HIGH-FIDELITY ANALYSIS OF MTR CORES USING SERPENT2/ SUBCHANFLOW

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ABSTRACT

A growing interest in developing high fidelity computer tools for simulating the detailed behaviour of MTR-cores is observed in recent years. In this work, the internal coupling of Serpent2/SubChanFlow is used to analyse the stationary and transient behaviour of the core of a Material Testing Reactor (MTR) defined in the frame of the generic IAEA 10 MW benchmark [1, 2]. Starting from a critical core, a thermal-hydraulic driven transient is analysed with the coupled code for the first time. In this hypothetical transient case, the coolant inlet temperature is linearly reduced from 311 K to 301 K within five seconds. The goal is to demonstrate the new capability of the coupled code Serpent2/SubChanFlow to describe the dynamic behaviour using a Monte Carlo code coupled to a subchannel thermal hydraulic code, where the local feedbacks are directly taken into account at plate-to-channel level. The critical position of the B4C control rods and the location of the coldest and hottest plates and respective channels are identified based on the results of the unique simulation in addition to the local cladding, fuel and coolant temperature axial evolutions. Furthermore, the evolution of global parameters such as core power and local safety parameters at the hottest and coldest plate/channel are discussed. Finally, conclusions and the perspectives of this research are described.

1. Introduction

In the last decade, the use of tools for the simulation of research reactors is increasing because of plans to build around 30 new reactors. Most of the advanced simulation tools are developed for the simulation of power reactors with cylindrical fuel element. Hence, other types of reactors loaded with curved plate and rectangular fuel plates are analysed using equivalent plate assumptions or heuristic methods, [3, 4]. In 2019, the McSAFE project started to develop high-fidelity coupled multi-physics codes by combining Monte Carlo with subchannel thermal-hydraulic and thermo-mechanic codes for pin/subchannel and fuel assembly/channel level simulations of steady state or transients for LWR [5]. In this frame, the Serpent 2 [6] and SubChanFlow code is coupled following the ICoCo or internal coupling approach [7, 8]. In 2020, the SubChanFlow code was extended to describe the thermal-hydraulic behaviour of a core loaded with plate-type fuel elements. For this purpose, a new heat conduction module for plates, downward flow and dedicated correlations for the heat transfer and pressure drop were added [9]. This work paved the way for the application of the coupled code Serpent2/SubChanFlow for the analysis of MTR-cores at very detailed resolution i.e., at plate-by-plate and subchannel level simulations of a full MTR-core taking care of the local feedbacks between the neutron physics and thermal-hydraulics.

In this paper, a generic IAEA 10 MW reactor described in [1] and [2] is analysed with Serpent2/SubChanFlow both in stationary and transient conditions. In Chapter 2, a brief description of the core is provided while in Chapter 3, the calculation tools and the coupled approach are discussed. Finally, Chapter 4 and 5 present the transient case and discuss the first-of-the-kind results obtained for the MTR-core.

2. Description of the MTR core

The main core data is obtained from the IAEA 10 MW benchmark, where the geometric characteristics, initial conditions, and materials are taken from [1, 2] and Table 1. The core configuration consists of 6x5 grid containing 21 Standard Fuel Assemblies (SFA) and 4 Control Fuel Assemblies (CFA), left Figure 1. The core is reflected by graphite on two opposite sides and surrounded by light water. Axially, all fuel assemblies (SFA and CFA) are reflected by 15 cm of Al-H2O with 20 % Al and 80 % of H2O, right Figure 1.

