Impact of Non-uniform Fuel Flow on Reactivity in a Molten Salt Reactor

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1. Introduction

The Molten Salt Reactor (MSR) is one of the Generation IV International Forum (GIF) nuclear reactor systems [1], and it provides many advantages such as low-pressure operation, liquid fuel, accident resistance and very high fuel utilization, etc. However, due to the flow of nuclear fuel, physical parameters such as neutron flux distribution, concentration of the delayed neutron precursors and reactivity have to be obtained in a different way than solid fuel.

Especially, the decrease in reactivity due to the movement of nuclear fuel in the molten salt reactor is one of the important information for safety assessment. The flow of fuel causes a change in the concentration of the delayed neutron precursors in the core. In addition, the external circulation of nuclear fuel may cause loss of delayed neutron precursors.

In this paper, the change in reactivity according to the flow rate is calculated. In particular, the difference in reactivity due to the difference in flow rate according to the region is calculated.

2. Reactor model and Method

2.1 Reactor model

The reactor model for the calculation uses what was mentioned in a previous work (F.mattioda, P.ravetto, G.Ritter) [2]. Figure 1 & table 1 shows the conceptual model and major reactor parameters of this model, respectively.

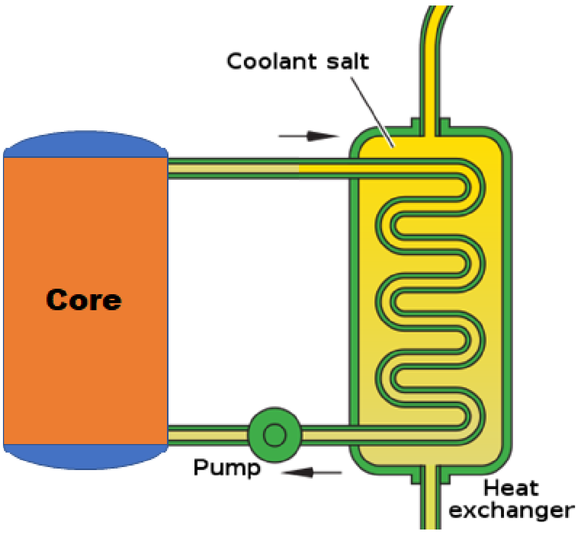

Figure 1. Conceptual model of MSR

Table 1. Reactor description (D=diameter, H=height)

Reactor type	Homogeneous Cylindrical Bare Reactor
Reactor dimension	D=3.0m, H=3.0m
Neutron energy group	3 groups
Delay neutron precursor	6 families

2.2 Calculation method

The multi-group diffusion model is used in this calculation. This model is also used in the previous work (F.mattioda, P.ravetto, G.Ritter) [2]. Equation 1 is the steady-state balance equation of multi-group diffusion model. A simbol 'u' is a velocity of the reactor fuel. The Finite Difference Method(FDM) is used to slove this equaion.

$$\begin{cases} \left(\frac{d}{dz}D_g\frac{d}{dz}-\Sigma_{R,g}\right)\Phi_g+(1-\beta)\,\chi_g\sum_{n=1}^{G}(\nu\Sigma_f)_n\,\Phi_n+\sum_{g'=1}^{g-1}\Sigma_{g'\to g}\Phi_{g'}+ \\ \sum_{g'=g+1}^{G}\Sigma_{g'\to g}\Phi_{g'}+\sum_{i=1}^{R}\chi_{i,g}\lambda_i C_i+S_g=0\,; \qquad g=1,2,...,G\,; \\ u\frac{dC_i}{dz}+\lambda_i C_i=\beta_i\sum_{n=1}^{G}(\nu\Sigma_f)_n\,\Phi_n\,; \qquad i=1,2,...,R\,. \end{cases}$$

Equation 1. Steady-state balance equation of multi-group diffusion model

2.3 Boundary condition

Several restrictions are applied to boundary conditions. Table 2 shows boundary conditions for neutron and delayed neutron precursors.

Table 2. Boundary condition

	Boundary condition
Neutron flux	$\Phi_g(z=0)=\Phi_g(z=H)=\Phi_g(r=R)=0$
Delayed neutron precursors	$C_i(z=0)=\ C_i(z=H)e^{-\lambda_i T_R}$ $T_R=Recirculation\ time$

It is assumed that fuel flows only in the axial direcion. During external circulation, delayed neutron precursors are uniformly mixed and re-entered into the bottom of the core. When going out of the core, each area has a different concentration of delayed neutron precursors, but they flow into the same concentration at the entrance. Figure 2 shows the conceptual design of fuel flow.

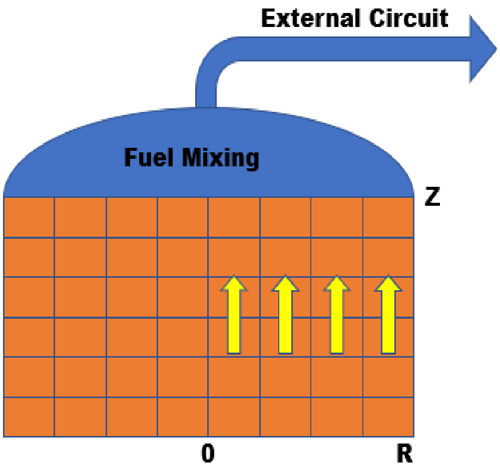

Figure 2. Reactor Flow model

In addition, the volume of the extenal devices, such as pipes, heat exchanger, is 2/3 of the volume of the core. Also, The faster the flow rate of the fuel, the shorter the recirculation time.

