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Mitigation of Freezing in Molten Salt Reactors Using Phase Change Materials

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1. Introduction

MSR (Molten Salt Reactor) has been selected and developed as one of the generation-IV nuclear reactors [1]. MSR, using uranium-dissolved fuel salt, is free from core melt down and can be operated at low pressure. Operating at high temperatures, it can produce electricity or hydrogen with high thermal efficiency. MSR reactors adopt a strategy of discharging molten salt into a drain tank during scheduled or accidental shutdowns. The drain tank safely removes residual heat from the molten salt in a sub-critical geometry and stores it for reuse. Freeze valves are utilized in some designs for discharge; however, failures should also be considered since they do not operate completely passively. If the fuel salt were to solidify inside the system, it could increase uncertainties in the thermal behavior of the system and make restarting difficult.

PCM (Phase Change materials) can store/release a large amount of energy by utilizing the latent heat from the phase change process, Therefore, it can store thermal energy and serve as a thermal buffer. PCM is used in solar energy, buildings, electronic devices, and energy storage. Studies using PCM are also being conducted in nuclear reactors [2].

In this study, the effect of applying PCM to delay the molten salt freezing is assessed in a micro-MSR. A fuel pump stop scenario without operator intervention was simulated using the GAMMA+ code. Some design parameters of the micro-MSR system were assumed using those of the MSRE (Molten-Salt Reactor Experiment).

2. Methodology

2.1 GAMMA+ Model

The GAMMA+ code is initially developed to predict physical behaviors in accident situations that may occur in HTGR (High Temperature Gas Cooled Reactor). Currently, models have been included to expand the scope of application to micro gas-cooled reactor (MMR), liquid metal reactor (LMR), molten salt reactor (MSR), and space power reactors (SPR), and a CAPP/GAMMA+ module for neutronics - thermo-fluid coupled transient analysis [3].

In previous studies, GAMMA+ input model was developed to interpret the MSRE [4, 5]. In this study, the input model of the MSRE was modified using the design parameters of the micro-MSR. KCl-UCl3 was utilized as the fuel salt.

2.2 Phase Change Material

To select a phase change material, several considerations should be taken into account. The melting point of the PCM should exist within the anticipated temperature behavior range to effectively delay temperature changes. In practice, if a material with a melting point lower than that of the fuel salt is applied, anticipating that the temperature of the wall will be lower than that of the fuel salt, the PCM can't serve its purpose as it would reach its melting point after the fuel salt has already begun to freeze. Additionally, a large latent heat is required to serve as a thermal buffer. And to minimize heat dissipation to the surroundings, it is preferable for the material to have lower thermal conductivity.

The fuel salt operates at over 600℃ during nominal operation, while its liquidus point is 537℃. Therefore, 70.6Al-25.5Cu-3.9Mg(wt.%) with a melting point of 560℃ was chosen as the PCM. Its properties are summarized in Table I. PCM is assumed to be located inside the structure, without considering its fabrication feasibility.

Table I: Properties of 70.6Al-25.5Cu-3.9Mg [6]

T_m (℃)	560
H_f (kJ/kg)	545
$\rho_{s/l}$ (kg/m3)	2300
$Cp_{s/l}$ (kJ/kgK)	1.39
$k_{s/l}$ (W/mK)	20 / 70

2.3 Simulation Set-up

The temperature behavior of the system was examined through calculations for the fuel pump stop scenario. Within 5 minutes after the pump stops, the reactor trips. The thickness of the insulator was determined separately for the vessel and loop regions (Fig. 1) to adjust the system's heat loss rate, and the thickness of the applied PCM was divided into vessel, loop, and heat exchanger regions. Calculations were performed for the cases where PCM was applied to both vessel and loop, as well as to each region individually.

The system was cooled through radiative heat transfer from the outer wall, assuming that the external temperature was maintained at 400℃.

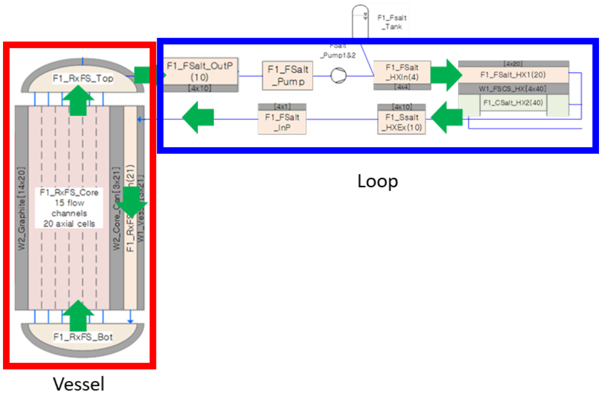


Fig. 1. Vessel region and loop region

3. Result and Discussion

Table II presents the results when the insulator was applied with a thickness of 2cm to the vessel and 1cm to the loop. 'Delayed time' is how long the fuel salt has been delayed to reach the liquidus temperature time compared to when PCM is not applied. A positive (+) means the delayed time, and a negative (-) means that it was reached rather quickly. When 7.5 cm of PCM was applied only to the vessel, the liquidus temperature was not reached for the guaranteed period.

