Setting boundary conditions for heat loss calculation in MSR : An integrated CFD and GAMMA+ coupling methodology

Junkyu Han[a, b], Nam-il Tak[a], HongSik Lim[a], Sang ji Kim[a], Jeong Ik Lee[b*]
[a]Korea Atomic Energy Research Institute, 11, Daedeok-daero 989, Yuseong-gu, Daegeon, 34057, Republic of Korea
[b]Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology
373-1 Guseong-dong Yuseong-gu, Daejeon, 305-701, Republic of Korea
[*]*Corresponding author: jeongiklee@kaist.ac.kr*

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1. Introduction

One of the significant features of Gen-IV reactors is the passive residual heat removal system, which offers substantially improved safety, economy, and versatility compared to traditional active systems. The passive system is designed to naturally dissipate heat from the reactor during accident scenarios without the need for external power or human intervention. Utilizing natural phenomena such as gravity, natural convection, and thermal radiation, this system safely discharges heat without consuming electricity, thus lowering the risk of failure and reducing operational costs. Moreover, its ability to function under diverse environmental and installation conditions, and its applicability to both small modular reactors and large-scale reactors, significantly enhances its versatility. The adoption of passive systems ensures that Gen-IV reactors are safer, more economical, and more adaptable to various applications compared to previous generations.

The molten salt reactor (MSR), one of the Gen- IV reactor designs, is characterized by the primary coolant which generates heat not only within the reactor core but throughout the system. Korea Atomic Energy Research Institute (KAERI) is exploring passive residual heat removal methodologies that can be implemented in reactors with limited space, one of which involves using heat loss. When utilizing heat losses, the amount of heat loss varies depending on the thermal fluid environment at the external environment (ambient temperature, convection heat transfer coefficient at the outermost wall, etc.). Therefore, it is necessary to model not only the reactor system but also the parts that are in contact with the external environment.

The heat loss mechanism is predominantly governed by radiative heat transfer phenomena; thus, three-dimensional factors (such as the view factor) must be considered. If accident analysis is conducted using only the TH system code, it becomes inevitable to handle boundary conditions for areas where three-dimensional effects are significant, making it challenging to determine reasonable boundary condition values under current operating conditions.

This paper introduces a methodology for designing MSR's passive decay heat removal function and analyzes the results using the GAMMA+ code compared with the proposed coupled analysis method. This analysis provides a basis for the necessity and justification of coupled analysis under the conditions of the passive decay heat removal system. Accident analysis is being conducted using the GAMMA+ code [1]. The GAMMA+ has demonstrated its capability for normal and accident analysis of MSRs by incorporating models such as delayed neutron precursor, nuclear species group transport, and properties of fuel salts and coolant salts, originally developed for modeling the MSRE operated by the oak ridge national laboratory in the 1960s [2].

2. Methods

2.1 MMSR primary system description

The KAERI is currently developing a micro modular molten salt reactor (MMSR). In the MMSR, the nuclear fuel salt exits the reactor core and passes through horizontal piping before entering the primary heat exchanger. Within the primary heat exchanger, the heat is transferred to the secondary coolant salt. Exiting the primary heat exchanger, the nuclear fuel salt is divided into two channels. The fuel salt from each channel, after passing through its respective fuel pump, converges into a single channel that flows back toward the reactor core. At the core inlet, the salt enters a downward flow path through the upper annular flow distributor of the core and circulates.

2.2 Radiative heat loss

To identify the main heat transfer mechanisms in the system, a preliminary Computational Fluid Dynamics (CFD) analysis was conducted as shown in Fig. 1. Accurate modeling of radiative heat exchange in enclosed spaces necessitates the consideration of multi-dimensional variables. Key elements in this process include the view factor, radiative shields, and convective heat transfer. The results of the sensitivity analysis, as shown in Table I, confirmed that radiation is the predominant mode of heat transfer. The detailed simulation conditions are presented in Table II and Fig. 2.

