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Preliminary Core Cavity Design of a Micro Molten Salt Reactor (MSR) Using CFD Code

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1. Introduction

A molten salt reactor (MSR) is considered the most suitable candidate for a mobile micro reactor. Various types of nuclear reactors have been developed, with a particular focus on Pressurized Water Reactors (PWR) and Molten Salt Reactors (MSR). In comparison, MSR operates at lower pressures, typically around 3~5 atm, and occupies less volume. This characteristic makes MSR a more suitable choice for a mobile micro reactor when compared to PWR. For a commercial pressurized water reactor (PWR), solid nuclear fuel is arranged in a bunch of assemblies at the core's center, and the coolant passes through the sub channel of fuel assemblies to remove heat from the core. In MSR, liquid salt nuclear fuel passes through the core cavity (reactor region), where nuclear reactions occur. In PWR, the thermal energy increases towards the core's center, while in MSR, the thermal energy increases towards the reflector boundary. Imbalances in fluid flow in the MSR cavity could lead to localized temperature increases, which may result in reactor damage. In PWR, the integrity of the cladding surrounding the nuclear fuel is a critical design factor. Similarly, in MSR, the design of the cavity is also a crucial consideration.

2. Methods and Results

2.1 Characteristic of MSR core cavity

Due to the adhesive nature of flowing fluids, it is challenging to achieve high fluid velocities near the cavity wall. Therefore, obtaining high fluid velocity at the high heat output core wall is crucial. Based on the configuration derived from the previous studies, it is necessary to conduct thermo-hydraulic evaluations for the cavity design, as well as the inlet/outlet pipe shape and arrangement. The key requirements include: (1) Velocity at the active core wall should not exceed 3.0 m/s, and velocity in the inlet/outlet piping should be kept below 4.2 m/s. (2) The temperature at the active core wall should be maintained below approximately 670℃. (3) The permissible pressure drop in the system is limited to 2.0 bar. Power distribution in the core was modeled based on nuclear physics analysis results, and thermo-hydraulic analyses in the active core were individually conducted using commercial computational fluid dynamics (CFD) codes. The analysis covered various core designs, including inlet/outlet pipe configurations, to determine the optimal core shape.

2.2 Previous Studies

Various shapes of molten salt reactors have been developed, and among them, various methods are being employed to achieve a uniform flow distribution within the core cavity. Regarding a cylindrical reactor, there are broadly two methods are adapted for obtaining a fast and radially uniform flow distribution from the core wall: one method utilizes flow distribution plates, as shown Figure 1 [1], and the other, seen in reactors like MSFR, involves designing the cylindrical side in a curved form to induce very fast flow along the core radius. When the core side is curved, the shapes of the inlet and outlet channels of the core must be configured as shown in Figure 2 [2].

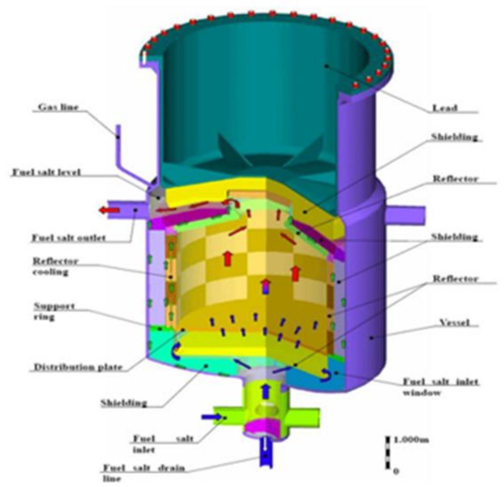


Fig. 1. Distribution plate of MOSART.