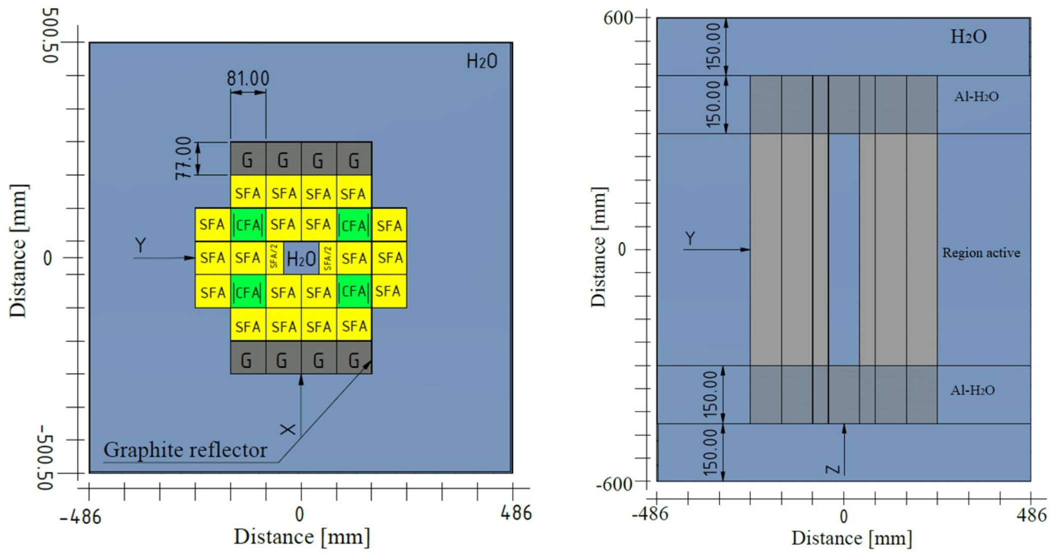
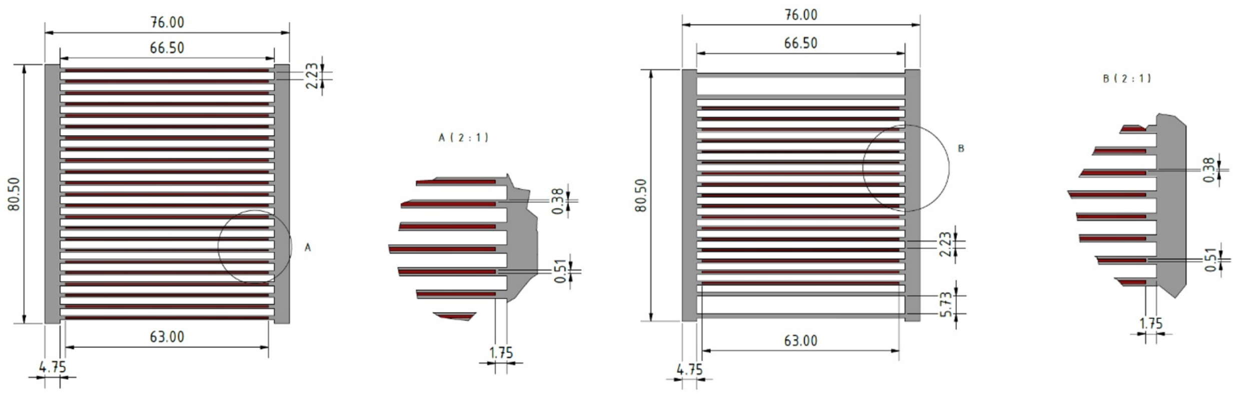


Fig. 1. Radial and axial scheme of the MTR core

The SFA has 23 plates (Figure 2, a) and the CFA has 17 plates (Figure 2, b). The CFA have a special region for the absorber plate. The absorber material can be of B4C, AgInCd or Hf.



a) Standard fuel assembly (23 plates)

b) Control fuel assembly (17 plates)

Fig. 2. Standard and Control Fuel Assemblies, dimensions mm

Material fuel HEU	Enrichment 93 wt. % ^{235}U 280 g ^{235}U per fuel element 21 wt. % of uranium in the UAl$_x$U-Al
Total power	10 MW
Coolant temperature inlet	311 K
Pressure at top of the core	1.7 bar
Coolant mass flow rate (downward)	1000 m^3/h

Tab 1: Benchmark MTR 10 MW specifications

3. Calculation tools

For the detailed analysis of the MTR core, the master-slave internal coupling of Serpent v2.1.3.1 (master) and SubChanFlow v3.7 (slave) has been used for the neutronic and thermal-hydraulic analysis of the core with plate type fuel assemblies, [8, 10, 11].
This SubChanFlow version is updated to describe the thermal-hydraulics and heat conduction of a narrow rectangular channel and plates as described in [9]. All other inherent capabilities of both codes are maintained.