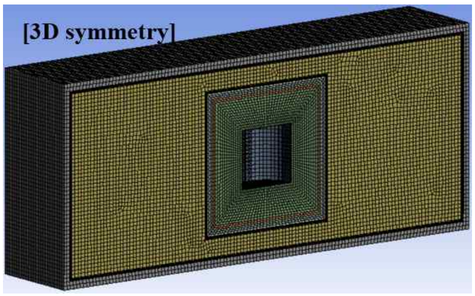

Fig. 1 Mesh modeling for sensitivity analysis

Table I: Sensitivity analysis of radiative heat transfer parameters

Case	Variables (Temperature, emissivity)			Part	Heat loss [kW]	Radiation ratio of heat loss
	T[℃]	ε_1	ε_2			
A	14	0.8	0.28	Bot.	2.6	0.88
				Side	11.1	0.83
				Top	2.5	0.89
B		0.6		Bot.	2.3	0.86
				Side	9.8	0.78
				Top	2.3	0.87
C	-33	0.8	0.8	Bot.	2.6	0.89
				Side	11.1	0.83
				Top	2.5	0.90
D	41		0.28	Bot.	2.6	0.89
				Side	11.1	0.83
				Top	2.5	0.90

Table II: CFD analysis conditions for sensitivity analysis

CFD code	STAR-CCM+	
Governing equations	Steady-state, Radiation, Gravity	
Discretization	2nd-order	
Equation of state	Ideal gas	
Thermal Radiation model	Surface to Surface	
Turbulence model	k-ω SST	
Initial condition	Core surface temperature	650℃
Boundary condition	Containment heat transfer coefficient (Top/Mid/Bottom)	8.16/3.03/4.51 W/m²K
	Ambient temperature	38℃ (air)
Containment	Inner fluid	Air
	Surface emissivity (containment inner/insulator)	0.9/0.28
	Conductivity	0.0375 W/m-K
	Thickness	0.01 m

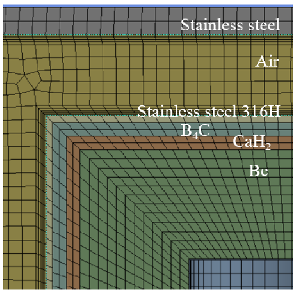

Fig. 2 Material condition for sensitivity analysis

2.3 Current status of modeling for safety analysis

In GAMMA+ code, radiation heat transfer can only consider heat transfer from a single surface. Therefore, for the conditions of the MMSR, a single surface radiation is assumed at the outermost surface of the primary system. However, the actual radiation mechanism involves surface-to-surface radiation transfer relative to the containment as shown in Fig. 3, and the required gas temperature for a single surface assumption is determined through complex heat transfer between the containment external environment and the primary system. At current GAMMA+ modeling, ambient temperature for single surface radiation was assumed to be 400°C [3].

According to preliminary accident analysis [4], a heat loss of 0.1% of the total output can affect the driving force of natural circulation during an accident, which indicates that a more accurate calculation method is necessary. This study evaluated the major equipment related to the primary system., as illustrated in Fig. 4.

Fig. 3 Radiation mechanism in MMSR

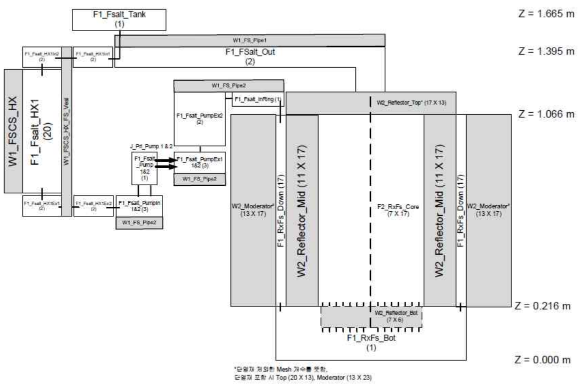

Fig. 4 Primary system modeling of the MMSR

2.4 CFD/TH system code coupled simulations

Two-way coupling was implemented on the outermost surface of the component's insulator (e.g., core, pipe, IHX, etc.). The heat transfer rates on the insulator surfaces were simulated using CFD, based on surface temperatures calculated in GAMMA+. These heat transfer rates were then established as boundary conditions in GAMMA+, and the surface temperatures were recalculated. This iterative process was repeated until the predefined conditions were met as shown Fig.5. The detailed analysis conditions are presented in Table III. Since radiation is the primary heat transfer mechanism, the effect of the grid size on the amount of heat transfer is negligible, as shown in Fig. 6, thus a minimal number of grids were used to enhance computational efficiency. The modeling distinctly categorized by equipment, and the reactor section, anticipated to be the hottest part, was divided into two sections (top and middle) to set boundary conditions.

