In-depth Elucidation of the Relationship between Heat Removal Performance and Operating Parameters using CFD

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1. Introduction

The Reactor Cavity Cooling System (RCCS) of a High-Temperature Gas-Cooled Reactor (HTGR) is a passive safety system that removes heat from the reactor pressure vessel (RPV) by natural circulation without active driving components such as pumps or fans, thereby controlling the reactor cavity temperature during normal operation and maintaining structural integrity through decay heat removal under accident conditions. This system manages the temperature within the reactor cavity during normal operation and maintains structural integrity by removing decay heat during accidents. However, predicting thermal behavior within the cavity is challenging due to the complex interaction between radiation and natural convection, as well as the presence of three-dimensional flow structures and temperature non-uniformity. In this study, the heat transfer characteristics of a water-cooled RCCS were evaluated using Computational Fluid Dynamics (CFD) under both normal and accident heat load conditions. The contributions of radiative and convective heat removal are separated to quantify the dominant mechanism, and the temperature fields and buoyancy-driven natural convection flow structures formed under various conditions are analyzed to compare changes in temperature distribution and flow characteristics with varying heat loads. Through this analysis, this paper elucidates the relationship between heat removal mechanisms and the characteristics of temperature and flow fields within the RCCS cavity, providing quantitative basis for RCCS thermal performance evaluation.

2. Numerical Analysis & Boundary Conditions

2.1 Analysis Model

This study established a three-dimensional computational model comprising the air region within the water-cooled RCCS cavity of the HTGR, the surrounding reflector, concrete regions, and the riser tubes. Considering the circumferential periodicity of the system, the computational domain represented a 1/45 th sector of the full geometry. In the reactor cavity, the heat released from the RPV is transferred to the surrounding structures and the riser tubes through coupled radiation and bouyancy-driven natural convection and is ultimately removed by the coolant flowing inside the riser tubes. The schematic of geometry and generated grids are shown in Fig. 1 and Fig. 2.

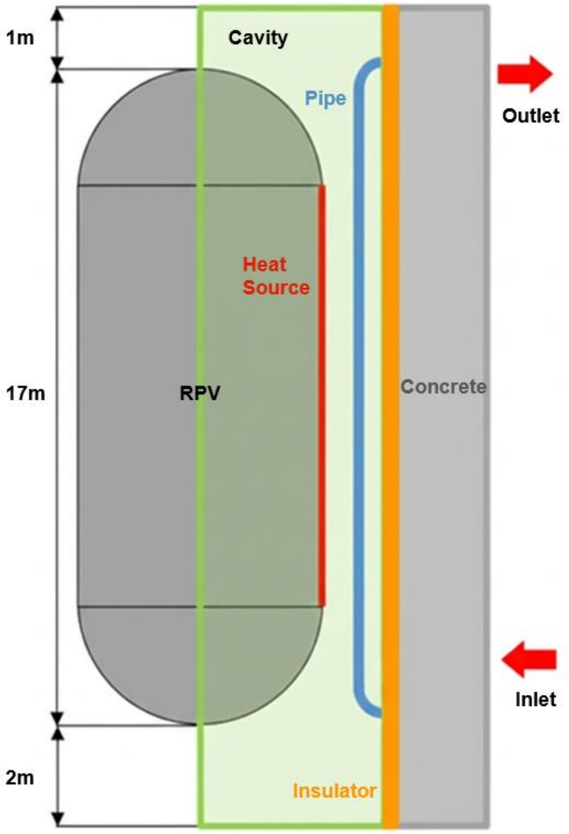


Fig. 1. The Schematic of Hectar HTGR RCCS Geometry

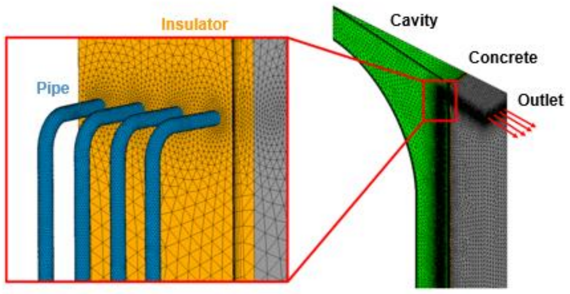


Fig. 2. Generated Grid of Hectar HTGR RCCS

2.2 Governing Models for Flow and Radiation

The flow and heat transfer were simulated using a steady-state Reynolds-Averaged Navier-Stokes (RANS) framework, and turbulence effects were modeled with the Shear Stress Trasport (SST) model to ensure robust near-wall predictions. To properly capture near-wall behavior, prism-layer meshes were applied along solid boundaries, ensuring a wall resolution of $y+ < 1$ within the unstructured gird framework. Since radiative heat transfer can be a dominant heat exchange mechanism in the high-temperature reactor cavity, radiative exchange within the cavity was modeled using surface-to-surface radiation. The radiative heat flux was computed using the Monte Carlo method, in which a large number of photon histories are stochastically emitted and traced to capture radiative heat transfer in complex geometries.

2.3 Grid System and Boundary Conditions

To investigate the thermal-hydraulic behavior of the RCCS under normal operation and accident conditions, total heat loads of 450 kW and 900 kW were applied to the outer wall of the RPV, respectively. These values were converted into uniform heat-flux boundary conditions of $2170\,W/m^2$ and $4340\,W/m^2$ respectively, based on the total surface area of the RPV. For the radiation analysis, the emissivity of the RPV surface was set to 0.8, while the emissivity of the riser tube surfaces was specified as 0.68 for the oxidized condition and 0.35 for the unoxidized condition. The coolant flow within the riser tube was simulated with an inlet mass flow rate of 0.04 kg/s and an outlet static pressure of 0 Pa. The boundary conditions and analysis cases are summarized in Table 1.

