Verification of GAMMA+ for Multi-Dimensional Heat Transfer in a Prismatic Core

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) has been developing the GAMMA+ code [1] for the design of a high temperature gas-cooled reactor (HTGR). The recent research for the GAMMA+ development is focusing on the verification and validation study. In 2016, an official report on the verification and validation of GAMMA+ for conceptual problems was issued [2]. The conceptual problems consist of fluid flow problems, heat conduction problems, thermo-fluid conjugated problems, and thermo-fluid transient problems. The verification and validation of GAMMA+ for integrated problems are under progress.

This paper presents the verification study of GAMMA+ code for multi-dimensional heat transfer in a prismatic core. One of main concerns of the present work is to verify the application of hybrid grids (i.e, mixture of hexagonal, triangular and cylindrical grids) for a prismatic core. A commercial computational fluid dynamics code (CFD) has been used to verify the results of the GAMMA+ code.

2. Benchmark Model

As a reference prismatic core, the design parameters of Phase I Exercise 2a of the OECD/NEA MHTGR-350 benchmark [3] were selected. The radial layout of the MHTGR-350 core is shown in Fig. 1 and the main design parameters are provided in Table I.

Table I: Main Design Parameters of MHTGR-350 Core (Phase I Exercise 2a)

	Values
Thermal power (MW_{th})	350
Coolant inlet/outlet temperatures (°C)	259/687
System pressure (MPa)	7
Coolant flow rate (kg/s)	157.1
No. of fuel columns	66
Active core height (m)	7.93
Bypass flow gap size (mm)	0
Crossflow gap size (mm)	0

In order to simply the calculation with maintaining key physical phenomena, the following assumptions are further made.

(1) Only active core and reflector regions are considered for the verification calculation. It means that the geometry outside the permanent side reflector (PSR) is neglected.
(2) Tiny helium gap around the fuel compact is neglected.
(3) Constant thermal conductivity of 37 W/mK is applied to all solid materials.
(4) All fuel compacts have uniform power density.

Two cases are tested with different boundary conditions on the outer surface of PSR as shown in Table II.

Table II: Two Types of Boundary Conditions at PSR

Problem	Condition
Case A	Adiabatic
Case B	-5000W/m^2

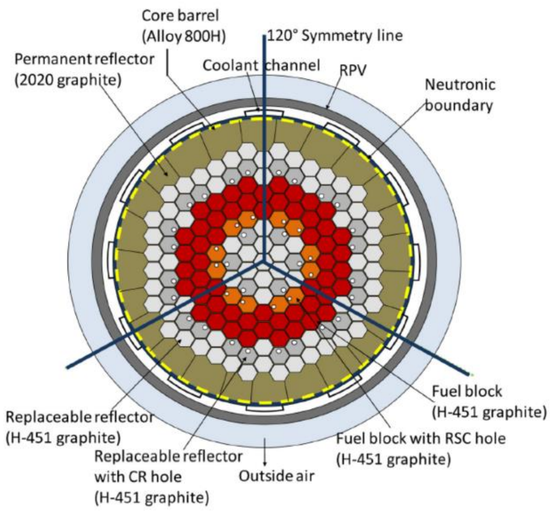


Fig. 1. Reactor core layout of MHTGR-350 [3].

3. Computational Models

3.1 GAMMA+ Model

A 1/3 core model was selected to calculate the core using symmetry condition in Fig. 1. Three different grid types were selected to solve multi-dimensional heat conduction efficiently as shown in Fig 2. The six triangular cells were generated in the fuel columns as well as the reflector columns next to the fuel columns. The hexagonal cells were used for the reflectors which are not adjacent to the fuel columns to reduce computational effort. In these regions, each hexagonal column has one cell. The cylindrical grid types are used for the permanent side reflector columns.

The coolant channels are grouped to match each triangular cell in the fuel column. 18 coolant channels in the same triangular cell are treated as a single coolant channel.

