Validation of GAMMA+ code using reactivity insertion tests of MSRE

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1. Introduction

Molten salt fueled reactor has different reactor physics from other solid fueled reactors. The delayed-neutron precursors circulate the entire fuel system, from the core to the loop and vice versa. To observe its dynamics, reactivity insertion tests were performed in 1970 with Molten Salt Reactor Experiment (MSRE) generating the maximum power about 8 MW [1].

The system analysis code, GAMMA+ code [2], has three kinetics models for predicting neutronics of MSR named as: 1) decay-term point reactor kinetics (DT-PRK), 2) delay-loop point reactor kinetics (DL-PRK), 3) nuclide groups transport kinetics (NTK). In this paper, we will compare the results of GAMMA+ calculations obtained by NTK with the experimental data obtained by reactivity insertion tests of MSRE. We will also perform the sensitivity study to investigate the effect of the core region of MSRE.

2. Method

2.1 MSRE System and Reactivity Insertion Tests

MSRE was designed as 10 MW and operated in 1960s by ORNL with the thermal power of ~8 MW. MSRE consists of a fuel salt system with a reactor vessel, a pump, a heat exchanger and coolant salt system with a pump and an air radiator to extract produced heat to the environment, as shown in Fig. 1. MSRE used the fuel salt as $LiF\text{-}BeF_2\text{-}ZrF_4\text{-}UF_4$ and the coolant salt as $LiF\text{-}BeF_2$.

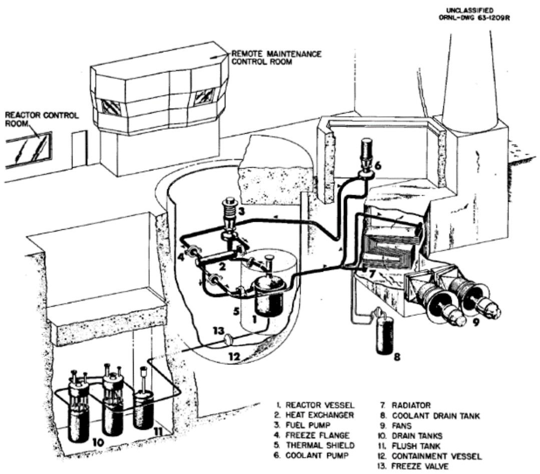

Fig. 1. MSRE system [1].

MSRE inserted the reactivity to observe time response of the system [3]. MSRE obtained the neutron flux versus time data with three experiments under the power of 1, 5, and 8 MW.

The amounts of the applied reactivity insertion are 24.8 pcm for 1 MW, 19.0 pcm for 5 MW, and 13.9 pcm for 8 MW, respectively. The reactivity values of 1 MW and 8 MW are exchanged from the original ORNL data [3], since several studies [4,5] claimed that documented reactivity values for 1 MW and 8 MW are not correct.

2.2 Reactor Kinetics Models in GAMMA+

The concept of DT-PRK in GAMMA+ was developed by ORNL [6]. The delayed-neutron precursors can decay when they are in the loop before they re-enter to the core. So, the last two terms are added with the equation (2) of conventional point kinetics to consider the effect of delayed-neutron precursors, as it follows:

$$\frac{dP}{dt} = \frac{\rho - \beta_{eff}}{\Lambda} P + \sum_{i=1}^{6} \lambda_i C_i \quad (1)$$
$$\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda} P - \lambda_i C_i - \frac{1}{\tau_c} C_i + \frac{1}{\tau_c} C_i(t - \tau_l) e^{-\lambda_i \tau_l} \quad (2)$$

where P, ρ, β, Λ, C_i, λ, τ_c, τ_l are the fission power, the reactivity, the effective fraction of delayed neutrons, the effective prompted neutron lifetime, the concentration of the delayed-neutron precursors, the decay constant of delayed-neutron precursors, the core transit time, and the loop transit time, respectively. The last two terms in the equation (2) are also applied to poison and decay heat nuclides in GAMMA+.

The limitation of DT-PRK is that it only solves for the core power from the concentration of the precursors in the core.

D. Zhang et al. [7] suggested additional equation to obtain the concentration of the delayed-neutron precursors in the loop as following equations:

$$\frac{dP}{dt} = \frac{\rho - \beta_{eff}}{\Lambda} P + \sum_{i=1}^{6} \lambda_i C_{c,i} \quad (3)$$
$$\frac{dC_{c,i}}{dt} = \frac{\beta_i}{\Lambda} P - \lambda_i C_{c,i} - \frac{1}{\tau_c} C_i + \frac{V_l}{V_c} C_{l,i}(t - \tau_l) \quad (4)$$
$$\frac{dC_{l,i}}{dt} = \frac{V_l}{V_c} C_{c,i} - \lambda_i C_{l,i} - \frac{1}{\tau_l} C_{l,i} \quad (5)$$

where $C_{c,i}$, $C_{l,i}$, V_c, V_l are concentrations of the delayed-neutron precursors in the core and the loop, and volumes of the core and the loop. The last two terms in the equation (4) and the equation (5) are also implemented to poison and decay heat nuclides in GAMMA+.