Table 1. Designed Boundary Conditions of Hectar HTGR RCCS

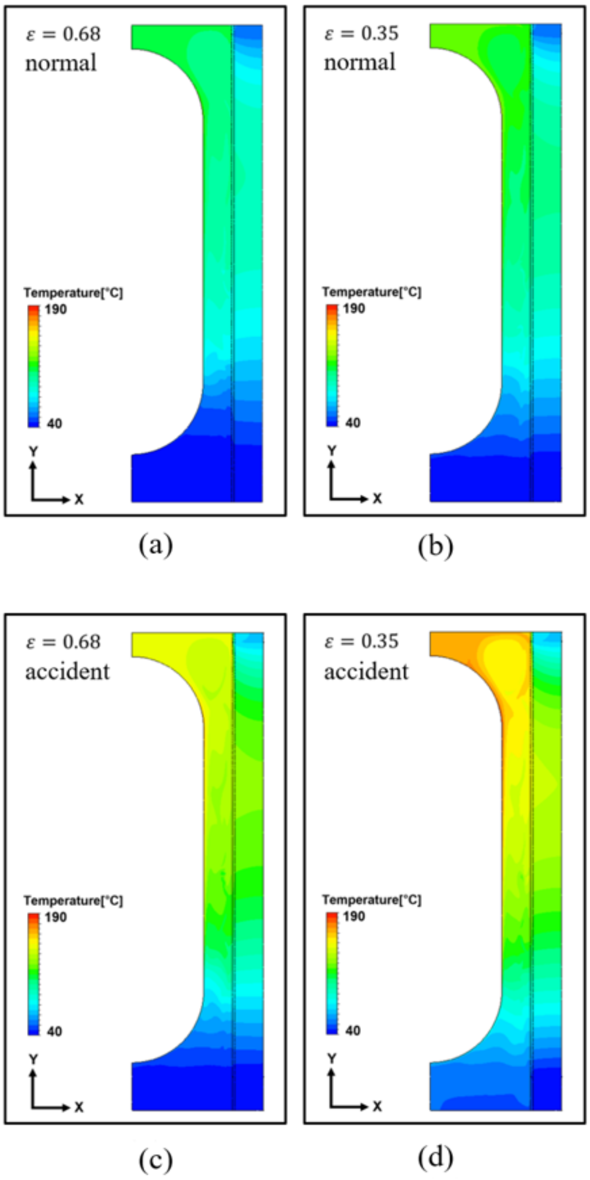
Parameter	Value [Unit]
y+	<1
Turbulence Model	SST
Radiation Model	Monte Carlo
Radiation Mode	Surface to Surface
RPV Heat Source (Normal, Accident)	450 kW, 900 kW
RPV Emissivity	0.8
Pipe Emissivity (Oxidized, Pristine)	0.68, 0.35
Reflective Surface Emissivity	0.07
Water Inlet	0.04 kg/s
Water Outlet	0 Pa

3. Conclusions

Table 2 summarizes the heat transfer components for the 4 cases with varying riser tube emissivity under both normal and accident heat load conditions. In all cases, heat removal through the riser tube was dominated by the radiative component, and the contribution of radiation increased as the heat load was elevated. In contrast, the heat absorbed by the reflector was relatively small, ranging from 0.01 kW to 0.08 kW, compared to the heat removed by the riser tubes. The resulting cavity temperature distributions corresponding to this heat source partitioning are shown in Figure 2. Under normal conditions, as illustrated in cases (a) and (b), a heated air layer rises along the RPV outer surface, forming a relatively mild high-temperature region in the upper part of the cavity. Under accident conditions, as shown in case (c) and (d), the overall cavity temperature level increases, and the high-temperature region near the upper cavity becomes more pronounced due to the increased heat load. When the riser tube emissivity is high, radiative heat is more effectively transferred to the riser tubes and subsequently removed by the coolant, resulting in reduced heat accumulation within the cavity and comparatively lower temperature levels. Conversely, when the emissivity is low, a larger portion of the radiative heat remains within the cavity air, leading to increased temperatures and steeper temperature gradients in the upper region. Overall, the present study confirms that heat removal in the water cooled RCCS is dominated by radiation under all conditions with the radiative contribution becoming more significant at higher heat loads. Furthermore, variations in heat load and surface emissivity influence the degree of heat accumulation within the cavity, thereby affecting the formation of high-temperature regions and the resulting temperature distribution characteristics. These findings suggest that RCCS thermal performance evaluations should account for both the radiation-dominant heat transfer structure and the associated heat accumulated behavior within the reactor cavity

Table 2. Radiative and Convective Heat Removal Components for the Four Analysis Cases

Parameter	Normal		Accident	
	ε=0.68	ε=0.35	ε=0.68	ε=0.35
Radiative Heat Emitted by RPV	7.01 kW	6.54 kW	15.48 kW	14.75 kW
Convective Heat Transferred by RPV	2.95 kW	3.42 kW	4.44 kW	5.16 kW
Radiative Heat Removal by Pipe	7.09 kW	6.4 kW	15.61 kW	14.46 kW
Convective Heat Removal by Pipe	2.81 kW	3.54 kW	4.39 kW	5.46 kW
Radiative Heat absorbed by Reflective Surface	0.02 kW	0.01 kW	0.08 kW	0.02 kW



(a) (b) (c) (d)

Fig. 3. Cavity Temperature Distributions Under Different Heat Loads and Riser Tubes Emissivity

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