2.4 Material data

Three neutron energy groups are used as in the previous work (F.mattioda, P.ravetto, G.Ritter) [2] and six delayed neutron precursor families are used in a U-235 fuel data [3]. Table 3 and 4 show three energy groups and six delayed families, respectively.

Table 3. Material data

Group	Σ_a	Σ_f	ν	D	$\Sigma_{g\to g}$	$\Sigma_{g\to g+1}$
1	2.22E-4	4.78E-5	3.12	1.34	2.28E-1	1.97E-2
2	1.13E-3	3.57E-4	2.89	0.761	4.31E-1	5.94E-3
3	1.68E-2	6.00E-3	2.88	0.800	4.00E-1	-

Table 4. Six delayed neutron precursor families

Family	1	2	3
Fraction (β_i)	2.150E-04	1.424E-03	1.274E-03
Half-life [sec]	55.72	22.72	6.22
Family	4	5	6
Fraction (β_i)	2.568E-03	7.480E-04	2.730E-04
Half-life [sec]	2.30	0.610	0.230

3. Results

3.1 Uniform flow rate

Based on the zero-flow rate, the loss of reactivity according to the fuel velocity is calculated. The fuel flow rate is the same anywhere in the core. Table 5 shows that the faster the flow rate, the greater the loss of delay neutron precursors, so it lead the bigger loss of reactivity.

Table 5. Impact of fuel flow rate (Uniform flow rate)

Fuel Velocity [cm/s]	Recirculation time [sec]	K_{eff}	Reactivity loss [pcm]
0	∞	0.931365	0
20	10	0.929301	-238
40	5	0.928632	-310
50	4	0.928510	-330

3.2 Different flow rate depending on the region

The flow rate of fuel in the core may vary by region for various reasons. Section 3.2 shows the impact of difference flow rate by region. However, it is assumed that the recirculation time is the same as in table 5.

1) Double difference in flow rate

It is assumed that the flow rate inner region (0~75cm) was double as fast as outer region (75~150cm). Even in this case, the average flow rate was the same as in Table 5. Table 6 shows the impact of difference flow rate by region.

Table 6. Impact of difference flow rate by 2 regions *(Double difference in flow rate)*

Average Fuel Velocity [cm/s]	Actual fuel velocity [cm/s]		K_{eff}	Reactivity loss [pcm]
	Inner	Outer		
0	0	0	0.931365	0
20	32	16	0.928986	-275
40	64	32	0.928373	-346
50	80	40	0.928208	-365

Since the inner flow rate is faster than the average, the loss of delayed neutron precursor is large, and the loss of reactivity occurs more than 10% compared to table 5.

2) Triple difference in flow rate

It is assumed that the flow rate inner region (0~75cm) was triple as fast as outer region (75~150cm). Even in this case, the average flow rate is the same as in Table 5. Table 7 shows the impact of difference flow rate by region. The loss of reactivity occurs more than that of table 6.

Table 7. Impact of difference flow rate by 2 regions (Triple difference in flow rate)

Average Fuel Velocity [cm/s]	Actual fuel velocity [cm/s]		K_{eff}	Reactivity loss [pcm]
	Inner	Outer		
0	0	0	0.931365	0
20	40	13.3	0.928866	-288
40	80	26.6	0.928278	-357
50	100	33.3	0.928120	-375

3) Different flow rate in the three region

The core is divided by three regions. It is assumed that the flow rate inner region (0~50cm) and the middle region (50~100cm) are triple and double fast as outer region (100~150cm), respectively. Even in this case, the average flow rate is the same as in Table 5.

In this case, when three region is converted to two region, the difference in flow rates between the inner and outer region is 1.94:1, which is similar to Table 6 (Double flow rate) case. Figure 2 shows the flow rate of each region according to the conversion. A simbol 'A' is an average fuel velocity of the core.

Inner	Middle	Outer
27A/14	18A/14	9A/14

↓

1.57A	0.81A

Figure 3. The flow rate conversion

Table 8. Impact of difference flow rate by 3 regions

Average Fuel Velocity [cm/s]	Actual fuel velocity [cm/s]			K_{eff}	Reactivity loss [pcm]
	Inner	Mid	Outer		
0	0	0	0	0.931365	0
20	38.6	25.7	12.8	0.928866	-289
40	77.1	51.4	25.7	0.928248	-360
50	96.4	64.3	32.1	0.928083	-379

Even if the average flow rate of the entire core is the same, it can be seen that the difference in flow rate according to the region shows a different in reactivity reduction. Table 8 shows the loss of reactivity occurs more than that of table 6.

4. Conclusions

The decrease in reactivity due to the movement of nuclear fuel in the molten salt reactor is one of the important information for safety assessment. In order to calculate the effect of flow of fluid fuel, multi-group diffusion model is solved by the Finite Difference Method(FDM).

The faster the flow rate, the greater the loss of delay neutron precursors, so it lead the bigger loss of reactivity. In addition, even if the average flow rate of the entire core is the same, it can be seen that the difference in flow rate according to the region shows a different in reactivity reduction. It shows the similar results as previous studies [4] that more reactivity loss occurs when the flow rate of the inner core is faster than that of the outside.

Therefore, in order to accurately evaluate the safety of molten salt reactors, the reactivity loss should be calculated by considering not only the average flow rate but also the flow rate for each area.

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