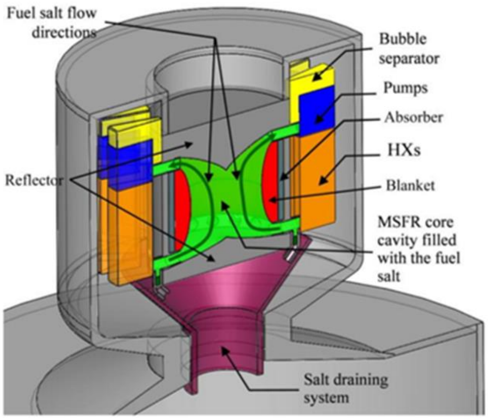
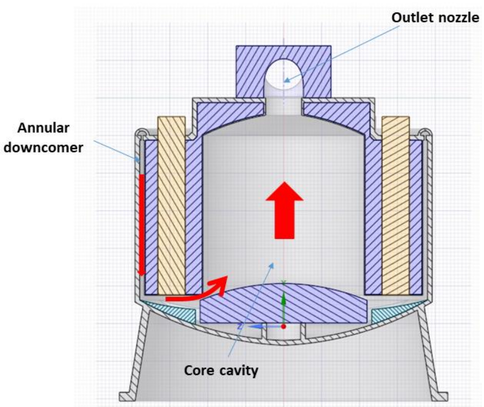


Fig. 2. Curved wall of MSFR.

2.3 Analysis of the Impact of Flow Distribution Plate and Curved Wall

Based on the previous studies, analyses were conducted to verify the effects of flow distribution plates and curved structures. Figure 3 illustrates the reactor configurations used in the analysis of the impact of flow distribution plate. The liquid fuel salt flows into the core from the annular down comer, where it is heated by fission in the core cavity. The reactor has a diameter of approximately 2.16 m and is surrounded by a reflector. Figure 4 depicts the power distribution of the core obtained from radiation transport calculation results. The power is higher than at the center of the core, reaching up to 9 times, due to the effect of neutron deceleration. Based on the results of radiation transport calculations, the power distribution in the core was modeled for CFD analysis.



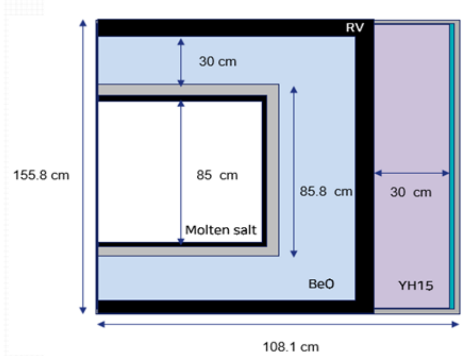


Fig. 3. Reactor configuration for the analysis of the impact of flow distribution plate.

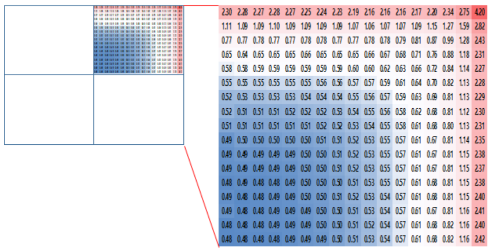


Fig. 4. Power distribution of the core.

The sort of fuel salt is KCL-UCL3. Inlet and outlet temperature are 620 ℃ and 650 ℃ respectively. The Fluent program was used for the analysis. A 180° symmetry model was employed for the analysis, where the reflector was simulated only inside the down comer, and the upper part was omitted. The flow at the inlet was assumed to be uniform, originating from the down comer inlet. k-ω SST turbulence models was used. To compare the effects of the down comer gap, lower plenum, and flow distribution plates, the analysis was divided into five cases and the cases were summarized in Table 1.

Table I: Cases for the analysis of the impact of flow distribution plate.

	Inlet dia. (cm)	Down comer gap (cm)	Inlet height of lower plenum (cm)	Presence of flow distribution plate
Case 1	19	2.5	6	X
Case 2	19	5.5	11	X
Case 3	19	7.5	16	X
Case 4	30	7.5	16	X
Case 5	30	7.5	16	O

As illustrated in Figure 5, in case 1, the rapid flow in the lower plenum led to swift flow observed in the cavity, with significant recirculation occurring along the core wall. As a result, the temperature of the core wall was relatively high, leading to the occurrence of a hot spot.