DL-PRK has capabilities to calculate the decay heat in the loop and the concentration of the delayed-neutron precursors in the loop. However, the data of the entire loop is represented as the one point.

So NTK is suggested to calculate the concentration of the delayed-neutron precursors in every cell as following equations:

$$\frac{dP}{dt} = \frac{\rho-\beta_{eff}}{\Lambda}P + \Sigma_{j=1}^{core}\sum_{i=1}^{6}\lambda_i C_{i,j} \quad (6)$$

$$\frac{dC_{i,j}}{dt} = \frac{\beta_i}{\Lambda}P - \lambda_i C_{i,j} + \frac{1}{V_j}[(uAC_i)_{in} - (uAC_i)_{ex}] \quad (7)$$

where *j* is the index of the cell, V is the volume, *u* is the velocity, and *A* is the flow area.

2.3 GAMMA+ Input Models

Base input model for GAMMA+ calculations is constructed with fuel and coolant salt systems, as shown in Fig. 2. Base input model refers the ORNL documents as possible.

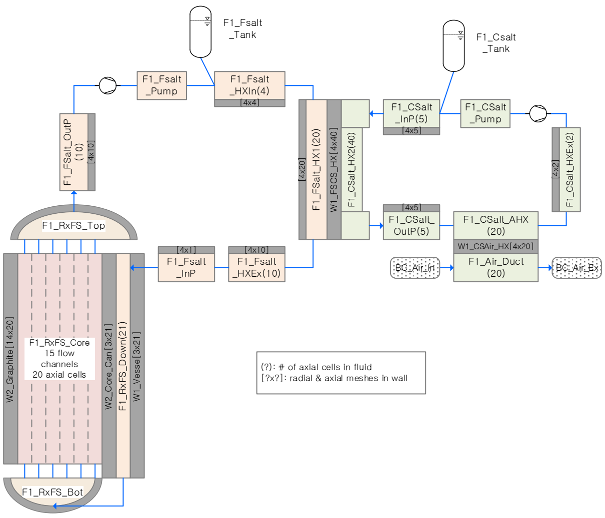

Fig. 2. GAMMA+ base input model for MSRE.

We confirm the validity of the base input model by the comparison of steady-state value under 10 MW.

As explained in section 2.2, there are efforts to calculate accurately the fission power by obtaining the concentration of the delayed-neutron precursors in the core and the loop. Through equations (1)~(7), we can notice that the fission power and the concentrations are significantly influenced the occupied region of the core. However, the determination of the core region is not clear in the MSRE system since fission reaction occurs at the graphite region as well as outside the graphite region in the reactor vessel (i.e., top plenum, bottom plenum, and downcomer). It would be confused whether the core region should be defined as from the downcomer to the top plenum or any partial region in the vessel.

Thus the sensitivity inputs are constructed from the base input, as shown in Fig. 3. Sensitivity inputs divide both the top and bottom plenums from 1 cell to 2 cells, as shown in Fig. 3. The division heights at the top and bottom plenums are determined that the power of 95%, 97.5%, 99% are occupied without the uppermost region of the top plenum and the lowermost region of the bottom plenum from the heat distribution data [9]. We again confirm the validity of the sensitivity input with the base input by the comparison of the steady-state results.

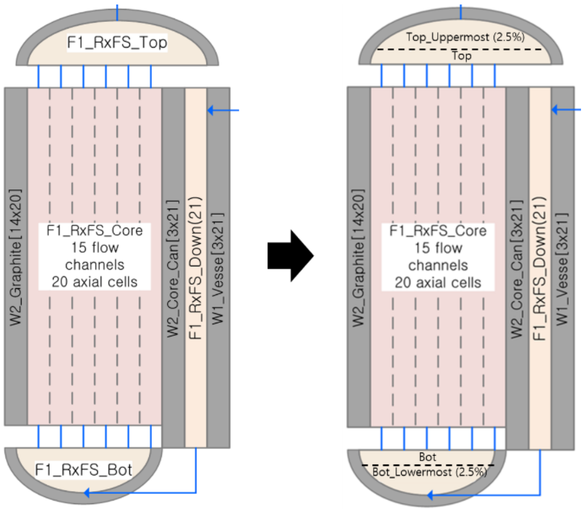

Fig. 3. GAMMA+ sensitivity input model for the vessel.

