Preliminary Validation of Radiation Model Comparison for Radiative Heat Transfer Analysis in MHTGR RCCS

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1. Introduction

The High-Temperature Gas-Cooled Reactor (HTGR) is one of the next-generation nuclear reactors, providing a new alternative for the future energy society with its high core outlet temperature. With a core outlet temperature of 700°C, HTGR can supply industrial process heat and offer significant advantages for hydrogen production. Hydrogen can be extracted from water through high-temperature electrolysis and thermochemical cycles such as the Sulfur-Iodine (S-I) cycle. Both methods require high-temperature process heat. Consequently, HTGR has strong potential to be integrated with these hydrogen production systems [1].

The HTGR which can be integrated with various industrial plants requires a high level of safety due to its use of nuclear energy. To ensure the safety of this reactor, the Modular High-Temperature Gas-Cooled Reactor (MHTGR) developed by General Atomics (GA) in the United States adopts the Reactor Cavity Cooling System (RCCS) as a dedicated safety system.

RCCS operates to cool the reactor core under both normal operation and accident conditions. The MHTGR adopts an air-cooled RCCS that removes heat through natural circulation. As a fully passive cooling system, it ensures the safe removal of heat from the Reactor Pressure Vessel (RPV) without requiring any external power supply, even under accident conditions. By operating without the need for emergency power, it enhances the overall safety and reliability of the reactor, ensuring effective heat dissipation and preventing overheating in critical situations.

The RCCS is typically designed to remove approximately 0.5% of the reactor's total power output. Due to the high-temperature operation of the HTGR, radiative heat transfer dominates the heat transfer within the reactor cavity. Therefore, the simulation of radiative heat transfer within the RCCS cavity is critically important.

In this study, Computational fluid dynamics (CFD) is utilized to accurately simulate the thermal behavior within the RCCS cavity of MHTGR [2]. A comparative analysis is conducted on the four Radiation Models supported by commercial software ANSYS CFX to evaluate their applicability and accuracy. This comparison aims to determine the most suitable model for simulating radiative heat transfer within the RCCS of HTGR.

2. Numerical Methodology

2.1 Analysis Model

The RCCS of the MHTGR consists of a total of 60 downcomers and 227 riser ducts. For the preliminary analysis aimed at comparing radiation models, the geometry was modeled based on a single downcomer. The schematic of geometry is shown in Fig. 1. The Reactor Pressure Vessel (RPV) transfers heat to the cooling panels, known as riser ducts. The heated riser duct generates an upward airflow due to the density difference caused by temperature variations. This natural circulation, driven by the chimney effect, removes the decay heat from the RPV. This mechanism enables RCCS to passively remove decay heat from the RPV. Within the cavity, heat is primarily transferred through conduction, convection and radiation. Due to the high-temperature operation of MHTGR, more than 90% of the heat transfer occurs via radiation [3].

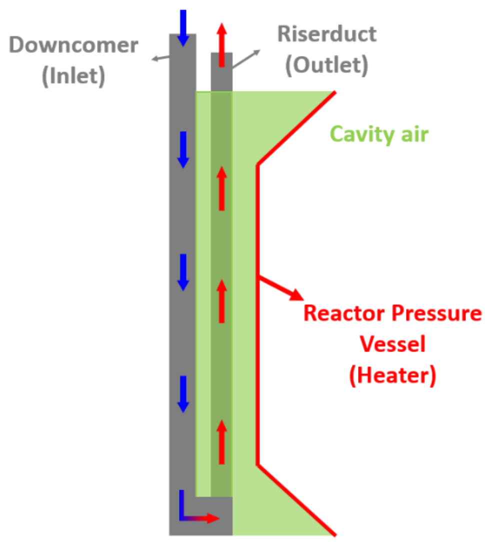

Fig. 1 Schematic of MHTGR RCCS system

2.2 Radiation Model Governing Equation

The goal of radiative heat transfer analysis in CFD is to solve the Radiation Transport Equation (RTE). The RTE represents the physical processes of absorption, emission, and scattering of radiation. It describes how radiative energy propagates through a medium in the form of rays, accounting for interactions with the surrounding environment. The equation of RTE is shown in Equation (1).

$$\frac{dI_v(r,s)}{ds} = (-(K_{av} + K_{av})I_v(r,s) + K_{av}I_b(v,T) + \frac{K_{sv}}{4\pi}\int dI_v(r,s')\Phi(s \cdot s')\,d\Omega' + S) \quad (1)$$

CFX solves the RTE by classifying it into four different models, each modifying the radiative rays and equations for computation. The four radiation models are the Rosseland model, P1 model, Discrete Transfer Model (DTM), and Monte Carlo (MC) model [4].