When PCM was applied to all regions, there were cases where it slowly reached the liquidus temperature, and conversely, it could also reach it more quickly. Specifically, when the PCM thickness was thin in the loop region and thick in the vessel region, the approach to the liquidus temperature was slower. Conversely, thicker PCM application in the loop region resulted in a faster reach of the liquidus temperature.

In cases where PCM was applied only to the loop, the time to reach the liquidus temperature was faster, and this trend accelerated with thicker application (Fig. 2). In contrast, when applied only to the vessel, the time to reach the liquidus temperature was delayed, and this delay increased with thicker application (Fig.3).

Since both the vessel and loop are cylindrical geometry, and the critical thickness of insulation in this problem is about 1m, the surface area increases as the PCM thickness increases and the heat loss increases. In particular, because the loop has a small diameter, it has a large surface area increase effect, causing considerable heat loss, while the vessel has a large diameter (~0.7m), so the surface area and the heat loss increase effect were relatively insignificant.

Indeed, as observed in Fig. 3, when PCM was applied only to the vessel, the temperature began to decrease more rapidly due to the increased surface area. However, as PCM released latent heat, the temperature remained constant for a certain period and reached the liquidus temperature later.

Table II: Results of PCM Application

PCM thickness (cm)			PCM weight (t)	Delayed time (hr)
Heat exchanger	Loop	Vessel		
1.27	0.655	5.0	1.89	19.3
5.0	5.0	5.0	2.86	-10.9
5.0	5.0	1.44	1.62	-37.1
2.5	2.5	-	0.51	-23.8
5.0	5.0	-	1.13	-34.2
-	-	2.5	0.82	12.6
-	-	5.0	1.73	27.1
-	-	7.5	2.63	Not solidified

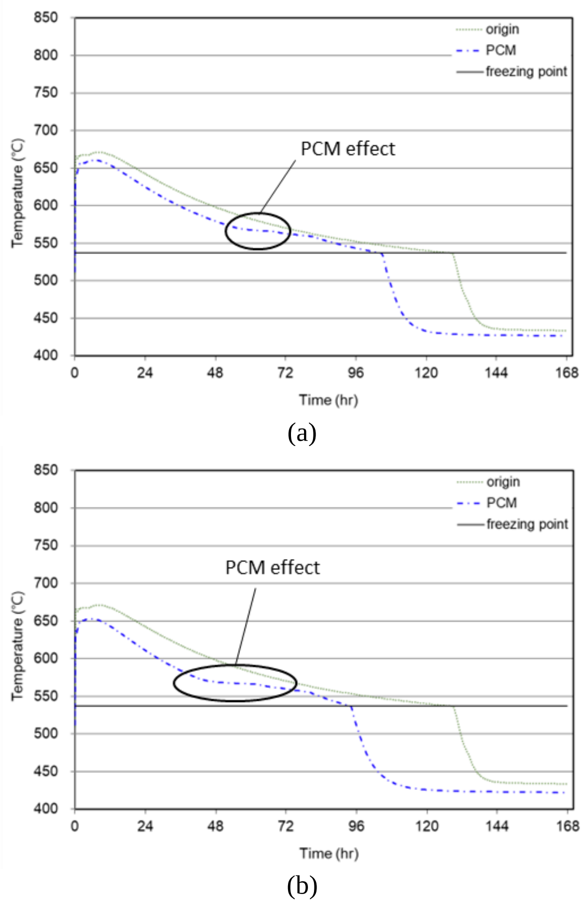
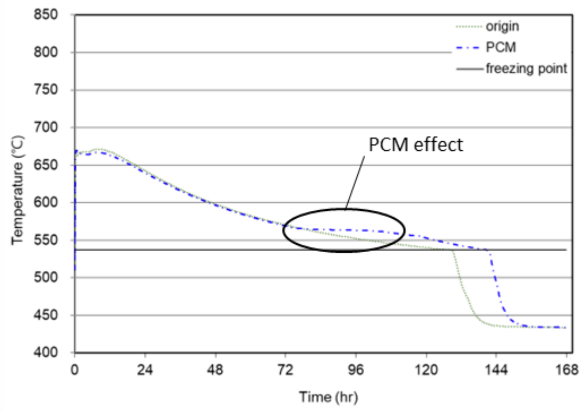
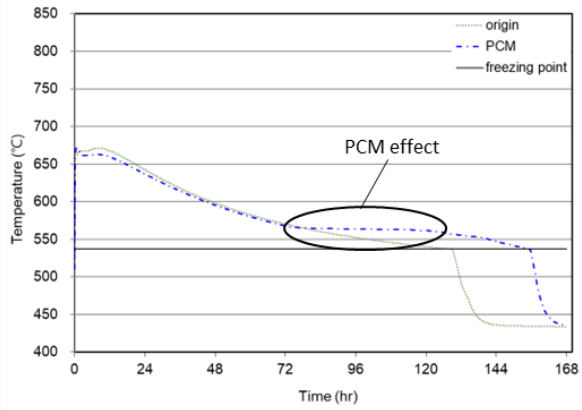