3. Results

In this paper, the experimental results from MSRE are compared with GAMMA+ results by NTK since it is the most advanced one among three kinetics models implemented in the current GAMMA+ version. The comparison graphs are shown as Figs. 4-6. In the legend, 'NTK_Core' means F1_RxFS_Core in Fig. 3 and 'NTK_Vessel' means the core region is defined as the area from the downcomer to the top plenum. Figs. 4-6 show that overall agreements are good between the GAMMA+ results and the measured data. They also show the selection of the core region is crucial in the application of NTK.

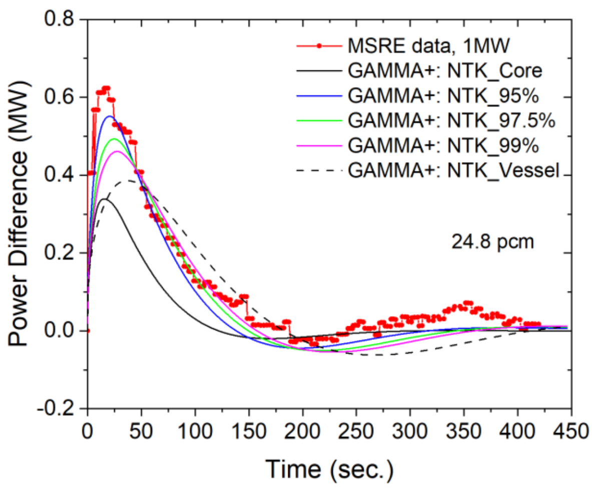

Fig. 4. Power difference vs. time for 1 MW case with MSRE and GAMMA+.

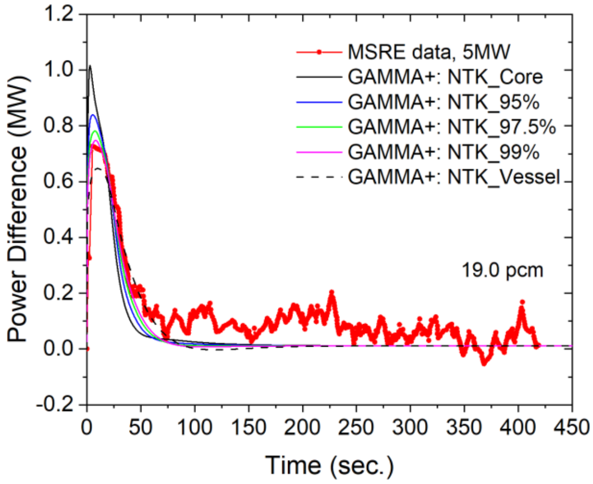

Fig. 5. Power difference vs. time for 5 MW case with MSRE and GAMMA+.

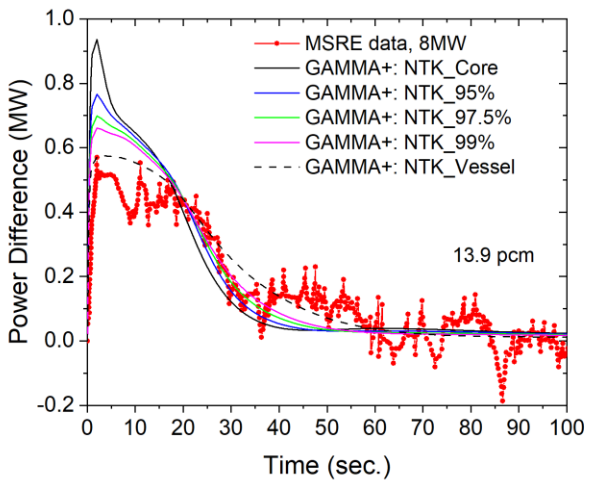

Fig. 6. Power difference vs. time for 8 MW case with MSRE and GAMMA+.

4. Conclusions

We pursue the validation of GAMMA+ code for dynamics of the MSR, using the MSRE data which was operated reactor in 1960s at ORNL. Among introduced reactor kinetics models, we select NTK to compare the MSRE data and perform sensitivity study to investigate the effect of the core region.

From the comparison between MSRE data and GAMMA+ results, it can be seen that GAMMA+ with NTK well predicts the MSRE data in terms of the peak value and the overall trends with the power difference. It is also found that the selection of the core region is crucial in the application of NTK.

Further researches are required to determine the best choice of the core region in the simulation of the MSRE system.

Acknowledgement

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