Applicability of GeN-Foam to fast-spectrum molten salt reactors with BeO reflector and preliminary analysis

Wooseong Park [a] and Yong Hoon Jeong [a*]
[a] *Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology*
291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea
[*] *Corresponding author: jeongyh@kaist.ac.kr*

***Keywords :** molten salt reactors, multi-physics analysis, GeN-Foam, OpenMC

1. Introduction

Fast-spectrum molten salt reactors (F-MSRs) have distinctive advantages, but there are numerous physical phenomena that require analysis and clear identification.

One important research area in F-MSRs is neutronics (N) – thermal hydraulics (TH) coupled analysis. Substantial advancements have been achieved during the development of molten salt fast reactor (MSFR) in the frame of the EVOL and SAMOFAR projects. A pure TH analysis was conducted for MSFR core, which shows that toroidal-shaped geometry can remove large recirculation and local hot spot zone [1]. In addition, several attempts have been made to develop simulation codes for TH-N coupled multi-physics analysis that can handle unstructured geometry. Based on the developments, critical phenomena in MSFR such as delayed neutron precursor (DNP) drift and loss of DNP have been successfully analyzed.

Concurrently, several researches have explored the applicability of beryllium oxide (BeO) as a reflector material for F-MSRs [2, 3]. Due to its excellent neutronic performance, BeO holds the potential to substantially decrease the active core size, making it an appealing choice for micro reactor where weight and size are critical design constraints. However, to the best of the author's knowledge, a multi-physics analysis for the F-MSR core incorporating BeO reflector has not yet been conducted. Specifically, the use of BeO reflector is known to induce a highly skewed power distribution towards all. This introduces notable design complexities as achieving precise control of flow distribution in F-MSR seems challenging.

Accordingly, the present study conducted a multi-physics analysis for F-MSR with BeO reflector. Firstly, OpenMC [4] model was developed to generate multi-group constants. Then, GeN-Foam was used to perform TH-N coupled analysis [5]. The analysis was conducted for two cases: simplified cyinder model to ensure GeN-Foam's capability, and full core model including flow inlet and outlet parts.

2. Methods and Results

2.1 Simplified cylinder model

OpenMC is open source Monte Carlo particle transport code, have been developed by Computational Reactor Physics Group (CRPG) at Massachusetts Institute of Technology (MIT) [4]. OpenMC geometry to generate multi-group constants is shown in the Fig. 1. For the reference core design, parameters from the previous study were adopted [3]; The height and diameter of fuel salt region are 80 cm, and thickness of reflector is 30 cm. The composition of fuel salt is KCl-UCl_3 (46-54 mol%) with 99% enrichment of Cl-37. Boundary condition for BeO outer surface was set to vacuum, and ENDF/B-VII.1 was used for nuclear data library. Previous MSFR analysis used 6 group energy structure for diffusion neutronics; in here, one group was added to account for thermal neutron (see Table I.).

TABLE I. Flux energy group structure

Group	Lower energy bound (eV)	Upper energy bound (eV)
0	2.23e6	20.0e6
1	4.98e5	2.23e6
2	2.48e4	4.98e5
3	5.53e3	2.48e4
4	749.0	5.53e3
5	0.625	749.0
6	0	0.625

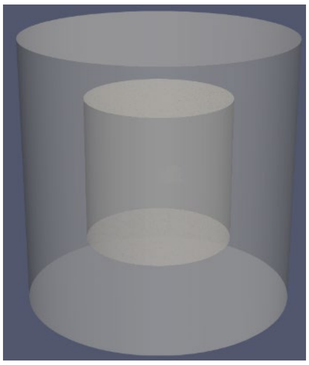

Fig. 1. Simple cylindrical geometry for OpenMC run.

GeN-Foam is an OpenFOAM-based solver to analyze reactors featuring pin-type, plate-type or liquid fuel [5]. TH sub-solver in GeN-Foam inherits much part from OpenFOAM, and N sub-solver provides multi-group diffusion, SP3, and SN models. In this study, multi-group diffusion model was used to conduct N analysis. Detailed theory and modeling parts can be found in the reference [5]. Fig. 2 shows cylinder model and generated mesh for GeN-Foam analysis. Outer surface was set to vacuum condition, and pure N analysis was performed.