Rosseland model approximates the RTE using the diffusion approximation method. It treats radiative heat transfer similarly to conduction phenomena, providing a simplified approach to solving the RTE. The corresponding equation is shown in Equation (2).

$$k_r = -\frac{16\sigma n^2 T^3}{3\beta} \quad (2)$$

P1 model approximates the RTE using the Spherical Harmonic Expansion method. The P1 approach assumes that radiation intensity at a given spatial location is isotropic or independent of direction. The corresponding equation is presented in Equation (3).

$$\nabla \cdot \left(\frac{1}{3(K_{av} - K_{sv})} - AK_{sv}\right)\nabla G_v = K_{av}(G_v - 4E_{bv}) \quad (3)$$

DTM model does not solve the RTE analytically but instead employs a numerical approach using the ray tracing method. This model tracks the paths of radiative rays from surfaces by following multiple fixed-direction rays to perform calculations. As the radiation propagates in specific directions, the model accounts for absorption, emission, and scattering along the ray paths.

MC model solves the RTE using a probabilistic sampling approach. By modeling individual radiation rays and tracing their paths stochastically, this method enables highly precise calculations. MC demonstrates high accuracy in capturing radiation that is non-uniformly distributed or concentrated in specific directions. However, since each radiative ray is computed separately, the MC model requires significantly high computational resources.

2.3 Grid system and Boundary Conditions

The computational grid system used for the analysis is illustrated in Fig. 2. Approximately 5.5 million structured grids were employed. The turbulence model was set as the $k-\varepsilon$ model. The radiation mode used in the analysis was the Surface-to-Surface (S2S) model, which assumes radiative heat transfer occurs only between surfaces while treating the medium as transparent. To simulate natural circulation driven by buoyancy, both the inlet and outlet were set as opening pressure boundaries. This configuration allows the heated air inside the riser duct to generate an upward flow, effectively modeling natural circulation. Boundary conditions for analysis is represented in Table 1.

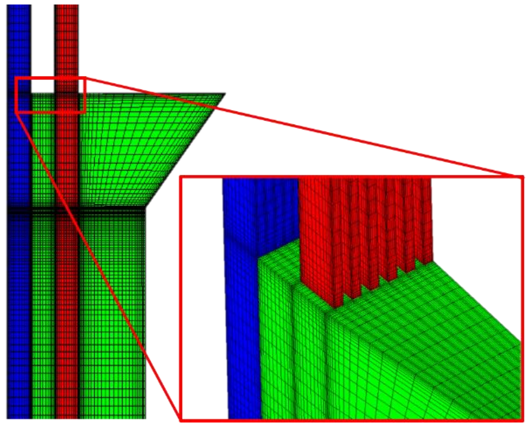

Fig. 2 Computational grid system

Table 1: Boundary conditions

Parameter	Value [Unit]
y+	30<y+<100
Turbulence Model	k- ε
Radiation Model	Rosseland, P1, DTM, MC
Air Inlet (Opening, Static Pressure)	1 atm
Air Outlet (Opening, Static Pressure)	1 atm
Heat Flux	4200W/m^2

3. Results

The preliminary analysis results for the comparison of radiation models are presented in Fig. 3. Figure 3 illustrates the temperature distribution of the RPV for each radiation model. During normal operation of the HTGR, the temperature of the RPV is 300°C. The P1 and Rosseland models apply modifications to the RTE based on predefined physical assumptions. It is not suitable for accurately representing the normal temperature distribution of the RPV.

P1 model approximates radiative energy transfer using a diffusion-based approach, assuming isotropic radiation. Consequently, it is unable to accurately capture anisotropic radiation concentrated in specific directions on high-temperature surfaces. This limitation results in an underestimated temperature distribution, leading to an RPV temperature of 187.3°C.

