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A Study on the Application of Equivalence Theory to Molten Salt Fast Reactor

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1. Introduction

The Molten Salt Reactor (MSR), one of the Generation IV International Forum (GIF) [1] reactor, has several characteristics such as low-pressure operation, liquid fuel, accident resistance and very high fuel utilization, etc. In order to overcome the weakness of conventional thermal spectrum-based MSRs, the Molten Chloride Salt Fast Reactor [2] was mentioned in previous study.

As a result of previous studies [3], the neutron diffusion equation (hereinafter, NDE) and the Monte Carlo method show a difference of several hundred pcm in the reactivity calculation of the Molten Salt Fast Reactor. Therefore, it is seen that a general diffusion theory can bring large error to the calculation of the reactivity of the Molten Salt Fast Reactor.

This paper identified the degree of error in NDE calculation in MSFR's reactivity calculation. In addition, it is confirmed that differences could be reduced by using equivalence theories such as nodal equivalence theory using discontinuity factor (hereinafter, DF).

2. Reactor model and Method

2.1 Reactor Model

The reactor model for this study is two models as shown in figure 1 & 2. Figure 1 shows that a reflector surrounds the side of the reactor fuel. (Gray: Fuel, Yellow: Side reflector)

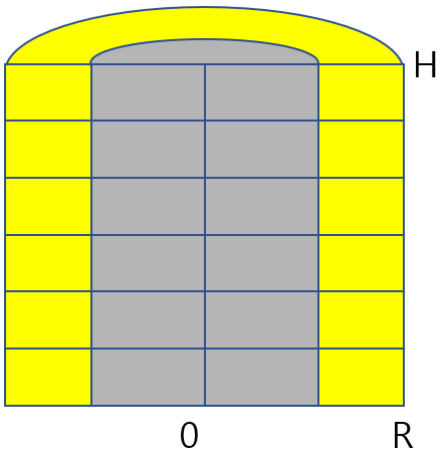

Fig. 1. Side Reflector MSFR (Model 1)

Figure 2 shows that a reflector surrounds the entire reactor fuel. (Gray: Fuel, Yellow: Side reflector, Orange: Top/bottom reflector)

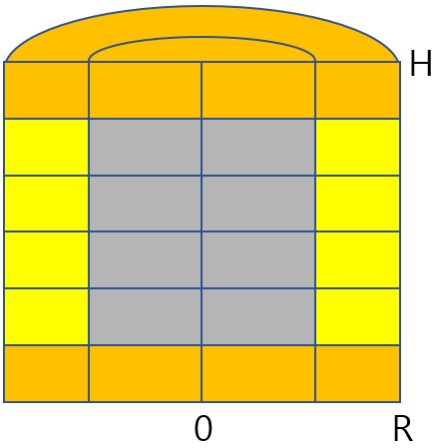

Fig. 2. Side, Top/bottom Reflector MSFR (Model 2)

2.2 Reactor Materials

The reactor materials used in this study are the same as those used in previous study [2]. However, the U-235 concentration of the fuel is 19.75 w%. Table 1 shows the information of the materials used in this study.

Table 1. Materials Data

Materials	Data
Fuel salt	46KCl-54UCl_3
U-235 enrichment	19.75 w%
Cl-37 enrichment	99.0 a%
Reflector	Stainless steel 304

2.3 Calculation Method

2.3.1 Monte Carlo Method

The SERPENT2 code is used as the code for making reference data, such as K_{eff}, group libraries and surface current, etc. Also, critical core size is determined using SERPENT2 code. Table 2 shows the calculation information applied to the SERPENT2 code.

Table 2. SERPENT Information

Code name	SERPENT 2.1.31
Libraries	ENDF/B-VII.1
Particles	500,000
Cycle	Inactive: 200, active: 300

2.3.2 NDE Method

The multi-group diffusion model is used in this calculation. In the case of thermal reactors, most nuclear fission reaction occurs below 0.625 eV, so the energy group is usually divided into two groups, such as thermal/fast. However, in the case of fast reactors, fission reaction occurs in a wide energy region, so it is necessary to divide them into several energy groups. In this study, it is divided into 9 energy groups as shown in the table 3.

Table 3. Energy Groups

Group	Upper Bound Energy (MeV)
1	20
2	6.07
3	1.35
4	4.98E-01
5	1.83E-01
6	6.74E-02
7	2.48E-02
8	9.12E-03
9	3.35E-03

Equation 1 is the steady-state balance equation of g-th group diffusion model at position r. It is assumed that the fuel of MSFR is homogeneously mixed. Therefore, it is assumed that the nuclear data in the fuel area are the same regardless of the location. The Finite Difference Method(FDM) is used to slove this equaion.

$$\nabla \cdot D_g(r)\nabla\varphi_g(r) - \Sigma_{r,g}(r)\varphi_g(r) + S_g(r) = 0$$

Eq. 1. Steady-state Balance Equation of g-th Group Diffusion Model

3. Calculation Strategy and Results

3.1 Calculation Strategy
3.1.1 Determination of the Critical Size of the Reactor

The critical size of the reactor is calculated using SERPENT2 code. The size of the fuel is determined to have a value similar in diameter and height, but longer in height.

