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Development of thermal analysis module of MSRE core for Monte Carlo neutron transport code

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1. Introduction

Molten Salt Reactor (MSR) is a reactor type that uses molten salt as a coolant. The MSR attracts attention among the Gen-IV reactors because of their inherent safety, which can prevent loss of coolant accidents and their simple structure. Also, the MSR has advantages such as a high thermal efficiency of up to 44% [1] and enhanced safety with a primary side pressure of 3.5 bar [2] compared to a PWR.

Seoul National University is developing a neutronics-thermo-fluid coupled analysis tool based on a Monte-Carlo neutron transport code, McCARD. As the MSR incorporates largely different reactor core configuration, it is required to develop a new thermo-fluid analysis module in order to accurately predict the temperature distributions in the fuel channel and moderator. Motivated by this, the present study aimed to develop a MSR thermal analysis module for McCARD and validate it.

The MSRE (Molten Salt Reactor Experiment) was started in 1964 at ORNL to study civilian power production from MSR. The MSRE core consists of graphite stringers as moderators and liquid fuel flowing between graphite stringers. The experiment data greatly informed later MSR research. This paper used these data for the validation of the developed thermal analysis module.

2. Numerical Method

This section describes the heat transfer model and the assumptions for the thermal analysis of the MSRE.

2.1 Heat Transfer Model

In the MSRE, the liquid fuel moves from the bottom to the top of the core through the fuel channel. A 1-D heat advection equation needs to be solved for each fuel channel to calculate the fuel temperature. The governing equation for the fuel temperature is as follows:

$$\nabla \cdot \left(\rho_f c_{pf} \vec{u} \cdot T_f\right) = q_f''' \quad (1)$$

where ρ_f (kg/m^3) is the density of the fuel, c_{pf} (J/kg K) is the specific heat of the fuel, u (m/s) is the velocity of the fuel, T_f (K) is the temperature of the fuel, and q_f''' (W/m^3) is the volumetric heat generation rate of the fuel.

The temperature of the graphite is calculated by the 3-D heat conduction equation. In order to save the computational time, each graphite block is modeled using a single cell as a lumped parameter model. The governing equation is given by

$$\nabla \cdot \left(-k_g \nabla T_g\right) = q_g''' \quad (2)$$

where k_g (W/m K) is the thermal conductivity of the graphite, T_g (K) is the temperature of the graphite, and q_g''' (W/m^3) is the volumetric heat generation rate of the graphite.

In this study, the thermal connection between the fuel channel and the graphite is considered through convective heat transfer. The heat transfer between the fuel channel and the graphite block is as follows:

$$\mathrm{Q} = \mathrm{hA_f}\left(T_{wall} - T_f\right) \quad (3)$$

where h (W/m^{2}K) is the convective heat transfer coefficient and T_{wall} (K) is the interface temperature between the fuel channel and the graphite block. The finite volume method (FVM) was used to discretize the heat transfer equation.

2.2 Convective Heat Transfer Coefficient

In MSRE, the fuel flow velocity is low, and the MSRE core height confines the length of the fuel channels. Therefore, the thermal entrance effects of heat transfer are significant [3]. During normal operation, the fuel flow regime is laminar and forced convection. The Muzychka correlation is appropriate to use in this condition [4].

$$Nu(z^*) = \left[\left(\frac{f(Pr)}{\sqrt{z^*}}\right)^m + \left(\left\{0.501\left(\frac{fRe}{z^*}\right)^{\frac{1}{3}}\right\}^5 + \left\{3.86\frac{fRe}{8\sqrt{\pi}}\right\}^5\right)^{\frac{m}{5}}\right] \quad (4)$$

$$fRe = \frac{12}{2 \times \left[1 - \frac{192}{\pi^5}\tanh\left(\frac{\pi}{2}\right)\right]} \quad (5)$$

$$f(Pr) = \frac{0.886}{\left[1 + (1.909Pr^{1/6})^{9/2}\right]^{2/9}} \quad (6)$$

$$m = 2.27 + 1.65Pr^{1/3} \quad (7)$$

where Nu is the Nusselt number, $z^*(m)$ is the dimensionless position of the fuel channel, Re is the Reynolds number of the fuel flow, Pr is the Prandtl number of the fuel flow, and f is the friction factor.

