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

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PRESENTATION TITLE

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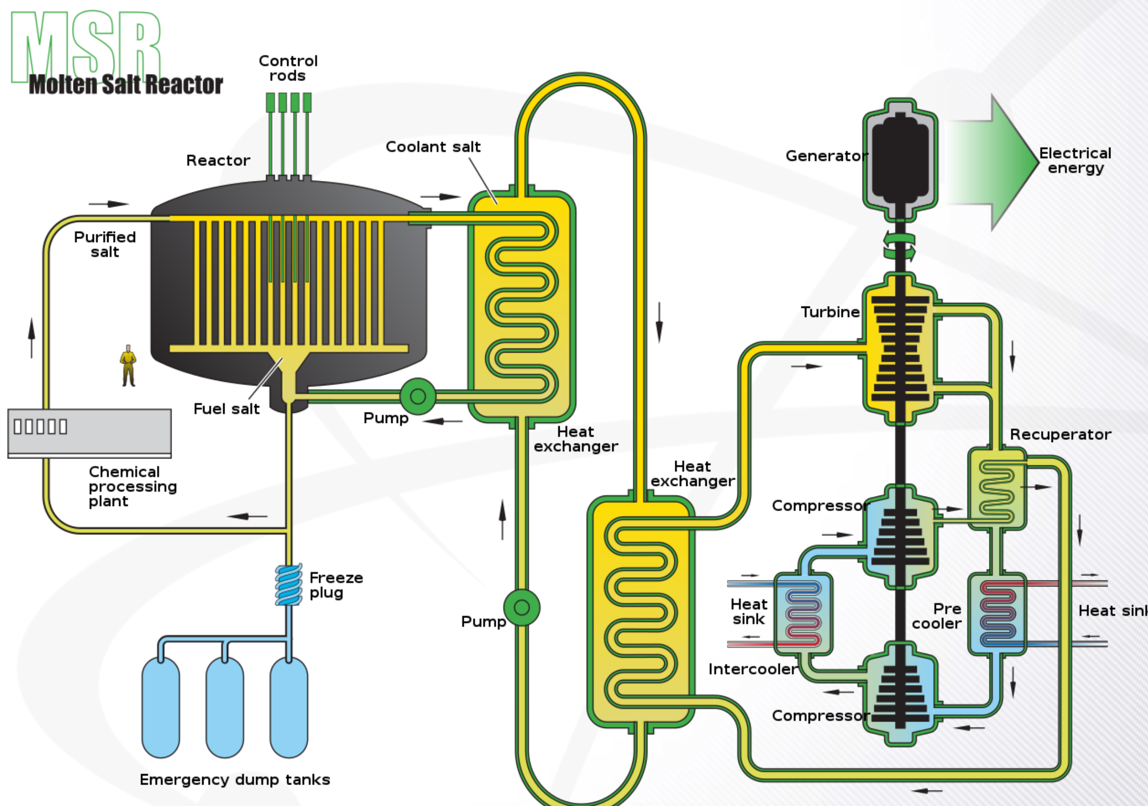
01
Introduction

Molten Salt Reactor

- **Molten Salt Reactor(MSR) : One of the Generation IV International Forum (GIF) nuclear reactor systems**
  - ◆ Low pressure operation
  - ◆ Liquid fuel
  - ◆ Accident resistance
  - ◆ High utilization



Previous Studies for MSR

» Reactivity loss of Molten Salt Reactor

- The circulation of liquid fuel lead to reduction of the effective fraction of delayed neutrons.
  - MCNP Based Calculation of Reactivity Loss due to Fuel Circulation in Molten Salt Reactors(by Jozsef KOPHAZI etc.) – Figure 1
  - Effective Delayed Neutron Fraction for Fluid-Fuel System(by P. Ravetto etc.) – Figure 2

- Need to realistic fluid dynamics model in order to perform accurate and reliable evaluations.
  - Interactions between Fluid-Dynamics and Neutronic Phenomena in the Physics of Molten Salt Systems(by S. Dulla & P. Ravetto) – Figure 3