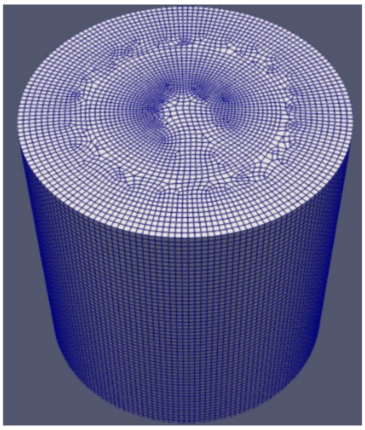

Fig. 2. Simple cylindrical geometry and mesh for GeN-Foam run.

Fig. 3 shows the power distribution from OpenMC and GeN-Foam calculation. It is seen that power distribution is highly skewed and its peak is presented at fuel/BeO boundary.

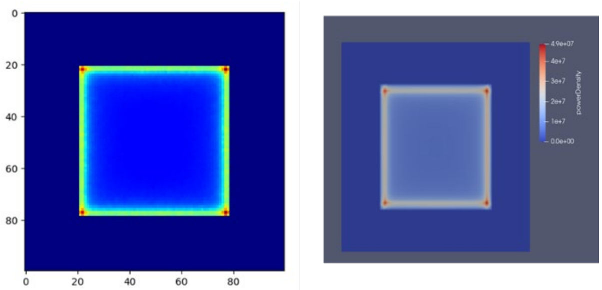

Fig. 3. Power distribution from OpenMC (left) and GeN-Foam (right).

Fig. 4 plots neutron flux distributions along center x-line and z-line. Due to BeO reflector, a considerable amount of thermal neutrons exist in reflector region while main core region still exhibits a fast-spectrum, enabling to take advantages from both spectrums. Although some deviations between OpenMC and GeN-Foam results are observed, the differences are not large and multiplication factors are in a good agreement considering the fundamental limitations of diffusion approach. k_{eff} values from OpenMC and GeN-Foam are 1.14616+/-0.00013 and 1.15442, respectively. From these results, GeN-Foam's applicability to BeO applications were confirmed.

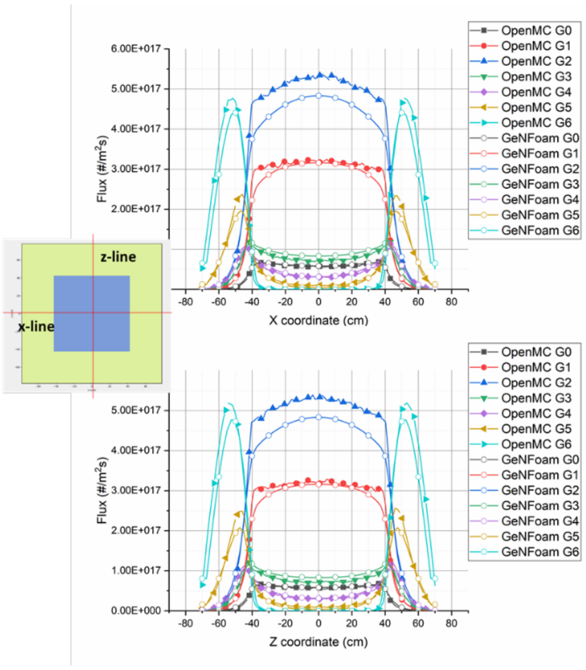

Fig. 4. Flux distributions along x-line (top) and z-line (bottom).

2.2 Full core model

Based on the cylinder model, MSFR-like full core model with inlet and outlet parts were configured. Fig. 5 shows 2D axisymmetric geometry and boundary conditions for TH and N domains.

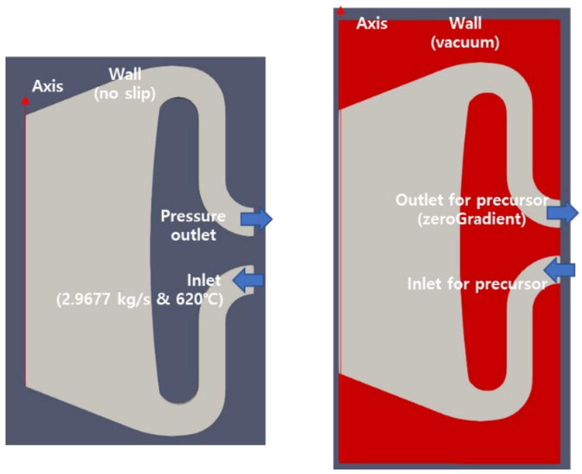

Fig. 5. Geometry and boundary conditions for TH (left) and N (right) domains.