2.3 Wall temperature between fuel channel and graphite

FVM calculates the average temperature of the graphite and requires the wall temperature between the fuel channel and the graphite to calculate the heat transferred through convective heat transfer accurately. Therefore, the difference between the two needs to be calculated. Engel's approximation method was used to assume the wall temperature, calculating two approximations as upper and lower bounds and applying the value in between for the MSRE geometry [5]. The lower bound was calculated by replacing the graphite stringers with cylindrical rods of the same cross-section area. The cylindrical rod has a radius of 0.0254 m. The difference between the average graphite and wall temperatures is calculated as follows.

$$T_g - T_{wall} = \frac{1}{8} * \frac{q_g''' r_c^2}{k_g} \quad (8)$$

The upper bound was calculated by assuming the graphite stringer to be a flat plate spaced as far as the width of the fuel channel (0.0254m). The difference between the average graphite and wall temperatures is calculated as follows.

$$T_g - T_{wall} = \frac{1}{3} * \frac{q_g''' l^2}{k_g} \quad (9)$$

The difference between the average temperature of the graphite and the wall temperature for the MSRE geometry was calculated by linear interpolation of surface-to-volume ratio and is given by

$$T_g - T_{wall} = 9.2624 * 10^{-5} * \frac{q_g'''}{k_g} \quad (10)$$

3. Model Description

The MSRE core was modeled as a 1/4 symmetrical geometry. In the horizontal cross-section, there are 159 cells, and in the vertical direction, there are 33 stacked cells. The adiabatic condition was applied to the outer sides. The overall 1/4 MSRE core model is shown in Fig 1. and Fig. 2. below. The parameters used in the MSRE core, including the physical properties of the grade CGB graphite and liquid fuel used, are shown in the Table. I. below.

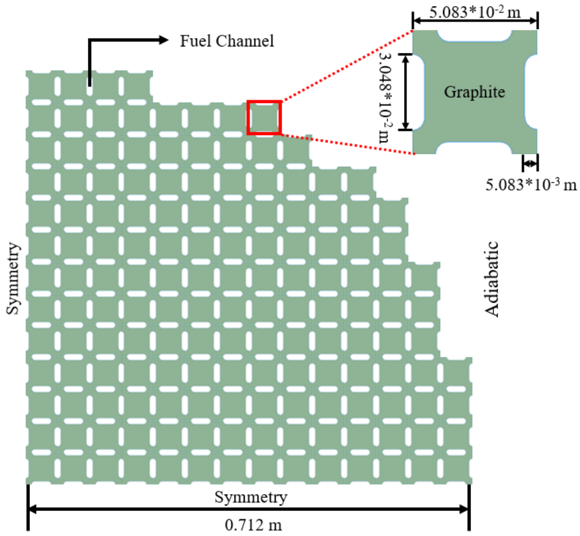

Fig. 1. Horizontal cross-section of the model

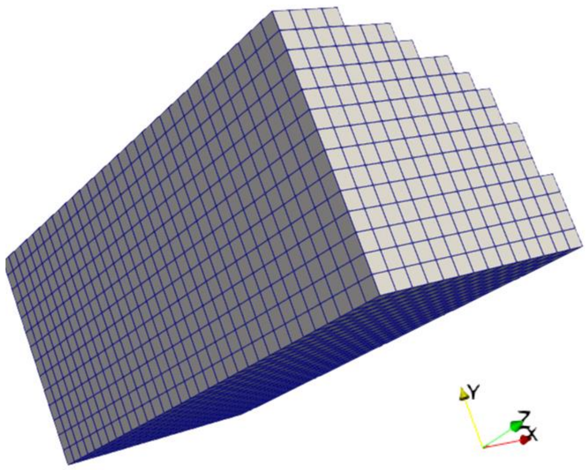

Fig. 2. 3-d geometry of the MSRE core

Table I: MSRE core physical properties

Parameter		Value
Fuel channel inlet temperature (K)		908
Graphite block side length (m)		$5.08339*10^{-2}$
Reactor Radius (m)		0.712
Reactor Height (m)		1.6764
Graphite cell	Thermal conductivity (W/m K) [7]	$3763*T_g^{-0.7}$
	Specific heat (J/kg K) [7]	1760
	Density (kg/m^3) [2, 8]	$1860*\exp(-1.8*10^{-5}*(T_g-922))$
	Total power (MW)	0.48
	Initial temperature (K)	908
Fuel	Thermal conductivity (W/m K) [9]	1.44
	Specific heat (J/kg K) [9]	1967.8