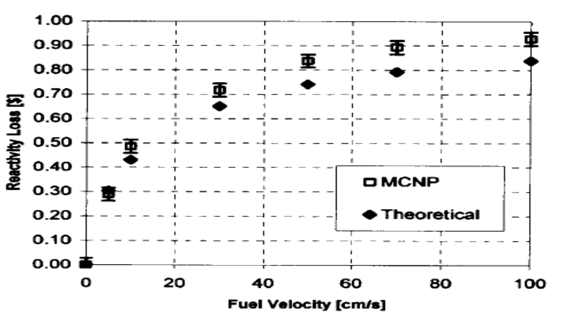


Fig. 1 Reactivity loss vs. fuel velocity, in the case of infinitely long (100000 s) recirculation time

<Figure. 1>

Table II

Ratios $\tilde{\beta}/\beta$ for different fluid velocities to the value for solid fuel, as a function of u for $T_R = 0$, $z_s = 0$ and $\sigma_s = H/10$. k_{eff} values refer to solid-fuel systems.

u [cm/s] →	0	15	30	60	100	150
$k_{eff} = 0.95009$	1.0	0.891	0.864	0.842	0.835	0.831
$k_{eff} = 1.00001$	1.0	0.891	0.862	0.843	0.834	0.829

<Figure. 2>

Flow Regime	$\Delta\rho$ (pcm)
No flow	0
Slug	−115.8
Parabolic	−130.7
ADF	−140.2
SOD	−123.6
SOI	−110.8

<Figure. 3>

Molten Salt Reactor

» Characteristics of Liquid Fuel Reactor

- ◆ Change in the concentration of delayed neutron precursors in the core
- ◆ Loss of the delayed neutron in the external circulation
- ◆ Reactivity decrease

» Calculation of

- ◆ The change in reactivity according to the fuel flow
- ◆ The difference in reactivity due to the difference in flow rate according to the region

02
Reactor model and Method

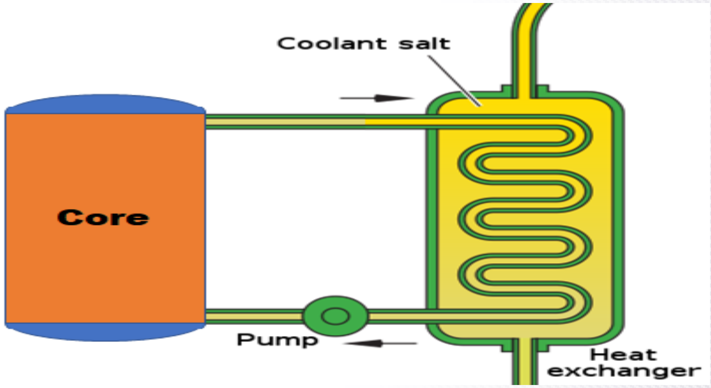
Reactor model

MSR model

- Homogeneous Cylindrical Bare Reactor
- Refer to the previous work[F.mattioda, P.ravetto, G.Ritter]

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

<Reactor description (D=diameter, H=height)>



<Conceptual model of MSR (X-Z plane)>

Calculation method(1)

» The Multi-group Diffusion model

- Steady-state balance equation of multi-group diffusion model
- Using Finite Difference Method(FDM)

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

- Leakage
- Removed
- Prompt neutron
- Down scattering
- Up scattering
- Delayed neutron precursor
- Flow of Delayed neutron precursor
- Decay
- Generation of Delayed neutron precursor

Calculation method(2)