3.1 Serpent 2 code

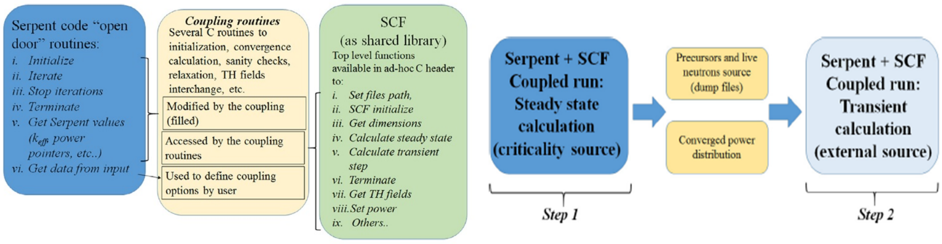
Serpent 2 is a multi-propose 3D continuous-energy Monte Carlo transport code, developed by VTT Technical Research Centre of Finland. Serpent 2 is a state-of-the-art code that uses the standard ACE format Nuclear Data Libraries (NDL) to perform static and dynamic 3D burn-in calculations [6].
A new feature implemented in 2012 [12] and enhanced in 2017 [13] is the multi-physics interface. The interface allows the exchange of thermal-hydraulic parameters e.g. density and temperature of the nuclear material between a thermal hydraulic solver and Serpent 2.
The effect of the coolant density and fuel temperature on the neutron multiplication are handled in Serpent 2 through the rejection sampling techniques combined with Target Motion Sampling (TMS). The aforementioned multiphysics features can be used with the definition of a mesh that superimposes the thermal-hydraulic fields with the geometrical model (IFCs input) [14].

3.2 SubChanFlow code

The SubChanFlow code has been developed at Karlsruhe Institute of Technology for the thermal-hydraulic analysis of BWR, PWR, VVER and MTR cores [9]. It solves three mixture conservation equations for water and steam and an additional equation for the cross flow between neighbor subchannels or averaged channels representing a fuel assembly [15].
In addition, steam water state equations are used according to the IAPWS-97 formulation. The heat conduction in a fuel rod/plate is solved with a standard finite volume method. The heat transfer coefficient between fuel rod/plate and the coolant is determined by empirical correlations.
Constitutive equations are implemented for the calculated of void fraction, pressure drop, wall friction and turbulent mixing [9, 15].

3.3 The internal coupling approach of Serpent2/SubChanFlow

The internal coupling of SSS-SCF (Serpent2/SubChanFlow) was developed in [11]. It is based on master-slave approach retaining all the inherent features of Serpent 2 (Master) and SubChanFlow (Slave), Figure 3 a.
The exchange of thermoal-hydraulic and fission power values are managed through an interface superimposed on the reactor geometry called IFC; in this work the IFC type 22 is used. A peculiarity of this coupling is the use of an external remapping file for complicated geometries, which is generated by a preprocessor implemented for SubChanFlow [16].
The transient calculation scheme is based on a two-step coupled approach as shown in Figure 3 b. First of all, a coupled static core analysis has to be done (step-1) to obtain an initial distribution of live neutrons and delayed neutrons.
During this stage, the distributions of live neutrons and precursor neutrons are recorded in specific files (dump files). After step one, the dump files provided to Serpent 2 while the power distribution is provided to SubChanFlow.
Finally, the IFC file is updated at each time interval, and Serpent 2 internally stores the temperatures and densities at the beginning and end of the time interval to perform an interpolation and display them to the user [11, 16].



a) Schematic implementation of the new internal coupling approach

b) Transient two-step approach for coupled calculations

Fig. 3. Coupling approach for Serpent2/SubChanFlow [8]

