fuel load.
2. 3D modeling taking into account the holes in the outer shell of the fuel basket but not taking into account the horizontal partitions (Case 3) creates favorable conditions for the circulation of helium in the fuel basket and, as a result, the maximum temperature of the basket tube is the smallest.
3. If the holes in the outer shell and the horizontal partitions in the fuel basket are not taken into account (Case 2), the circulation of helium in the fuel basket is less intensive because there is no interaction with the helium in the gap between the inner surface of the cask and the outer surface of the fuel basket. In this case, the maximum temperature of the basket tube is very close to the 2D modeling case (Case 1).
4. When modeling also includes the horizontal partitions (Case 4), there are fundamental changes in helium circulation. Due to a rather limited space between the partitions, the helium circulation velocity decreases, and the temperature distribution along the axis of the cask becomes more even. The maximum temperature of the basket tube is close to the 2D case (Case 1).

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