Boundary Condition

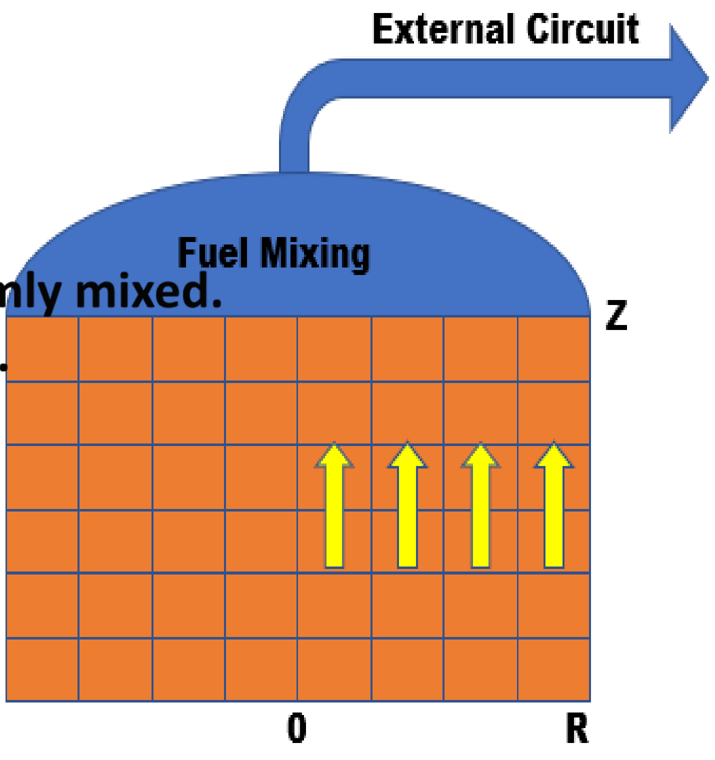
- Flux zero boundary
- Decay of delayed neutron precursors in the external circulation

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

Calculation method(3)

Assumption

- All fission/delayed neutrons are belong to highest energy group.
- Axial flow of fuel(Only Z-direction)
- During external circulation
  - Delayed neutron precursors are uniformly mixed.
  - Re-entered into the bottom of the core.
- Volume of the external circuit
  - 2/3 of the volume of the core
  - The faster the flow rate of the fuel, the shorter the recirculation time.



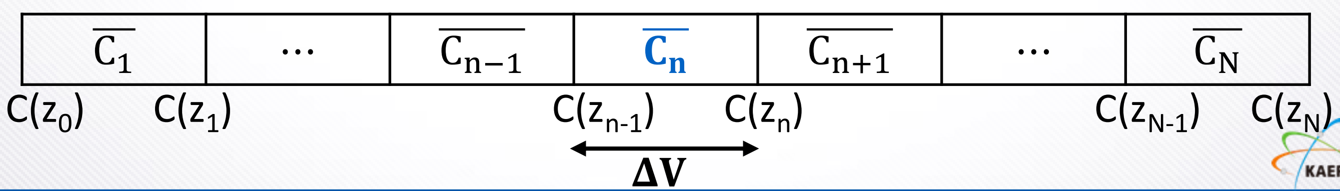
Calculation method(4)

Neutron flux

- 3D R-Z problem with Box scheme ($\overline{\Phi}$)

Delayed Neutron Precursor concentration

- $C(z_0) = C(z_N) * exp(-\lambda T_R)$
- $u\frac{dC}{dz} + \lambda C = \beta * \nu\Sigma_f\Phi$ ->integrating over ΔV
- 1-st region of z-direction
  - $dC = C(z_1) - C(z_0), \overline{C_1} = \frac{C(z_0) + C(z_1)}{2}$
  - $\frac{u}{\Delta z}[C(z_1) - C(z_0)] * \Delta V + \lambda\left[\frac{C(z_0) + C(z_1)}{2}\right] * \Delta V = \beta\nu\Sigma_f\overline{\Phi_1} * \Delta V$
  - $\left[\frac{\lambda}{2} - \frac{u}{\Delta z}\right] C(z_0) * \Delta V + \left[\frac{\lambda}{2} + \frac{u}{\Delta z}\right] C(z_1) * \Delta V = \beta\nu\Sigma_f\overline{\Phi_1} * \Delta V$
  - $C(z_1) = \frac{\left[\beta\nu\Sigma_f\overline{\Phi_1}\Delta V - \left[\frac{\lambda}{2}\Delta V - \frac{u}{\Delta z}\Delta V\right] C(z_0)\right]}{\left[\frac{\lambda}{2}\Delta V + \frac{u}{\Delta z}\Delta V\right]}$
- n-th region of z-direction
  - $C(z_n) = \frac{\left[\beta\nu\Sigma_f\overline{\Phi_n}\Delta V - \left[\frac{\lambda}{2}\Delta V - u\Delta A\right] C(z_{n-1})\right]}{\left[\frac{\lambda}{2}\Delta V + u\Delta A\right]}$