Rosseland model assumes an optically thick medium and simplifies radiative heat transfer into a form analogous to conduction. Radiative heat transfer transmits energy through electromagnetic waves, whereas conduction transfers heat within a material through molecular collisions. In actual radiative heat transfer, thermal radiation is emitted from surfaces. However, the Rosseland approximation assumes that heat is diffused only within the medium, neglecting radiative heat loss effects. Consequently, this limitation can lead to an abnormally high temperature in the RPV, reaching 4918°C.

DTM and MC retain the original form of the RTE and numerically approximate it by employing different ray-tracing methods. DTM method offers relatively low computational cost but has limitations in accurately accounting for scattering effects. MC model calculates radiative transfer by probabilistically tracing radiation rays. It accurately accounts for scattering, emission, and absorption, making it well-suited for RCCS applications. Although it has high computational costs and slower processing speeds, adjusting the number of rays allows for the most precise results. The RPV temperatures analyzed using the DTM and MC models were 304°C and 301°C, respectively, showing the smallest error.

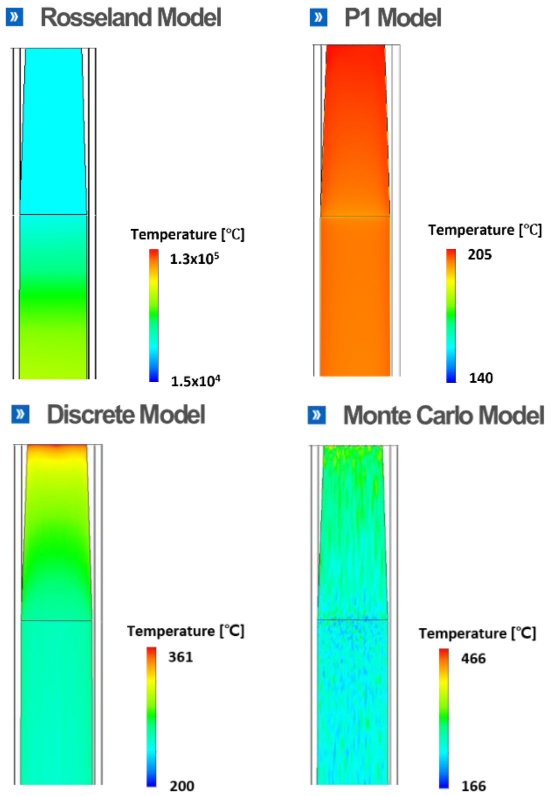

Fig. 3 Temperature distribution by radiation model in RPV

4. Conclusion

This study analyzed the differences in radiative heat transfer simulations for the Reactor Cavity Cooling System (RCCS) of the MHTGR developed by GA, using various radiation models supported by ANSYS CFX. The results indicated that each model exhibited differences in the temperature distribution of the reactor pressure vessel (RPV) due to variations in their physical assumptions and approaches to solving the Radiation Transport Equation (RTE). Among the evaluated models, the Monte Carlo (MC) model was found to be the most suitable for radiative heat transfer analysis in the air-cooled RCCS of the MHTGR.

As a follow-up study, radiative heat transfer analysis and natural circulation simulations will be conducted using the MC model for a half-scale MHTGR RCCS geometry.

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REFERENCES

[1] S. Kubo, S. Kasahara, et al., "A Pilot Test Plan of the Thermochemical Water-Splitting Iodine–Sulfur Process," Nuclear Engineering and Design, Vol. 233, No. 3, pp. 355-362, 2004.
[2] S. Lomperski, W. D. Pointer, et al. "RCCS Studies and NSTF Preparation Air-Cooled Option," Argonne National Laboratory, ANL-GenIV-142, 2010.
[3] S.H. Kim, B.H. Cho, et al., "Evaluation of Methodology for Axisymmetrc Simulation of RCCS in VHTR," Journal of Computational Fluids Engineering, Vol. 15, No. 1, pp. 1-8, 2010.
[4] ANSYS Inc., *ANSYS CFX-Solver Theory Guide*, Release 2024 R2, Canonsburg, PA, USA, 2024.