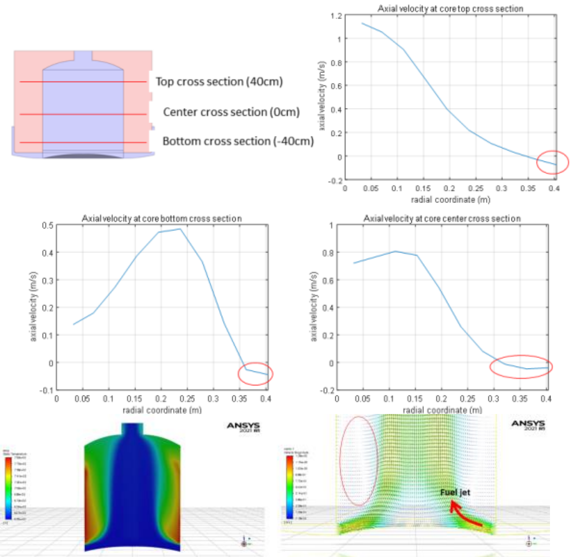


Fig. 5. Results of case 1.

As shown in Figure 6, in case 2 through case 4, as the flow area at the inlet widened, the jet effect diminished. The flow distribution at the inlet and outlet became more uniform as the outlet piping area increased.

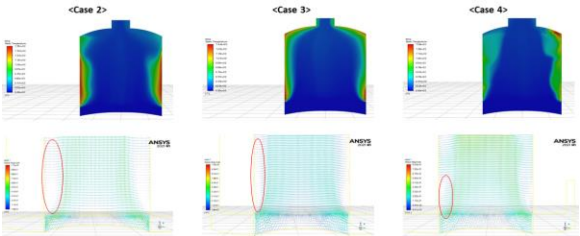
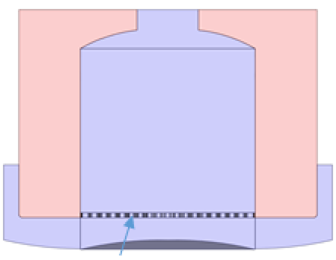


Fig. 6. Results of case 2, 3, and 4.

Figure 7 depicts the installation positions and shapes of flow distribution plates within the core. The flow distribution plate takes the form of a perforated plate with numerous orifices, and to control the velocity within the core, the sizes of the orifices are divided into two groups and set differently. The design factors of the flow distribution plate are summarized in Table 2.



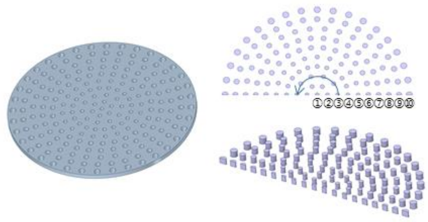


Fig. 7. Flow distribution plate

Table II: Flow distribution plate design factor

Length of orifice	2.5 cm
Clearance between orifice and plate	0.58 cm
Dia. of group 1 to 5	2.12 cm
Dia. of group 6 to 10	2.46 cm

Figure 8 displays that the flow distribution plate, a relatively uniform flow distribution could be obtained compared to the results without the flow distribution plate. However, a hot spot was still observed near the outlet. As intended, rapid flow could be achieved on the wall. The results of Case 5 indicate that the shapes of the outlet piping and the core wall need further improvement. It is also evident that the axial velocity deviation exists depending on the hole's location on the flow distribution plate that means the design of the flow distribution plate is important.

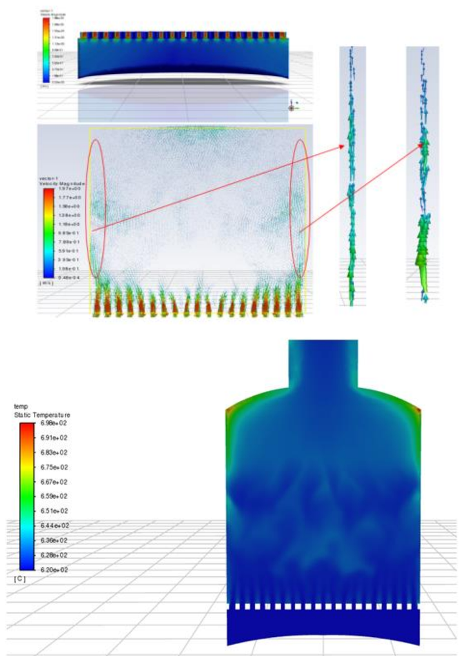


Fig. 8. Results of case 5.

