Feasibility Study on the Application of Multipurpose PCM System for Heat Loss Prevention and Decay Heat Removal for PMFR

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1. Introduction

Molten salt reactor (MSR) is one of the advanced reactors identified by the Generation IV International Forum. The unique feature of the MSR distinguished from any other reactors is its liquid fuel. In the MSR system, fissile materials are dissolved with the coolant as a form of halogen compounds. The compound circulates the primary system of the MSR, and the fission heat is generated mainly when it passes through the core region.

Due to the physicochemical characteristics of molten halide salts, the MSRs have the inherent safety advantages [1]. The most fission products obviously exist in the fuel salt depending on chemical properties. Because of this, the persistent purification of the salt is needed during operation. Typically, these are removed through a salt processing loop connected to the reactor, and the gaseous products are transported to the off-gas system via helium bubbling. As a result, the amount of fission product remaining inside the fuel salt during normal operation is expected low, and the heat load for the decay heat removal in an accident is expected to be small.

Recently, the advanced MSR concept called Passive Molten salt Fast Reactor (PMFR) was suggested. PMFR is an MSR that combines the latest fast spectrum core design and SMR technology under development at the I-SAFE-MSR center [2]. PMFR excludes fuel purification systems for simplicity and regulatory acceptance with a long-life core design of 40 years. Accordingly, the amount of fission products in the fuel of PMFR is expected to be more than usual, which makes the requirements of components such as pumps difficult. Researchers of I-SAFE-MSR have tried to overcome this issue through natural circulation design for normal operation [3].

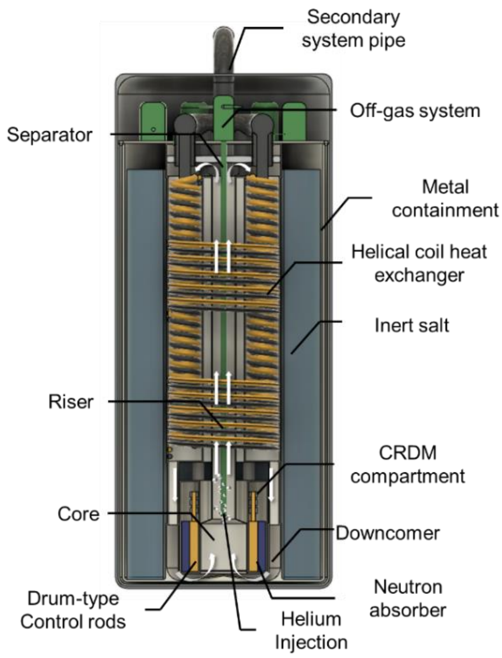

figure 1 Schematics of PMFR system

However, the characteristics of the PMFR long-life core are expected to also increase the heat load for decay heat removal. This is because normal fission product removal by salt purification does not occur. Fortunately, the natural circulation SMR design offers two distinct advantages in terms of decay heat removal. First, a large amount of fuel salt is loaded relative to the fission power to ensure natural circulation and long-life core design. This will reduce the volumetric heat generation of decay heat throughout the reactor loop. Another is the large surface area of the reactor vessel. This, combined with the high operating temperature characteristics of the MSR, suggests the possibility of heat removal through the reactor vessel.

Unfortunately, although these characteristics allow the decay heat removal by reactor vessel, this would result in significant heat loss during normal operation. When installing insulation for reactor vessel, additional process or mechanism must be followed to remove the reactor insulation in the accident condition, which does not ensure passive safety feature.

To solve this issue, our research team proposed a system that applied phase change material (PCM). PCM is a thermal medium that utilizes solid-liquid phase change heat, and has been recently studied for application to thermal management systems. As shown in Figure 1, the proposed PCM system is a concept that places PCM cells filled with inert salt between the reactor vessel and the containment vessel. The purpose of the system is to secure the insulation of the reactor vessel by remaining partially in a solid state under normal conditions. In addition, when the reactor vessel is heated by decay heat, the heat of fusion of the PCM is primarily intended to remove the decay heat. Furthermore, after all the PCMs are melted, heat removal through natural convection heat transfer could be expected to enhance the heat removal.

The main objective of this study is to investigate the feasibility of PCM system for the PMFR in terms of insulation and decay heat removal. A one-dimensional analysis was performed to evaluate the amount of heat loss and reactor cooling capacity. The results were compared with the case where the proposed system was not applied.