4. Neutronic and Thermal-Hydraulic models

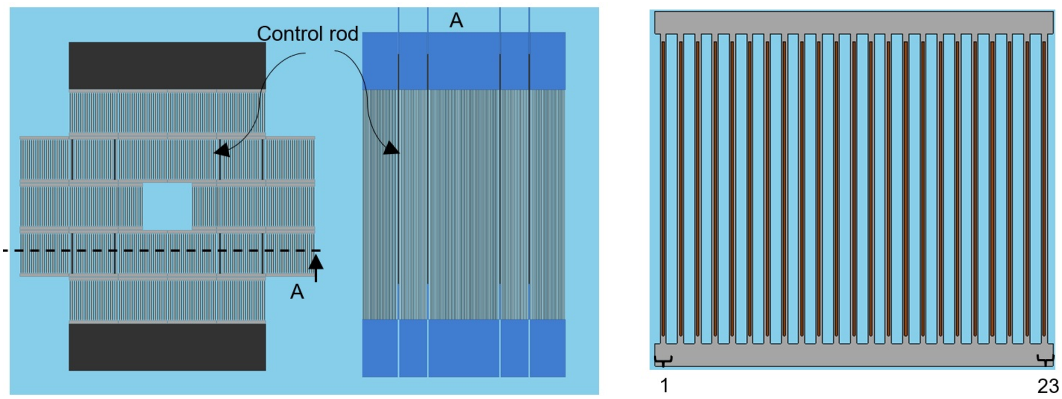
4.1 Serpent model

A very detailed 3D core model at plate-by-plate level was created according to the specifications of the technical documents [1] and [2] (Figure 4 a). The main parameters and boundary conditions are in Table 1, furthermore, additional considerations were made:

- IFC type 22 was used for the data transfer between Serpent 2 and SubChanFlow considering 20 axial zones for each plate and channel
- Nuclear data library ENDF/B-VII was used
- The absorber material for the control fuel assemblies consist of B4C
- 20 inactive and 200 active cycles were considered, each consisting of 150,000 particles for the criticality calculation
- The dynamic mode of Serpent 2 is performed with 150,000 particle populations as external source and 100 time binning
- An axial reflector zone bellow and above the core are considered consisting of water
- Radially, the core has a graphite reflector but only at two sides (black color Figure 4 a)
- Vacuum boundary conditions for neutron simulations were considered.

4.2 SubChanFlow model

The detailed SubChanFlow thermal hydraulic model is plate-centered resolving each channel as a subchannel. It consists of 20 axial nodes. For the heat conduction solver, each plate is subdivided radially in 3 and 2 cells for the fuel meat and cladding, see the discretization of a SFA (23 plates) in Figure 4 b.



a) Serpent 2: axial and radial core discretization b) Radial SFA discretization

Fig. 4. Main meshing for SCF model

Additionally, The SubChanFlow model was developed considering the following aspects:

- Correlations for the friction factors and heat transfer, Blasius and Colburn respectively, [9, 17, 18].
- Downward mass flow of the coolant
- Downward mass flow of the coolant
- Numbers of plates are equal to numbers of channels (total plates = 552)

4.3 Mapping between the neutronic and thermal hydraulic solvers

To assure a consistent data transfer between the detailed models of the core developed for Serepnt2/SubChanFlow, a remapping external file was created which contains the information about the thermal-hydraulic feedback parameters and the fission power. In Figure 5, the numbering of the plates and the coolant subchannels according to the plate-centered approach is shown for better understanding of the discussion of results.

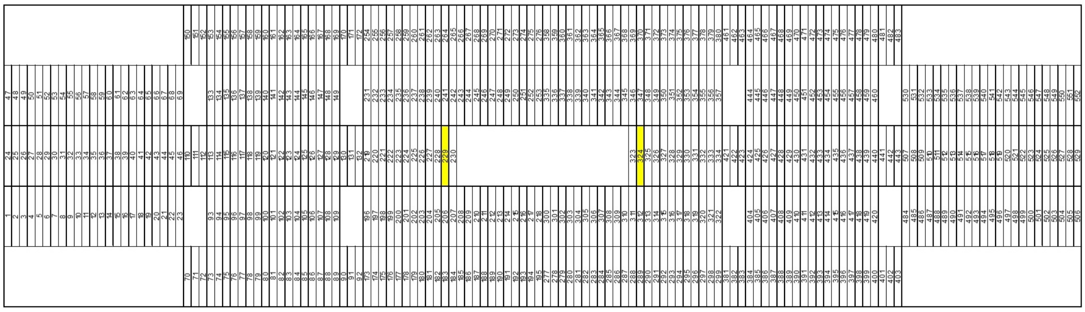


Fig. 5. Numbering of the plates and coolant channels for the radial mapping between Serpent2/SubChanFlow

4.4 Definition of the transient problem

In order to study the capabilities of SSS-SCF with internal coupling, a hypothetical transient scenario where the inlet temperature of the coolant decreases from 311 K to 301 K within 5 seconds is defined. It is assumed that the reactor is in criticality condition with Keff $\sim$ 1 and stable thermal-hydraulic conditions.
The critical control plate position predicted by the coupled code is the following: all four control plates are inserted until a height of 9.315 cm measured from the lowest point of the fuel plates. When performing the dynamic simulation of this transient with Serpent2/SubChanFlow, a uniform time binning of 50 bins is considered.