2.4 Analysis of Toroidal-shaped Design

Preliminary analysis was conducted for the case where the side of the cylindrical core has a curved shape. This is a form adopted by the European Molten Salt Fast Reactor (MSFR). To address the flow recirculation issue within the core, the design involves placing the inlet and outlet in the annular region (the edge of the upper and lower surfaces of the cylinder) to allow the molten salt to flow rapidly along the curved surface. For analysis, a 1/6 symmetry was employed, as depicted in Figure 9.

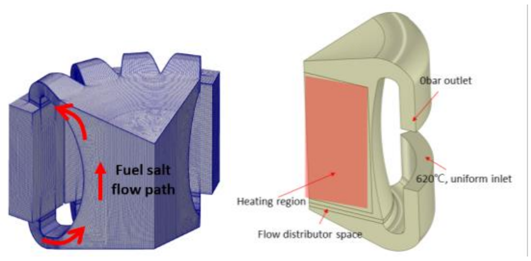


Fig. 9. Reactor configuration for the toroidal-shaped design.

The analysis results indicate that recirculation occurs in the central lower part and in some regions near the wall. However, intensities of the recirculation are very small. The axial velocity profiles at the bottom (-40cm), middle (0cm), and top (40cm) of the active core are illustrated in Figure 10. The flow is uniformly formed in the + direction, but near the high-output wall, the velocity is relatively slower, especially in the middle region. Consequently, hotspots occur in a wide range of area near the wall, and the maximum temperature rises up to approximately 674℃. This indicates that the toroidal-shaped design alone does not perfectly achieve homogenization of the heat flux distribution.

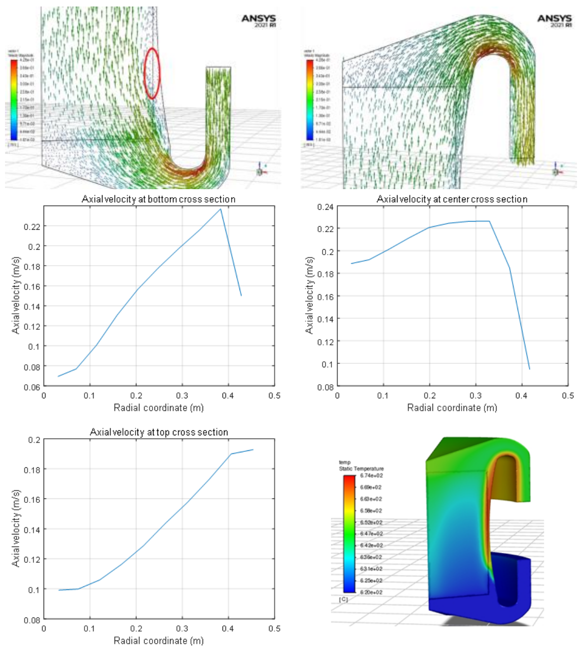


Fig. 10. Results of toroidal-shaped design.

3. Conclusions

In the cylindrical micro MSR reactor, the output at the core wall is exceptionally high. If the heat at the wall is not adequately removed, the reactor could be damaged due to thermal peaks. To prevent this, two approaches have been proposed: using flow distribution plates and designing the core wall in a curved shape. CFD analyses were conducted for both methods, and it was confirmed that each of these alone could not prevent the thermal peak in the core. Therefore, for uniformity within the core and to prevent thermal peaks, a suitable combination of these two methods should be employed.

ACKNOWLEDGMENTS

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