Numerical evaluation of thermal behavior of freeze valve system for K-MSR

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1. Introduction

With the huge demand for electric power and the need for eco-friendly energy, Molten Salt Reactor (MSR), one of the next-generation reactors, is being actively developed due to its safety and efficiency. The K-MSR is a 100 MW_{th} class MSR under development in Korea for power source of marine ships.

One of the features of MSR is the Freeze valve (FV) system, which controls the flow of salt by utilizing the phase change of salt; that is, the valve is closed by freezing the molten salt, and the valve is opened by thawing it. In order to control the freezing and thawing of the FV, the FV is composed of a valve body and cooling and heating system around it. Compared to general mechanical valves, the internal structure of FV is relatively simple, which make it easy to improve corrosion resistance through surface treatment. In addition, FV has better sealing preventing fission product from leaking.

FVs are applied to various systems in the MSR and not only contributes to the normal operation, but also plays a major role in controlling the draining of fuel salt in an emergency. Therefore, it is essential to determine an appropriate cooling and heating system for the opening and closing control of the FV. Therefore, in this study, the cooling and heating behavior of the FV for K-MSR are described via FE analysis and evaluated.

2. Methods and Results

In this section, the concept, shape, and main dimensions of the FV for K-MSR are introduced, and FE analysis is performed to simulate cooling and heating process of the FV.

2.1 Concept of the FV for K-MSR

In this study, we refer to the FV shape used in MSRE, actually operated in 1960s [1] and set target operating time about 10 minutes for opening and closing of the FV. Recently, various studies on the FVs have been performed and the basic concepts of them are similar [2-4].

Fig. 1 shows the general components consisting of FV system. The FV can be divided into Flat section, Shoulder, and Normal pipe areas. Flat section and Shoulder areas are the main areas that determine opening and closing of the valve through the phase change of salt. To control the phase change of salt, a cooling and heating system is placed around the valve body, and several thermocouples are attached for monitoring of the temperature of the salt.

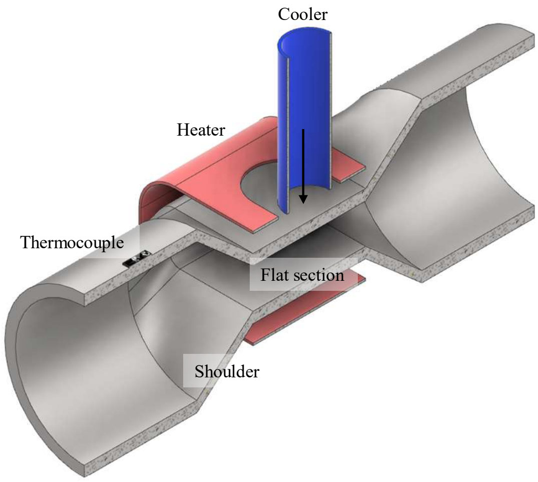

Fig. 1. Components of the FV system.

2.2 Shape and dimensions of the FV for K-MSR

Considering the 100 MW_{th} capacity of K-MSR and additional engineering characteristics, the initial shape and dimensions of the FV were adopted as shown in Fig. 2.

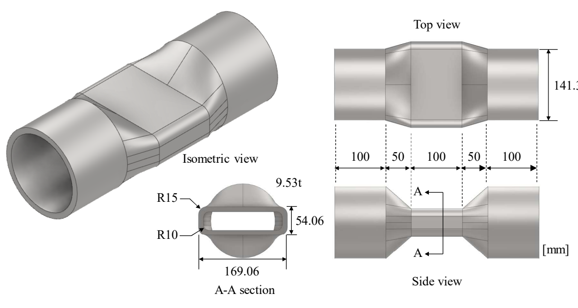

Fig. 2. Shape and dimensions of the FV for K-MSR.

The NPS 5 in. Sch. 80 pipe is applied. The length of the flat section is 100 mm, and the cross-section area is 150 x 35 mm^2. The shoulder connecting cylindrical pipes and flat section is 50 mm. The volume of the region where phase change occurs is 13.72 x 10^5 mm^3.

2.3 FE modeling of the FV

In this study, heat transfer analysis was performed based on FEM to describe the freezing and thawing of the FV. The FE analysis was performed using the commercial software ANSYS. The freezing and thawing of the FV is performed without salt flow, and the natural convection that occurs during the phase change of the salt is negligible. Therefore, the FEM-based heat transfer analysis not considering the flow of the salt is reasonable.

Fig. 3 shows the FE model for the FV and salt from one shoulder to the other shoulder. For computational efficiency, the quarter model was used. The elements for both FV and salt are SOLID279. Mesh size is approximately 4 mm, resulting that the number of total elements and nodes are 17,874 and 81,727, respectively, which is small enough for the FE analysis results to converge.

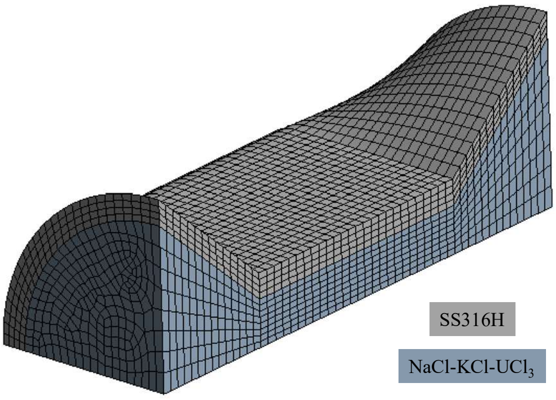

Fig. 3. FE model of the FV for heat transfer analysis.