Calculation method(5)

» Material data

- 3 neutron energy groups(Refer to the previous work[F.mattioda, P.ravetto, G.Ritter])
- 6 delayed neutron precursor families(U-235 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	-

<Material data>

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

<Six delayed neutron precursor families>

03
Results

K_{eff} of solid fuel

» Fuel velocity = 0 cm/s

» Analytic solution

- $k_{eff} = 0.931328$

» This study

- Convergence condition : Less than 10^{-8} [K_{eff}, Flux]

	R direction Mesh number	Z direction Mesh number	k_{eff}	Δk(pcm)
Case 1	**30개**	**30개**	**0.931365**	**3.7**
Case 2	15개	15개	0.931475	14.7

Impact of fuel flow rate

Uniform flow rate

- The fuel flow rate is the same anywhere in the core.
- The faster the flow rate, the greater the loss of reactivity.
  - The greater the loss of delay neutron precursors

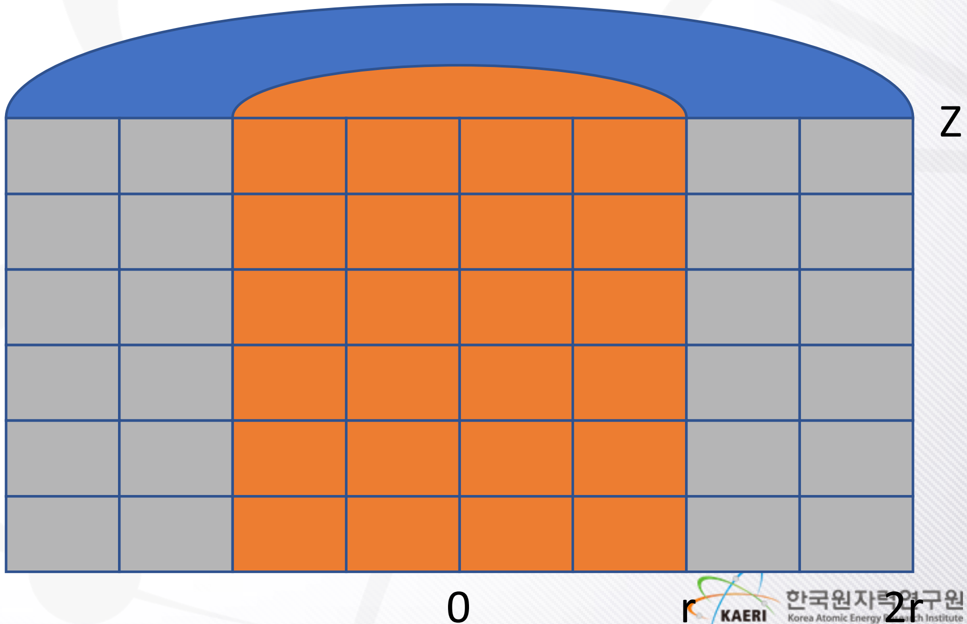
Fuel Velocity	Recirculation time	K_{eff}	Reactivity loss[pcm]
0 cm/sec	inf	0.931365	0 pcm
20 cm/sec	10 sec	0.929301	-238
40 cm/sec	5 sec	0.928682	-310
50 cm/sec	4 sec	0.928510	-330

Impact of fuel flow rate

Non-uniform flow rate (2 region)

- The average fuel flow rate of the core is the same with uniform flow rate.
- The recirculation time is the same with uniform flow rate case.