5. Discussion of results

First of all, a static core simulation with the coupled code was performed according to [1] and adding the B4C plates as specified in [2] for the full power thermal hydraulic conditions of the MTR-core. For this purpose, hybrid parallel computation using MPI and OpenMP were used. Starting from a stationary core condition, the transient case is initiated by the linear reduction of the nominal coolant temperature from 311 K to 301 K within 5 s.
The resulting power change due to the feedbacks of the thermal-hydraulic parameters on the neutron moderation and resulting fission power is predicted by the coupled code taking into account the local feedbacks according to the detailed nodalisation of the core i.e. between each plate and the surrounding subchannel along each axial elevation.
The CPU simulation time was 36.4 hours using 4 MPI processes with 12 OpenMP threads, with a total of 48 cores in a Linux cluster. In Figure 6, the time evolution of the core power is shown. It steadily increases reaching the highest value of 20 MW at 5 s.This is caused by the decrease of the coolant temperature at the core inlet which leads to an increase of the density coolant and hence of the moderation of the thermal neutrons.

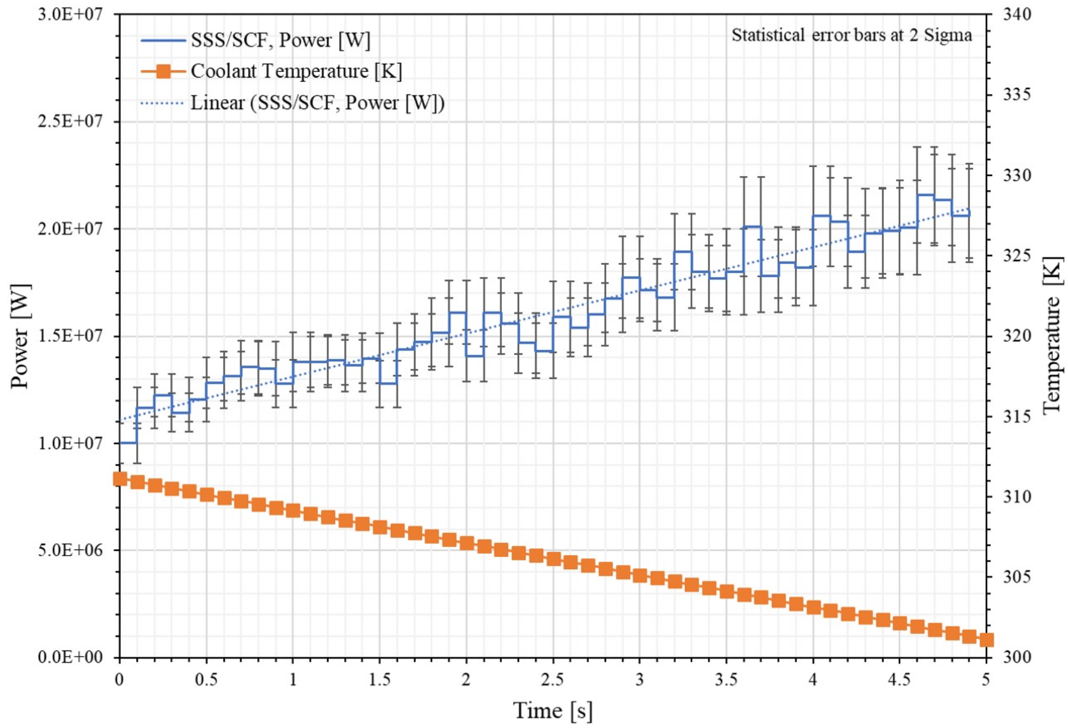
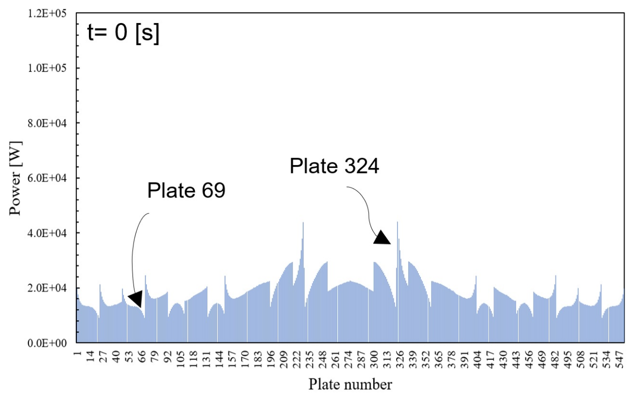