2. Methodology

The heat removal rate of entire system should be evaluated over a long period of time, on the order of several days to investigate the system response of the decay heat removal. For fastening the calculation, the system geometry was simplified as 1-D geometry. The entire system was simulated as a multi-layered r-direction concentric cylinder. The shape of the PMFR reactor vessel and containment vessel was considered as a simple cylindrical shape. The materials and properties are summarized and listed in Table 1.

Table 1. Properties of the materials

Materials & parameters	**Values**
Fuel salt properties [4]	UCl_3 – UCl_4 – KCl
Heat capacity	98.90 J/mol·K
Viscosity	3.5 cP – 2.0 cP
Density	3142.5 kg/m^3 – 3003.3 kg/m^3
Thermal conductivity	1 W/mK (Assumed)
PCM salt properties [5]	NaCl-KCl Eutectics
Heat of fusion	318310 J/kg
Melting point	662 °C
Heat capacity	894 J/kgK
Viscosity	0.09 cP
Density	1507 kg/m^3
Thermal conductivity	1 W/mK (Assumed)
Structural material [6]	Hastelloy-N
Maximum allowable temperature	1000 °C (Assumed)
Heat capacity	871 J/kg·K
Density	8860 kg/m^3
Thermal conductivity	20 W/mK

In this calculation, single numerical node was assigned to each material for the fuel salt, reactor vessel, PCM liquid, PCM solid, containment vessel, the ambient. The finite difference method was used to calculate temperature and PCM thickness, which came from the mass of solid layer. The mass of the solid and the liquid of the PCM change continuously through phase change. The liquid-solid interface of the PCM was considered as a vertical annular wall due to the 1-D simplification. From this, the thickness of the solid be evaluated.

The considerations of the heat transfer phenomenon for each node were summarized as following table 2. Natural convection heat transfer was divided into two types: type 1 was the natural convection phenomenon for a vertical wall, and type 2 was the natural convection heat transfer correlation for a coaxial cylinder encloser [7]. The PCM interface was obviously fixed at the melting point temperature of the PCM, and the melting or solidification rate was determined based on the net amount of heat added and removal at this layer with the heat of fusion.

In the case without the PCM system, the numerical nodes consisted of the fuel salt, reactor vessel, air in containment, containment vessel, and the ambient. Unlike the previous case, air was placed instead of the PCM system, and accordingly, radiative heat transfer between the reactor vessel and the containment vessel was considered.

Table 2. The heat transfer phenomenon for each node

From	**To**	**Heat transfer phenomenon**
The case with PCM system		
Fuel salt	RV*	Natural convection type 1 & Conduction
RV	PCM liquid	Conduction & Natural convection type 2
PCM liquid	PCM interface	Natural convection type 2
PCM interface	PCM solid	Conduction
PCM solid	CV*	Conduction
CV	Ambient	Natural convection type 1 & thermal radiation
The case without PCM system		
Fuel salt	RV	Same as the previous case
RV	Air in CV	Conduction & Natural convection type 2
RV	CV	Thermal radiation
Air in CV	CV	Natural convection type 2 & Conduction
CV	Ambient	Same as the previous case

*RV: reactor vessel, CV= containment vessel

The calculations consisted of two stages to fit the two objectives of the proposed system. The first stage was a steady-state situation where the fuel salt temperature was maintained at 700°C, which was for evaluating the heat loss during normal operation. At this time, it was assumed that the ambient temperature was maintained at 100°C.

The second was a transient situation for calculating the decay heat removal of PMFR. The transient situation was assumed to be a situation where the heat removal by the secondary system was completely lost, and the reactor was shut down. In the above situation, the PMFR was required to be able to cool the reactor vessel solely by the ambient. Here, the results of the previous calculations were used as initial conditions. In addition, a heat generation term from the decay heat was added to the fuel salt. As in the previous case, the temperature of the ambient is assumed to be maintained at 100°C.