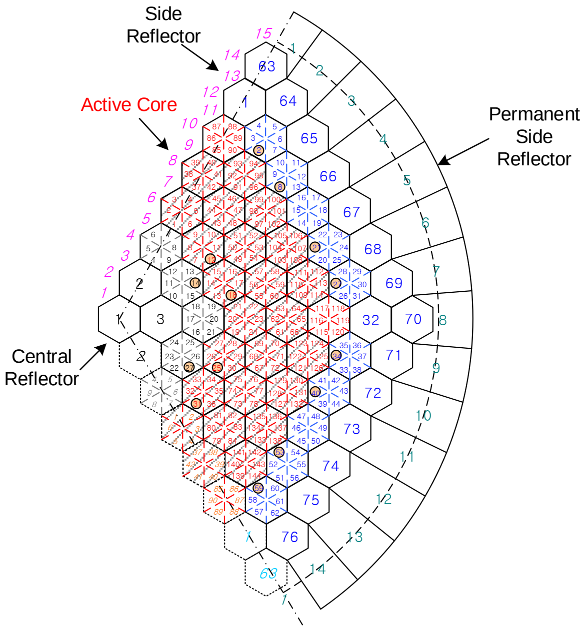


Fig. 2. Radial grid nodalization for GAMMA+ simulation.

3.2 CFD model

One sixth of MHTGR core has selected to increase computational speed and reduce the burden of RAM usages. The core consists of top reflector, 10 layer fuel blocks and bottom reflector in Fig. 3. Additionally, a fluid plenum was installed on the top reflector to distribute the coolant into the coolant holes. Four verification problems are solved to evaluate the heat transfer capability in the flow and the solid domain of GAMMA+.

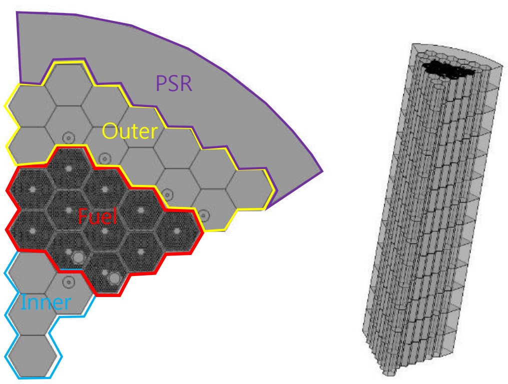


Fig. 3. CFD domain of MHTGR350

ANSYS CFX, Ver. 18[4] is used to solve heat transfer in the MHTGR core. The RNG κ - ε turbulence model is applied in the present study. The nodes generated in the fluid area are 96,902,264. The 103,372,593 nodes are generated in the solid region.

4. Results and Comparisons

4.1 Verification of Pure Heat Conduction

Before calculating the benchmark problems, preliminary calculations were conducted to verify the GAMMA+ capability for pure multi-dimensional heat conduction in radial direction. Only one single layer of the MHTGR350 core was considered to minimize computational effort. It was further assumed that the heat is generated in the entire fuel column. It means that the fuel compacts in the fuel columns were removed to simplify the test problem. The constant power density of 0.02554 MW/m^3 was applied in the fuel columns and the constant temperature boundary condition of 500°C was imposed on the PSR wall. Two grid types (i.e., hexagonal and triangular grids) were tested for the fuel columns. Table III shows that the results of GAMMA+ agree well with those of CFX. The results of the triangular grids have smaller differences than those of the hexagonal grids. The maximum differences are 2.5% and 1.9% for the hexagonal and triangular grids, respectively. Therefore, it is concluded that GAMMA+ can simulate multi-dimensional heat conduction with triangular grids as well as hexagonal grids.

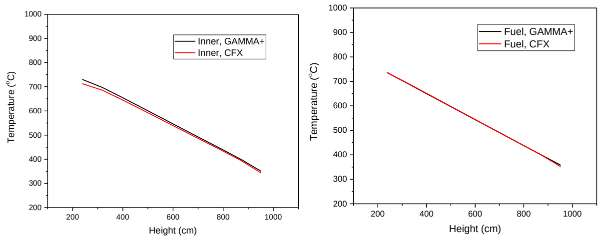
Table III: Comparison of Average Temperatures for Pure Multi-dimensional Heat Conduction Problem

	GAMMA+(°C)		CFX(°C)
	Hexagonal grids	Triangular girds	
Inner	1162	1159	1150
Fuel	1077	1064	1056
Outer	785	782	781
PSR	582	581	579

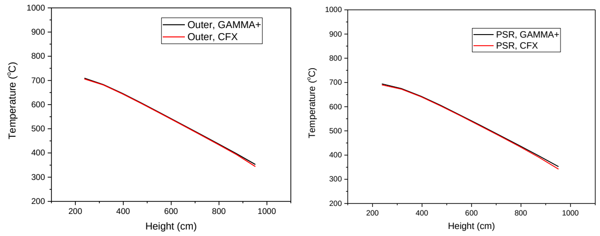
4.2 Results of Benchmark Problems

Compare to the preliminary study shown in Section 4.1, the benchmark problems are more complex due to three-dimensional geometry, the heat generation in the fuel compact, and heat convection in the coolant channels.