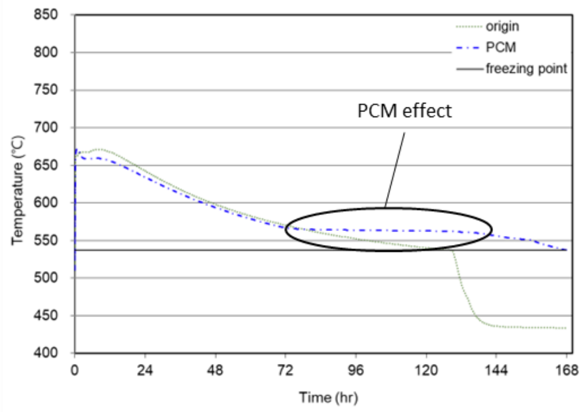
Fig. 2. Result of applying PCM only to the loop Thickness of PCM (a) 2.5cm (b) 5cm



(a)



(b)



(c)

Fig. 3. Result of applying PCM only to the vessel Thickness of PCM (a) 2.5cm (b) 5cm (c) 7.5cm

4. Conclusions

In this study the effect of PCM application in a micro-MSR system was investigated with GAMMA+ code to delay the time it takes for the fuel salt to reach its liquidus temperature.

The results demonstrate that the appropriate use of PCM can prolong the molten state of the fuel salt within the system. The addition of PCM increases the surface area for heat exchange, leading to higher heat loss, but also maintains the temperature constant for a certain period by releasing latent heat. In the large-diameter vessel area, the heat loss increase effect were insignificant, so PCM could be applied to obtain the desired effect, however when applied to a loop with a small diameter, heat loss was large, which was counterproductive.

Due to its passive operation without the operator intervention, it can be considered as a reliable strategy. Therefore, further research needs to be conducted in consideration of the geometry that can be actually manufactured.

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REFERENCES

[1] US DOE Nuclear Energy Research Advisory Committee. (2002). A Technical Roadmap for Generation IV Nuclear Energy Systems. GIF-002e00.
[2] Gadhave, P., Pathan, F., Kore, S., & Prabhune, C. (2022). Comprehensive review of phase change material based latent heat thermal energy storage system. International Journal of Ambient Energy, 43(1), 4181-4206.
[3] Tak, N. I., Lim, H. S., Hong, J., Yoon, J., Park, B. H., & Eoh, J. (2022). Improvement of GAMMA+ code for system transient and thermo-fluid safety analysis of sodium-cooled fast reactors. Nuclear Engineering and Design, 399, 112002.
[4] Tak, N. I., Lim, H. S., Lee, S. N., & Kim, S. J. Simulation of Natural Convection in the Molten Salt Reactor Experiment Using GAMMA. Transactions of the KNS Autumn Meeting, Changwon, Korea, October 20-21, 2022.
[5] Yoon, S. H., Tak, N. I., Lim, H. S. Validation of GAMMA+ code using reactivity insertion tests of MSRE. Transactions of the KNS Spring Meeting, Jeju, Korea, May 18-19, 2023.
[6] Costa, S. C., & Kenisarin, M. (2022). A review of metallic materials for latent heat thermal energy storage: Thermophysical properties, applications, and challenges. Renewable and Sustainable Energy Reviews, 154, 111812.