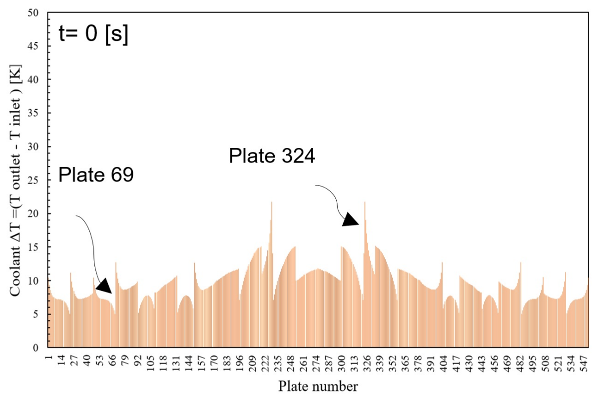
Fig. 6. Evolution of the core power and inlet coolant temperature during the transient

A novelty and peculiarity of the high fidelity coupled code Serpent2/SubChanFlow is that it allows the direct prediction of important safety parameters of the core with less approximations than the methods based on diffusion approximation and 1D thermal hydraulic codes.

In Figure 7 a. and b., the plate power and the coolant heat up of each subchannel at the beginning of the transient case i.e. at t=0 s is shown. Based on these figures, the location of the hottest plate (number 324, center left) and the coldest plate (number 69, upper left side in CFA 1), can be clearly identified.



a) Identification of the plate with the highest and lowest power

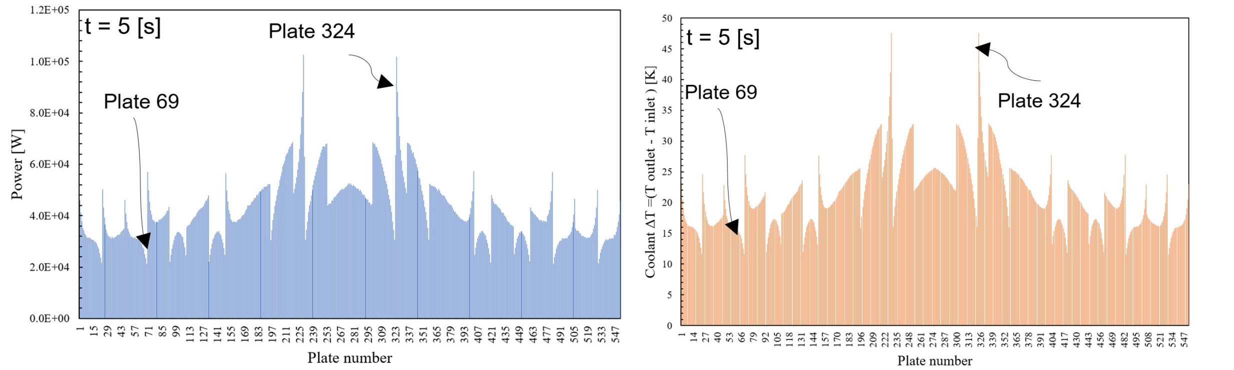


b) Identification of the channel with highest and lowest heat-up

Fig. 7. Power and core heat-up at transient time t=0 s

On the other hand, Figure 8 a and b show the power distribution and the coolant heat up at t=5 s where the total core power achieved its highest value.