The structural material of K-MSR is SS316H and the salt is NaCl-KCl-UCl_3. The thermal properties of the structural material and the salt at the operating temperature of the FV are shown in Table 1.

Table I: Thermal properties

	SS316H	NaCl-KCl- UCl_3
Density [kg/m^3]	7,750	3,450
Thermal conductivity [W/m·K]	21	0.4
Specific heat [J/kg·K]	560	610
Melting temperature [℃]	-	470
Enthalpy of fusion [J/kg]	-	144,523

In order to consider the enthalpy of fusion required for phase change of the salt, the equivalent specific heat of the salt, c_{eff}, is defined as

$$(1) \quad c_{eff}(T) = \begin{cases} c_p + \dfrac{h}{(475-465)} & for \;\; 465 \le T \le 475 \\ c_p & otherwise \end{cases}$$

where c_p, h, and T are specific heat, enthalpy of fusion, and temperature of salt, respectively.

Among the several FVs in K-MSR, the analysis is performed on the FV located below the reactor cell, directly related to the drain system. Fig. 4(a) shows the boundary conditions for freezing the salt to close the FV. Considering the operation temperature of the K-MSR, a temperature boundary condition of 540℃ is applied to the pipe and salt at one end and an adiabatic boundary condition is applied to the other end. The initial temperature of the FV and salt are 540℃ and 480℃, respectively. Heat flow boundary condition for cooling, -400 W, is applied to the outer surface of the FV.

Fig. 4(b) shows the boundary conditions for the case of thawing. They are the same with those of cooling at both ends. The initial temperatures of the FV and salt are 460℃. To reduce the pressure inside the FV deriving from the expansion of the melting salt, the heat flow boundary condition for heating, 50 W, is applied only to the one-side shoulder's surface.

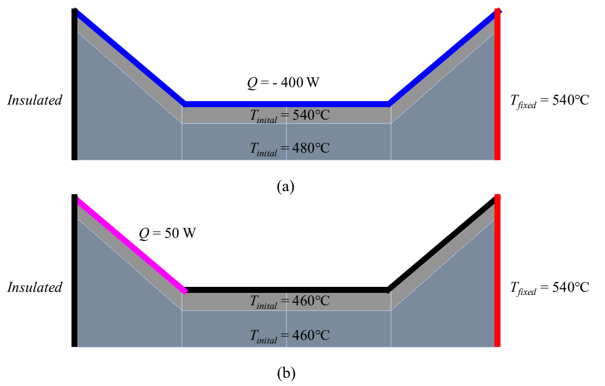

Fig. 4. Boundary conditions of FV for heat transfer analysis: (a) Freezing, (b) Thawing.

2.4 FE analysis results

Fig. 5(a) shows the temperature and phase distribution after cooling for 10 minutes. The salt in the flat section and shoulders are solidified. Therefore, it is judged that the flow of salt will be blocked when cooling is performed for 10 minutes with the corresponding heat flow. However, due to contact resistance between FV and salt and the heat removal efficiency of the cooling system, a longer time or a larger cooling system will be required.

Fig. 5(b) shows the temperature and phase distribution after heating for 10 minutes. Although there is some amount of salt in solid state, it will flow away with liquified salt by gravity in the actual FV, resulting the FV open. Since the reactor cell is utilized as a high-temperature heat source, thawing is possible with a relatively small heat flow compared freezing.

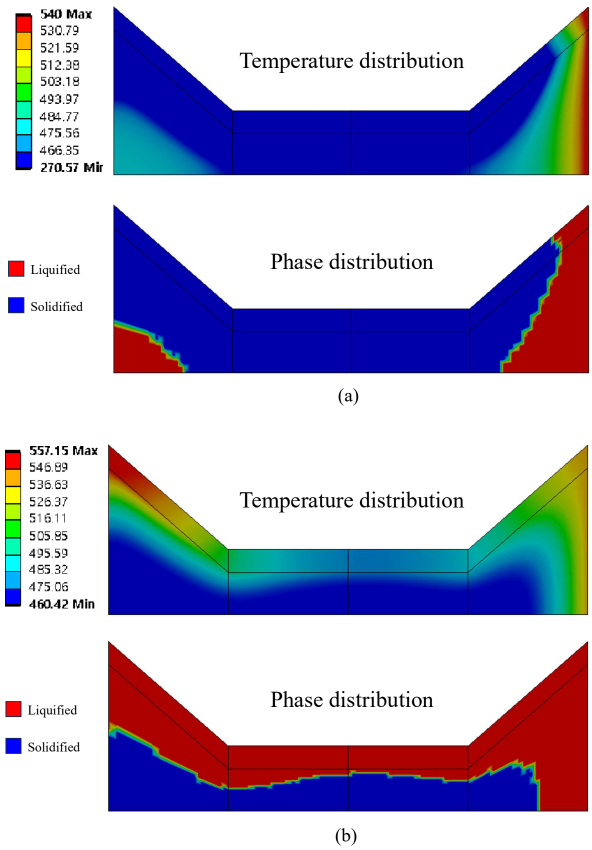

Fig. 5. Temperature and phase distribution form the FE analysis: (a) Freezing, (b) Thawing

3. Conclusions

In this research, the cooling and heating process of the FV for K-MSR were simulated via FEM-based heat transfer analysis. For opening and closing of the FV in 10 minutes, cooling and heating systems would require 1.6 kW and 200 W heat flow capacities, respectively. This research confirmed that heat transfer analysis based on FEM can be efficiently utilized for FV development. For future works, more realistic assumptions will be applied to FE analysis for more accurate results.

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