3.1.2 Determination of DF between Fuel and Reflector

The DF at the interface between the fuel and the reflector is obtained only two representative value(Fuel+, Reflector-) for each energy group. In order to obtain the DF of the reactor as shown in Model 1(a reflector surrounds the side of the reactor fuel), the infinite cylinder model as shown in Figure 3 is used with the SERPENT2 code. Similarly, an infinite plate model as shown in Figure 4 is used to obtain the DF between the fuel and the top reflector.

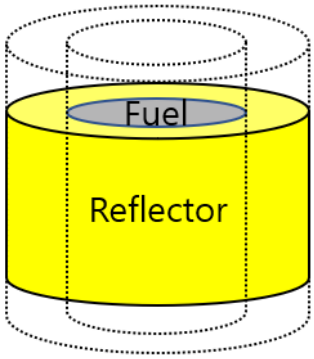

Fig. 3. Infinite Cylinder Model for Side DF

The K_{inf}, group libraries, and surface current values of the infinite core model are obtained using SERPENT2, and these values are applied to solve the infinite core model by NDE method. The solution of the NDE method obtains the representative surface current of each group in the interface.

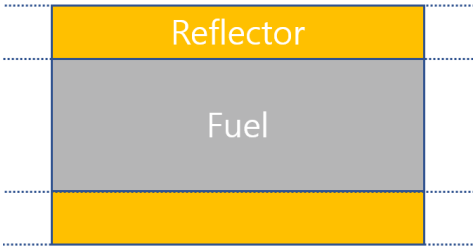

Fig. 4. Infinite Plate Model for Top DF

Equation 2 is an expression representing DF value. The DF value is determined by the ratio of surface flux obtained by SERPENT2 to surface flux obtained by NDE. Two DF values on the fuel side and the reflector side at the interface are obtained for each energy group.

$$f_g = \frac{\tilde{\phi}_{g,SERPENT}}{\tilde{\phi}_{g,NDE}}$$

Eq. 2. Discontinuity Factor

3.1.3 DF Implementation in NDE

$$J_g^{i,i+1} = \frac{2}{\left(\frac{\Delta r_{i+1} f_g^{i+1,-}}{D_g^{i+1}}\right) + \left(\frac{\Delta r_i f_g^{i,+}}{D_g^{i}}\right)} \left(\bar{\phi}_g^i f_g^{i,+} - \bar{\phi}_g^{i+1} f_g^{i+1,-}\right)$$

Eq. 3. Net Current Continuity on Surface using DF

Equation 3 shows the relationship between the surface current and the cell average flux using DF. Also, it shows that the surface current is continuous due to DF. Figure 5 shows each parameter at the interface between the fuel and the reflector used in equation 2 & 3.

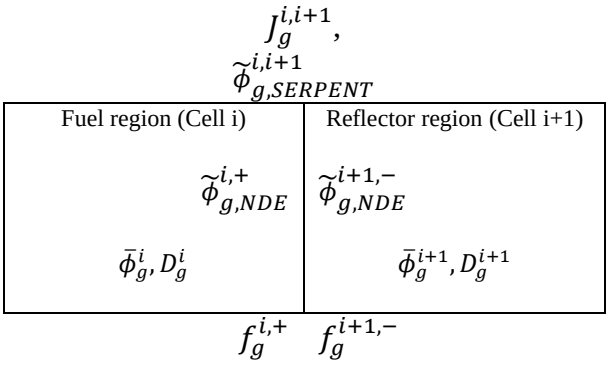

Fig. 5. Surface Flux Discontinuity

3.2 Results

3.2.1 Critical Size of the Reactor

As a result of SERPENT2 code calculation, the critical sizes of Model 1 and Model 2 are obtained as shown in Table 4.

Table 4. Critical Size of the Reactor

	Model 1	Model 2
Fuel radius	100 cm	90 cm
Fuel height	250 cm	200 cm
Reflector thickness(side)	40 cm	40 cm
Reflector thickness(top/bottom)	-	30 / 30 cm
K_{eff}	1.01173 ± 0.00005	1.01341 ± 0.00005

3.2.2 DF Values between Fuel and Reflector

Tables 5 and 6 show DF values of the interface between the fuel and the reflector, respectively. The DF of the interface facing the reflector in the fuel is calculated as a value near 1.0E+0. On the other hand, the DF of the interface facing the fuel in the reflector has values deviating from 1.0E+0. Especially in the low energy group, there is a big difference from 1.0E+0. This trend is common in Model 1 and 2.