It is observed that all plates and channels obtain a remarkable increase of the power and heatup compared to the values shown in the Figure 7. The hottest and coldest plates remain at the same location as compared to the transient initiation time i.e. at t=0 s.



a) Identification of the plate with more and less power

b) Identification of the channel with more and less heat up

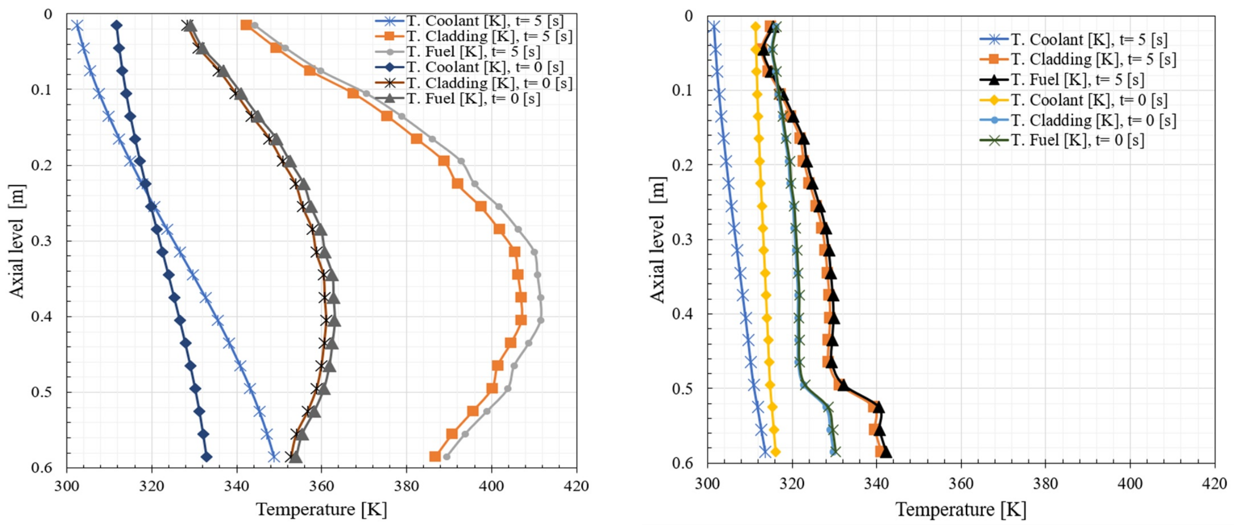
Fig. 8. Power and core heat-up at the transient time t=5 s

Figure 9 shows the axial distribution of fuel, cladding and coolant temperature of the hottest and coldest plates at t=0 s and at t=5 s. It can be observed that the maximum temperature values (fuel, cladding and coolant) are in a range of 0.4 and 0.3 meters measured from the top. It is worth to note that the coolant outlet temperature does not exceed 349 K.

The fuel temperature is slightly higher than the cladding temperature. A difference of approximately 47.4 K separates the temperature peaks between the fuel profiles at t=0 s, and t=5 s.

Figure 9 b shows the temperature profiles of the coldest plate at t=0 s and t=5 s. The coolant temperature profiles increase slightly without exceeding 320 K. On the other hand, the cladding and fuel temperature profiles show a slight difference of 10 K at the core exit.

A distortion of the profiles is observed at a height of 0.5 m and 0.6 m measured from the top. The distortion occurs at plate 69 which is very close to the absorber material B4C. In both cases, the temperature of the plates does not exceed 345 K.



a) Hottest plate at different time

b) Coldest plate at different time

Fig. 9. Axial coolant, cladding and fuel temperature at time 0 s and 5 s

6. Summary and outlook

This work has presented and discussed unique and very detailed results for a MTR-core predicted with the recently developed coupled code Serpent2/SubChanFlow at KIT. Eventhough the investigated transient scenario is not a realistic one, the investigations have shown the potentials of the novel coupling approach to predict local (plate/subcahnnel) safety parameters using a Monte Carlo solver and a subchannel thermal hydraulic code. Based on the results obtained, it can be stated that the radial power of the plates inside a fuel assembly is not uniform as used by all previous work based on diffusion or low-order transport solvers. Hence, this research work pave the way for the analysis of e.g. fast withdraw of a control element from the MTR-core and other safety-relevant transients.

The next step is to validate the capabilities of Serpent2/Subchanflow for MTR-safety analysis using the experimental data of the SPERT-IV test series performed for fuel assemblies with plates.

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