- Average fuel flow velocity : A
  - The flow rate of inner region (0~75cm) = N * outer region (75~150cm)
  - N=2 -> 1.6A, 0.8A
  - N=3 -> 2A, (2/3)A



Impact of fuel flow rate

Non-uniform flow rate (2 region)

- **The inner flow rate is faster than the average, the loss of reactivity occurs more than 10% compared to uniform flow rate case.**

Average Fuel Velocity [cm/sec]	Recirculation time	X1	X2		X3	
		Reactivity loss[pcm]	Reactivity loss[pcm]		Reactivity loss[pcm]	
			Inner core fuel velocity	Outer core fuel velocity	Inner core fuel velocity	Outer core fuel velocity
0	inf	0	0 pcm		0 pcm	
			0	0	0	0
20	10 sec	-238	-275 pcm (15.5%)		-288 pcm (21.0%)	
			32cm/sec	16cm/sec	40cm/sec	13.3cm/sec
40	5 sec	-310	-346 pcm (11.6%)		-357 pcm (15.2%)	
			64cm/sec	32cm/sec	80cm/sec	26.6cm/sec
50	4 sec	-330	-365 pcm (10.6%)		-375 pcm (13.6%)	
			80cm/sec	40cm/sec	100cm/sec	33.3cm/sec

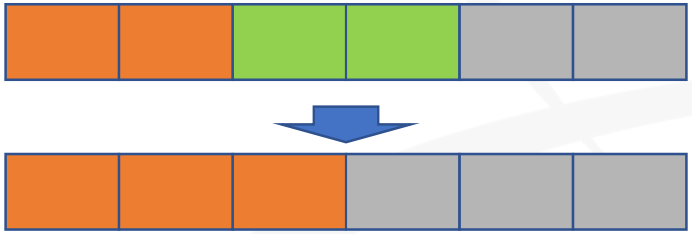
Impact of fuel flow rate

» Non-uniform flow rate (3 region)

- The average fuel flow rate of the core is the same with uniform flow rate.
- The recirculation time is the same with uniform flow rate case.
- Average fuel flow velocity : A
  - The flow rate of inner region (0~50cm) = 3N
  - The flow rate of middle region (50~100cm) = 2N
  - The flow rate of outer region (100~150cm) = 1N

    -> 27A/14, 18A/14, 9A/14

27A/14, 18A/14, 9A/14



1.57A, 0.81A

- 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 Double flow rate case.

Impact of fuel flow rate

Non-uniform flow rate (3 region)

- The difference in flow rate according to the region shows a different in reactivity reduction.

Average Fuel Velocity [cm/sec]	Recirculation time	Uniform flow rate	3 Region (2 region X2 case)		
		Reactivity loss[pcm]	Reactivity loss[pcm]		
			Inner core fuel velocity	Mid core fuel velocity	Outer core fuel velocity
0	inf	0 pcm	0 pcm		
			0	0	0
20	10 sec	-238	-289, 21.4%, (-275, 15.5%)		
			38.57cm/sec	25.71cm/sec	12.85cm/sec
40	5 sec	-310	-360, 16.1%, (-346, 11.6%)		
			77.14cm/sec	51.42cm/sec	25.71cm/sec
50	4 sec	-330	-379, 14.8%, (-365, 10.6%)		
			96.42cm/sec	64.28cm/sec	32.14cm/sec

04
Conclusions

Conclusions

1. 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.
   - Change in the concentration of delayed neutron precursors in the core
   - Loss of the delayed neutron in the external circulation
   - Reactivity decrease

2. The faster the flow rate, the bigger loss of reactivity.

3. 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.

4. The reactivity loss should be calculated by considering not only the average flow rate but also the flow rate for each area.

Future Works

1. **Feature of the Molten Chloride Salt Fast Reactor**
   - **Relatively large diffusion coefficient than thermal reactor**
   - **About 3~5[cm] ($D = \frac{1}{3\Sigma_{tr}}$)**

2. **Check if the diffusion theory fits well on the Fast Reactor**
   - **Find the appropriate equivalence theory**

THANK YOU

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