	Density (kg/m^3) [9]	2322.7-0.502* (T_f-922)
	Flow velocity (m/s)	0.231
	Reynolds number [5]	945
	Channel volume (m^3)	5.7504*10^{-4}
	Prandtl number [9]	11
	Total power (MW)	6.4
	Inlet temperature (K)	908

Radial and axial power distributions for the fuel channel and graphite were taken from ORNL MSRE design calculation [5,6]. The axial power density function is as follows.

$$P(z) = P_{max}\left(-1.384 + 2.383\, sin^2\left(\pi\left(z + \frac{1.448}{4.576}\right)\right)\right) \qquad (11)$$

where P_{max}(W/m^3) is the maximum axial power density, and z(m) is the axial position of the MSRE model. The radial power distribution function uses the Bessel function, assuming an idealized core.

$$P(r) = P_{max} * J_0\left(2.4 * \frac{r}{0.7112}\right) \qquad (12)$$

4. Simulation Results

4.1 Code-to-code comparison

Code-to-code comparison with a CFD was performed to verify that the module was developed properly. STAR-CCM+ was selected as a reference, and the geometry for the verification is shown in Fig. 3. The gray blocks represent the graphite and the yellow parts represent the fuel channels. All walls were assumed to be adiabatic. The physical properties used are mostly the same as Table. I, except that the volumetric heat generation rate is 4 MW/m^3 for the graphite blocks and 300 MW/m^3 for the fuel channels, and the inlet temperature is 922 K.

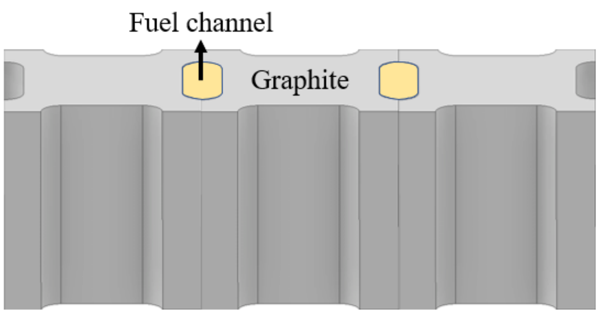

Fig. 3. Model used for the CFD calculation

The results of CFD calculation are shown in Fig. 4. The effective thermal conductivity of the graphite blocks and the heat transfer coefficient obtained from the CFD calculation were applied to the developed module. The comparison of the CFD and this study is shown in Fig. 5. The centerline temperature difference is up to 3.12% for the middle block. The comparison with CFD shows a good agreement.