Table 5. DF Values for Model 1

Group	Fuel+	Reflector-
1	9.22840E-01	1.11222E+00
2	9.81064E-01	1.05505E+00
3	1.01437E+00	1.03203E+00
4	1.04828E+00	9.97160E-01
5	1.03984E+00	1.04250E+00
6	1.00850E+00	1.02102E+00
7	1.25837E+00	8.87529E-01
8	1.15365E+00	7.69651E-01
9	9.97539E-01	5.08846E-01

Table 6. DF Values for Model 2

Group	Fuel-Side reflector		Fuel-Top reflector	
	Fuel+	Reflector-	Fuel+	Reflector-
1	9.22568E-01	1.11740E+00	9.35662E-01	1.13419E+00
2	9.77727E-01	1.05504E+00	9.91405E-01	1.06166E+00
3	1.01227E+00	1.03275E+00	1.01744E+00	1.02800E+00
4	1.04523E+00	9.96559E-01	1.05400E+00	9.94817E-01
5	1.03894E+00	1.04129E+00	1.03931E+00	1.03718E+00
6	1.01144E+00	1.01918E+00	1.00367E+00	1.01568E+00
7	1.25069E+00	8.85418E-01	1.28326E+00	8.83973E-01
8	1.14141E+00	7.67116E-01	1.18080E+00	7.62718E-01
9	9.97598E-01	5.08170E-01	9.97182E-01	4.62404E-01

The '+' sign indicates DF looking at the right/up boundary surface of the cell, and the '-' sign indicates DF looking at the left/down boundary surface of the cell.

3.2.3 Results of Applying DF to NDE

This paragraph shows the calculation result of the K_{eff} value according to DF application.

1) Side Reflector MSFR case (Model 1)

Table 7 shows the change in K_{eff} value according to DF application for Model 1. It shows when DF is not applied, when DF is applied on only one side, and when DF is applied on both sides, respectively. It shows that the application of DF can reduce the error in the calculation of NDE on the MSFR. In addition, it is shown that DF on the Fuel+ is more effective in reducing the error than DF on the Reflector-.

Table 7. Result of Model 1

Method	K_{eff}	Difference[pcm]
SERPENT2 (Reference)	1.01173 ± 0.00005	0.00
Normal NDE (DF not applied)	1.01874	680.3
Appling DF (Only 'Reflector –')	1.01701	513.4
Appling DF (Only 'Fuel +')	1.01390	211.3
Appling DF (Both)	1.01197	23.8

Table 8 shows the effect of improving the reactivity according to the number of groups. Even when applied to 4 or 6 group, it is found that the effect of DF application is good within tens of pcm.

Table 8. Group Sensitivity for Model 1

Group	K_{eff}		Difference[pcm]	
	Normal NDE	Appling DF	Normal NDE	Appling DF
9 Group	1.01874	1.01197	680.3	23.8
6 Group	1.02215	1.01220	1008.2	45.8
4 Group	1.02439	1.01231	1221.6	57.3

2) Side, Top/bottom Reflector MSFR case (Model 2)

Table 9 shows the change in K_{eff} value according to DF application for Model 2. It shows when DF is not applied, when DF is applied on only one reflector, and when DF is applied on entire reflectors, respectively. It shows that the application of DF can reduce the error in the calculation of NDE on the Model 2. In addition, it is shown that DF application on the side reflector is more effective in reducing the error than DF application on the top/bottom reflector. It is seen that there is a difference in the improvement effects as much as the area ratio between the side and top/bottom of the reactor. Therefore, it can be seen that the improvement effect is better as the area where the net current is preserved by applying DF is wide.

Table 9. Result of Model 2

Method	K_{eff}	Difference[pcm]
Serpent	1.01341 ± 0.00005	0.00
Normal NDE (DF not applied)	1.02508	1123.7
Appling DF (Only Side Reflector)	1.01668	317.1
Appling DF (Only Top/bottom Reflector)	1.02148	779.5
Appling DF (Entire Reflector)	1.01331	-9.8

4. Conclusions

In previous study, it was shown that a general diffusion theory can bring large error to the calculation of the reactivity of the Molten Salt Fast Reactor. As a result of this study, the neutron diffusion equation has an error of several hundred pcm in the reactivity calculation of the Molten Salt Fast Reactor.

It is found that the nodal equivalence theory using DF is effective in reducing the reactivity error. The DF at the interface between the fuel and the reflector is obtained only two representative value(Fuel+, Reflector-) for each energy group. As a result of applying DF, the reactivity error is reduced to several tens of pcm. It can be seen that only the representative DF value at the interface between the fuel and the reflector is effective in improving the reactivity error. Especially, DF on the Fuel+ is more effective in reducing the error than DF on the Reflector-. In addition, it can be seen that the improvement effect is better as the area where the net current is preserved by applying DF is wide.

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