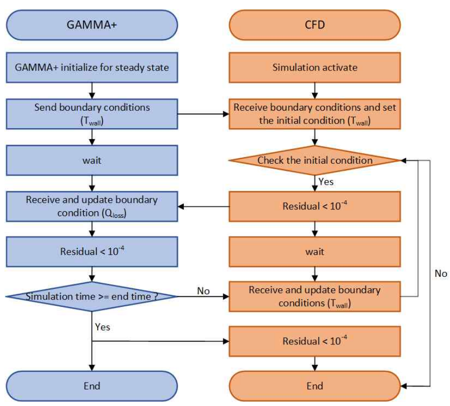

Fig. 5 Calculation logic of the coupling system

Table III: CFD simulation conditions

CFD code	STAR-CCM+	
Governing equations	Steady-state, Radiation, Gravity	
Discretization	2nd-order	
Equation of state	Ideal gas	
Thermal Radiation model	Surface to Surface	
Turbulence model	k- epsilon	
# of meshes	162,920	
Initial condition	Component temperature	462.1~470.6°C
Boundary condition	Heat transfer coefficient (vertical/horizontal)	5/1.5 W/m²K
	Ambient temperature	14°C (air)
Containment	Inner fluid	Air
	Surface emissivity	0.8
	Conductivity	0.0375 W/m-K
	Thickness	0.01 m

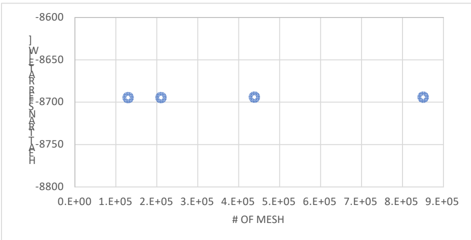

Fig. 6 Mesh sensitivity results

3. Results

As shown in Table IV, the results of the coupled simulations were compared with those obtained using the GAMMA+ stand-alone calculation. The analysis revealed that the heat loss predicted by the GAMMA+ code differs by approximately twice the amount when compared to CFD coupled analysis. This quantitative discrepancy is likely to influence the key variables such as the fuel salt temperature in safety analyses. As indicated in Table IV, the results from coupled simulations were compared with those from the GAMMA+ standalone analysis. The outcomes analyzed using the GAMMA+ show approximately 50% difference from the coupled analysis results. It was determined that such differences occurred due to assumptions such as single-surface radiation heat transfer (ambient temperature of 400°C). In reality, the external boundary conditions should be the external environment of the containment, but this occurred due to limitations of the code.

According to the results of the previous preliminary safety analysis [4], this quantitative difference is significant enough to affect factors such as the generation of driving forces in the fuel salt during safety analysis.

Table IV: Comparison of analysis results

Part	Heat transfer rate (% of thermal power)		Temperature [°C]	
	GAMMA+	Couple	GAMMA+	Couple
Rx top	0.017	0.047	443.5	269.4
Rx mid	0.051	0.072	442.0	256.0
Hot leg	0.012	0.010	409.9	259.3
Cold leg	0.019	0.016	408.2	256.2
IHX	0.007	0.063	412.0	257.5
Air	-	-	400.0	235.0
Total	0.105	0.208	-	-

4. Summary and Conclusions

The MMSR reactor is designed with its primary system located within the containment, targeting decay heat removal through heat loss. Utilizing heat loss necessitates considering three-dimensional elements, such as the view factor, due to the dominance of radiative heat transfer. When calculating heat loss solely with a TH system code, it is challenging to consider areas outside the outermost wall of the primary system, where radiative heat transfer predominates, because the heat transfer amount due to heat loss cannot be calculated directly from the outermost wall temperature of the primary system.

This study proposes a methodology for coupled analysis with CFD to address this issue. The wall temperatures calculated by the TH system code under steady-state conditions were used as inputs for calculating the heat loss heat transfer amount in CFD. The coupled analysis showed that the heat removal amount was about twice that of the TH system code stand-alone results, a difference significant enough to determine the presence or absence of natural convection during transient analysis.

This research confirmed the possibility of analyzing decay heat removal through heat loss, and established a coupled analysis system between the GAMMA+ code and STAR-CCM+. Future work includes transient analysis using coupling with CFD.

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