Study on the reduction of reactivity due to molten salt flow in MSR

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1. Introduction

A long-term cycle Molten Salt Reactor (MSR) powered by NaCl-KCl-UCl_3 fuel (U235 enriched 19.75 w/o) is being developed by FNC and KAERI [1]. In light water reactors, fission fragments (precursors) that emit neutrons are trapped inside the fuel rods, whereas in MSR, they flow through the core along with the fuel. Following nuclear fission in the core, the precursor nuclei, which should emit delayed neutrons, can escape through a heat exchanger or external piping and then release neutrons. Since the neutrons released outside the core don't contribute to the chain reaction, there are fewer delayed neutrons from the core's point of view, which lowers the control margin. For this reason, in MSR, the phenomenon caused by the flow of nuclear fuel must be considered in the core analysis [2]. The most recent version of OpenMC (0.15.4-dev24) now features a kinetic parameter calculation capability that allows the effective delayed neutron fraction to be determined. In this study, we calculate the change in k_eff for a simple reactor when the delayed neutrons remain in the reactor for varying lengths of time, both inside and outside. We then investigate whether these results are valid when the effective delayed neutron fraction is taken into account. This will serve as the foundation for predicting the decrease in reactivity when considering the in- and out-of-the-reactor neutron residence times of actual MSRs in the future.

2. Analysis Condition

To simulate the delayed neutron movement caused by molten salt movement in the OpenMC code, a new input delay_neutron_flow.xml is defined. This file includes information such as the molten salt movement velocity, the delayed neutron group-specific decay constant values obtained through a multi-group delayed neutron calculation in advance, the height of the core, and the length of the outer loop assuming the same cross-sectional area as the core. At this time, it was assumed that the height of the core was fixed, and input was generated by altering the speed of the molten salt and the length outside the core to adjust the time the molten salt stayed inside and outside the core.

2.1 Reactor Geometry

Figure 1 shows the geometric structure of the reactor employed in the analysis, with the area designated COR representing to the reactor core. It's height was set to 180 cm.

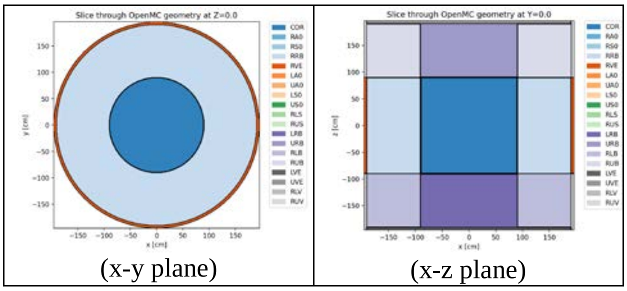

Fig. 1. The x-y and x-z planes of the MSR core

2.2 Methodology

Equation (1) illustrates the probability that the fission fragments produced by a nuclear fission reaction will not decay until time t and will decay in the interval t+dt. In Eq. (1), λ_g is the decay constant value of each delayed neutron group.

$$p(t)dt = e^{-\lambda_g t}\lambda_g dt \quad (1)$$

Since this is a probability value, if integrated over the entire time interval, it is confirmed to be 1.0, as in Eq. (2).

$$\int_0^\infty p(t)dt = \int_0^\infty e^{-\lambda_g t}\lambda_g dt = -e^{-\lambda_g t}\Big|_0^\infty = 1 \quad (2)$$

As a result, the time required for the generation of a delayed neutron can be sampled as shown in Eq. (3).

$$-e^{-\lambda_g t'}\Big|_0^t = xi, \quad t = -\frac{\ln(1.0 - xi)}{\lambda_g} \quad (3)$$

where, xi is a random number.

Once this time is established, the present position of the neutron and the velocity of the molten salt can be used to estimate where the delayed neutrons will originate. If the delayed neutrons were formed outside the core, they are predicted to be annihilated. This approach was applied to perform analysis with the open-source Monte Carlo code, OpenMC.

2.3 Analysis Set

As a reference for verification, the core analysis was initially performed in the absence of molten salt movement (R1 case), and the effective delayed neutron value was calculated. Second, the core analysis was carried out as if all delayed neutrons were generated outside the reactor (R2 case).

The analysis set was calculated for a total of 49 cases by merging the cases where the molten salt stays in-core for 1, 2, 5, 10, 20, 50, and 100 seconds with the cases where the molten salt stays ex-core for 1, 2, 5, 10, 20, 50, and 100 seconds.

Since the height of the in-core was set at 180 cm, inputs affecting the speed of the molten salt and the length of the ex-core were used to achieve this.

Monte Carlo calculation settings were applied as follows: 450 total cycles, 200 inactive cycles, and 1,000,000 total particles. The standard deviation of each calculation was set to be within about 25 pcm.

3. Analysis Results

To begin, it can be confirmed that the reactivity reduction of 0.00630 obtained from k_eff in the two reference cases is consistent with the effective delayed neutron fraction value of 0.00615 within the standard deviation value as presented in Table I. As expected, the results in Table II shows that the k_eff value increases as the molten salt remains in-core rather than ex-core. It is worth noting that when the time spent in-core is 1 second and the time spent ex-core is 100 seconds, the drop in reactivity is only 1/1.19987 - 1/1.20409 = 292 pcm as opposed to the R1 case. This demonstrates that, even during the brief 1 second spent in-core, a considerable number of delayed neutrons were generated inside the reactor, contributing to nuclear fission.

Table I: Reference Cases

	R1	R2	$\Delta\rho(1/k_{R2} - 1/k_{R1})$
k_eff	1.20409	1.19502	0.00630
β_eff	0.00615	-	-

Table II: k_eff according to the time that the molten salt stays in-core and ex-core

ex-\in-core	1[s]	2[s]	5[s]	10[s]	20[s]	50[s]	100[s]
1[s]	1.20106	1.20203	1.20301	1.2035	1.20381	1.20382	1.20408
2[s]	1.20068	1.20142	1.20243	1.20295	1.20356	1.2038	1.20389
5[s]	1.20017	1.20075	1.20159	1.20239	1.20312	1.20359	1.20381
10[s]	1.20011	1.20048	1.20121	1.20196	1.20264	1.20344	1.20368
20[s]	1.20011	1.2003	1.20119	1.2017	1.2024	1.20316	1.20354
50[s]	1.20017	1.20038	1.20092	1.20161	1.20214	1.20296	1.20341
100[s]	1.19987	1.2002	1.20093	1.20139	1.20237	1.20276	1.20326

3. Conclusions

It was quantitatively verified that the flow of molten salt in the MSR causes the movement of fission products, and that the duration of their stay in and out of the reactor determines the decrease in reactivity. Because the specific design of the MSR has not yet been finalized, the molten salt flow rate and the duration of its residence inside and outside the reactor could not be determined. Nonetheless, quantifiable confirmation of the expected trends was obtained. Furthermore, it was found that even when the molten salt remained inside the reactor for only one second, a considerable number of delayed neutrons were generated, impacting fission.

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