3. Results & Discussion

The heat loss during normal operation was calculated through steady state calculations for each case. In the case without the PCM system, the containment temperature was at the level of 360°C, which caused high radiative heat transfer to ambient, but in the case with the PCM system, the containment temperature was maintained at a low level of 180°C, showing low radiative heat transfer. Accordingly, the heat loss without PCM system was 1339.2 kW, and when PCM system was applied, it was calculated as 195.4 kW, which corresponded to 0.45% and 0.07% of the fission power of PMFR, respectively. This suggests the feasibility of the PMFR reactor insulation effect through the PCM system as it reduces the heat loss to 1/6.

Figures 2 and 3 show the results of transient analysis with the initial condition of normal operation results of each case. Despite the excellent heat loss reduction effect in the PCM application case, the fuel maximum temperature was found to be at a similar level. This meant that the PCM effectively prevented reactor overheating due to decay heat. Figure 4 is comparing the amount of heat released from the containment vessel to the surroundings and the amount of decay heat in the PCM case. The heat capacity of the PCM prevented the release of decay heat into the environment for the approximately 15 hours, but it was confirmed that after the PCM was sufficiently melted, heat removal exceeding the decay heat generation occurred. It was determined that there was no deterioration in the decay heat removal performance of PMFR due to the application of the PCM system.

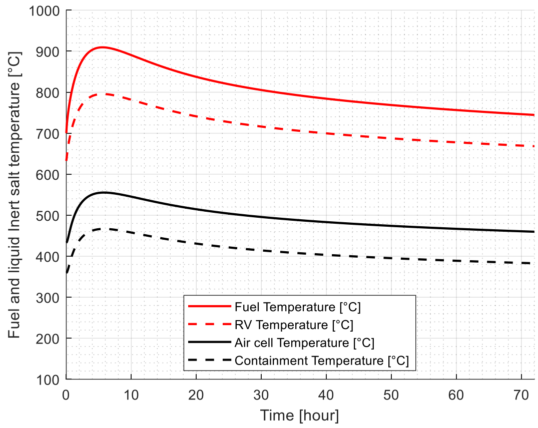

figure 2 Transient calculation results of the case without PCM system (Temperature for each layer)

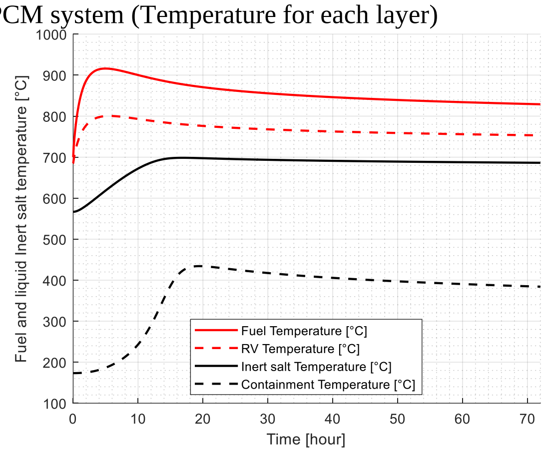

figure 3 Transient calculation results of the case with PCM system (Temperature for each layer)

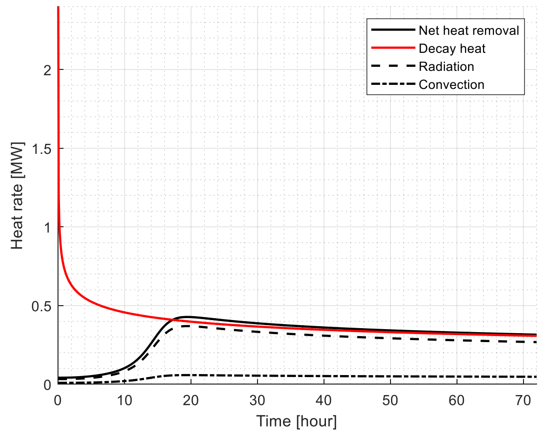

figure 4 Transient calculation results of the case with PCM system (heat removal rate from CV to the ambient)

4. Conclusion

This study was conducted to investigate the feasibility of multipurpose PCM system for the PMFR in aspect of preventing the heat loss and the decay heat removal. The 1-dimensional analyses were performed with and without the PCM system under steady-state and transient conditions for comparison. The main results of this preliminary analysis showed that when the PCM system is applied to PMFR, the heat loss during normal operation can be significantly reduced while maintaining the decay heat removal function under transient conditions. Since it was considered that both objective functions of the PCM system were satisfactory, it can be concluded that the PMFR application of the system is feasible.

Acknowledgments

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