Fig. 4 shows the average temperature comparison along the axial direction for Case A. The total calculation time for the CFX was 1 day and 18 hours with 12 cores. Each region was explained in Fig. 1(left). All data calculated by GAMMA+ agree well with the data calculated by CFX in the whole region.



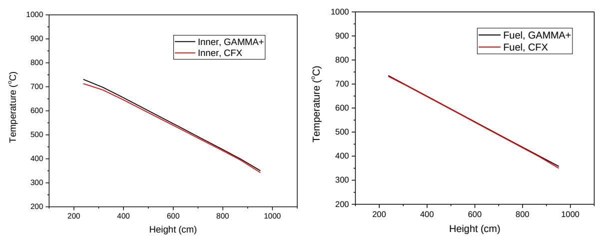
(1) Inner reflector region (2) Fuel block region



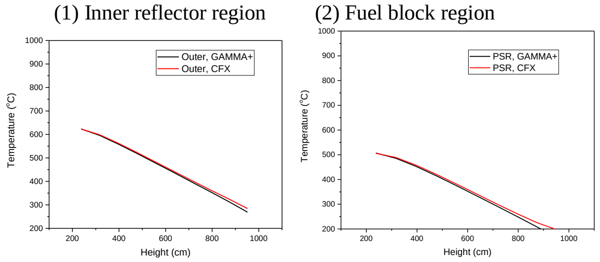
(3) Outer reflector region (4) PSR region

Fig. 4. Temperature comparison results by CFX and GAMMA+ on the adiabatic boundary condition (Case A).

Fig. 5 shows the average temperature comparison along the axial direction for Case B. The total calculation time for the CFX was 1 day and 5 hours with 12 cores. When the heat flux boundary condition is imposed, the temperature gradients in the radial plane are much larger in Fig. 6. The largest temperature difference at the height of 900~1000 cm where is the top reflector region are observed in Fig. 5. Such a difference seems to be from different heat transfer modeling at thermally developing region.

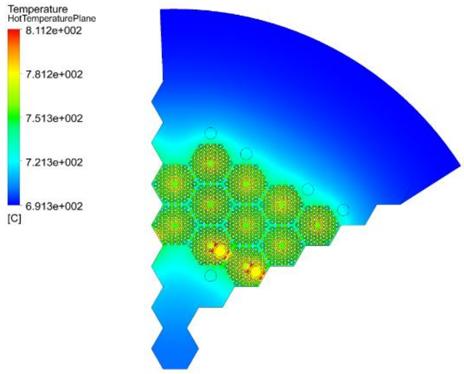


(1) Inner reflector region (2) Fuel block region

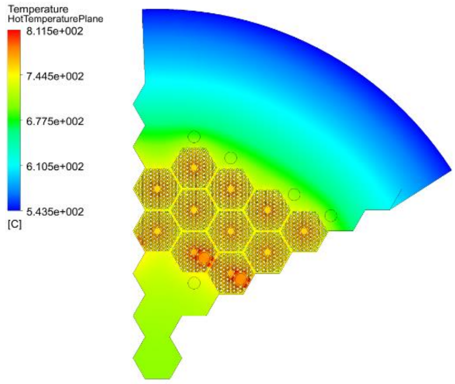


(3) Outer reflector region (4) PSR region

Fig. 5. Temperature comparison results by CFX and GAMMA+ on the constant heat loss boundary condition (Case B).



(1) Adiabatic condition



(2) heat flux condition

Fig. 6. Temperature distributions depending on the boundary condition (CFX results).

5. Conclusions

In this work, in order to verify the GAMMA+ capability for multi-dimensional heat transfer in a prismatic core, a simplified benchmark was proposed and the GAMMA+ and CFX calculations were conducted. The results of the calculation show that the data calculated by GAMMA+ agree well with the data obtained by CFX. It is concluded, therefore, that the GAMMA+ code can reliably simulate multi-dimensional heat transfer in a prismatic core.

Acknowledgements

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