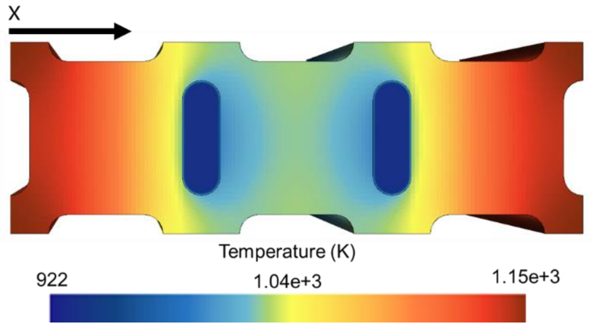

Fig. 4. CFD(STAR-CCM) calculation result

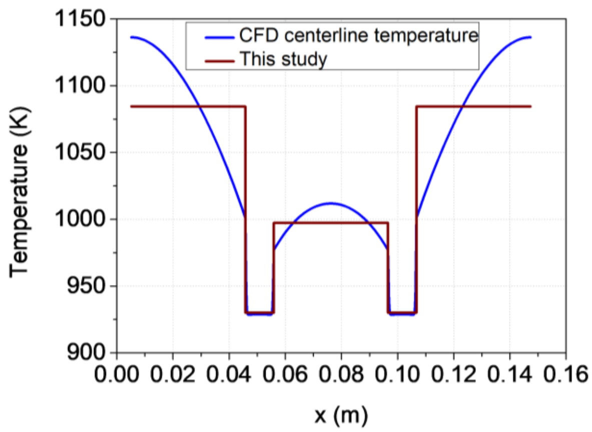

Fig. 5. Comparison of average centerline temperature between CFD and this study

4.2 MSRE core thermal analysis

The thermal analysis of the MSRE core for an 8 MW operating condition was performed. Fig. 6. shows the comparison of the temperature distribution in the hottest channel between this study and the ORNL MSRE design calculations. Fig. 7. and 8. shows the overall temperature distribution of the graphite and fuel. The fuel temperature increases monotonically, which causes the peak temperature of the graphite stringers to shift upward from the middle of the core. The peak temperature of graphite is 36K higher than that of the fuel due to the power from beta rays, gamma rays, and elastic scattering. The temperature difference between this study and the ORNL calculation is due to the error of not considering the axial heat conduction of the graphite in the MSRE design calculation and not knowing the exact power distribution [6]. Nevertheless, the similarity in the location of the peak temperatures and the tendency of the temperature to increase provides a good description of the core temperature in the MSRE.

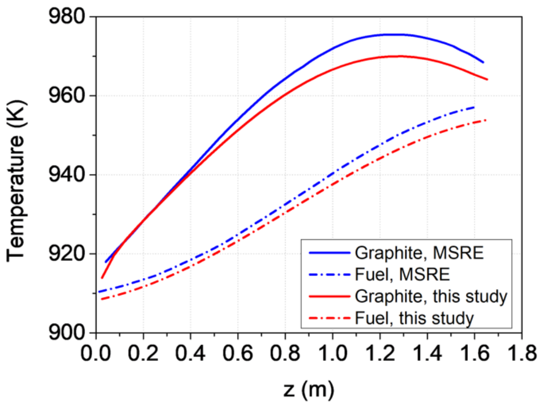

Fig. 6. Axial temperature distribution in the hottest graphite channel and adjacent fuel channels

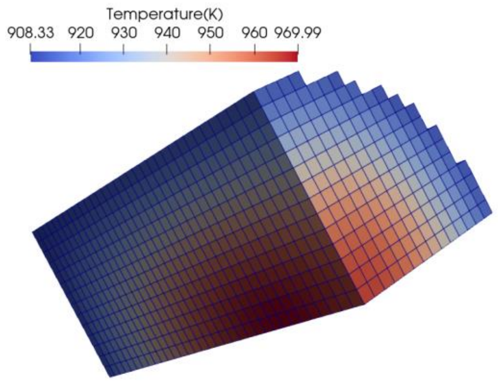

Fig. 7. Temperature distribution of the graphite

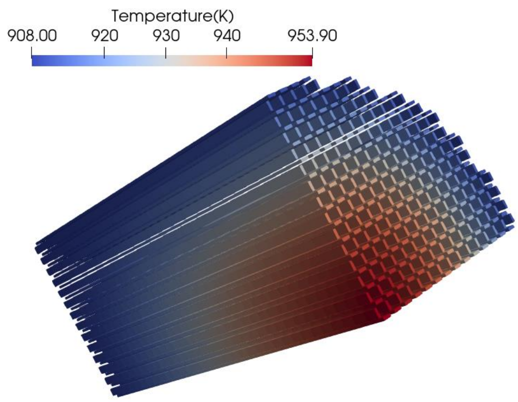

Fig. 8. Temperature distribution of the fuel

5. Conclusion

In this study, a code is developed to calculate the core temperature of MSRE using the finite volume method. Our model solves the governing equations for conduction and convection for a 3-D core to calculate the steady-state temperature. For the validation of the code, a comparison to the CFD calculation was conducted, and it was found to be in good agreement. Lastly, the thermal analysis of the MSRE core was performed, and the results showed a similar trend of temperature distribution compared to the design calculation of ORNL. A coupled analysis with neutronics calculation is required to obtain accurate output power and core temperature. In the future, this work will be merged into the neutronics analysis code as a thermo-hydraulics module.

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