In case of moving fuel, precursors need special boundary conditions for inlet and outlet. Outgoing precursors will experience decay in ex-core region and the rest will enter in-core region again. This can be represented as following equation, where C_{in}^{i} and C_{out}^{i} are precursor concentration at inlet and outlet respectively, λ^{i} is decay constant for each group, and τ_{loop} is flow residence time in ex-core region.

$$C_{in}^{i} = C_{out}^{i} \cdot exp(-\lambda^{i} \cdot \tau_{loop}) \quad (1)$$

Residence time of 10 s was assumed in this study, and outletMappedUniformInlet and zeroGradient from OpenFOAM was used for inlet and outlet respectively.

As a reference for neutronics and group constants, OpenMC was used again. Since the geometry is unstructured in this case, DAGMC utility was used to facilitate transport calculation. Fig. 6 shows cross-sectional plane of OpenMC geometry; in here, full 3D geometry was used with vacuum condition at outer surfaces.

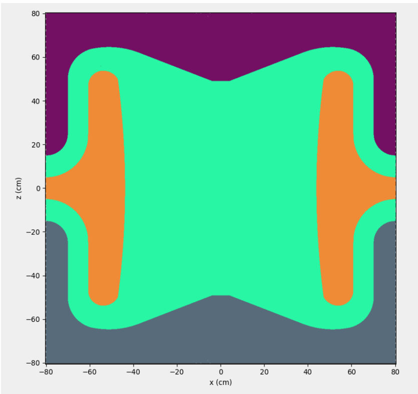

Fig. 6. OpenMC geometry for reference neutronics.

Fig. 7 shows power distribution and temperature distribution from GeN-Foam calculation. Similar to the previous cylinder model, it is seen that power density is considerably high near reflector region. Consequently, temperature distribution also exhibits its distortion along the power density. As the velocity near wall region is not sufficient to offset the high power density, local hot spot region shows maximum temperature of 667℃ (17℃ higher than outlet temperature)

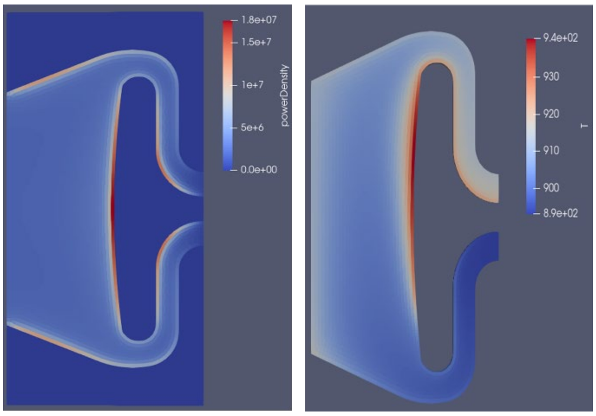

Fig. 7. Power distribution (left) and temperature distribution (right).

Lastly, the multiplication factors were compared with OpenMC results. In case of moving fuel, loss of DNP will result in the decrease of multiplication factor. From GeN-Foam analysis, it is shown that k_{eff} under static and moving fuel conditions are 1.15918 and 1.15765, respectively, indicating that fuel movement induces 153 pcm reduction. OpenMC results (static fuel condition) show k_{eff} value of 1.15404+/-0.00014, representing a good agreement between GeN-Foam and OpenMC results.

3. Conclusion

This study conducted multi-physics analysis for F-MSR with BeO reflector using GeN-Foam and OpenMC. Firstly, simple cylinder model was used to confirm GeN-Foam's capability. Then, it was applied to MSFR-like geometry. The results show that due to BeO reflector power distribution becomes highly skewed towards wall, and consequently, hot spot near the region is not avoidable. In addition, it was found that fuel movement induces k_{eff} decrement by 153 pcm. As further works, DNP drift and loss of DNP will be analyzed.

REFERENCES

[1] H. Rouch et al., "Preliminary thermal–hydraulic core design of the Molten Salt Fast Reactor (MSFR)", Annals of Nuclear Energy, 64, 449-456 (2014).

[2] B. Merk et al., "Innovative Investigation of Reflector Options for the Control of a Chloride-Based Molten Salt Zero-Power Reactor", Applied Sciences, 11, (2021).

[3] S. Yoon et al., "Multi-layer Shielding Design for Small-Sized Molten Salt Fast Reactor", Proc. ICAPP 2023, Gyeongju, South Korea, April 23-27 (2023)

[4] Paul K. Romano et al., "OpenMC: A State-of-the-Art Monte Carlo Code for Research and Development", Annals of Nuclear Energy, 82, 90-97 (2015).

[5] C. Fiorina et al., "Development and verification of the neutron diffusion solver for the gen-foam multi-physics platform", Annals of Nuclear Energy, 96, 212–222 (2016)