A study on short-term reactor behavior using a simplified analytic reactor dynamic model on AnyLogic platform

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1. Introduction

The Korea Institute of Nuclear Nonproliferation And Control (KINAC) is developing an analysis model that can simulate the entire nuclear fuel cycle [1]. As part of this project, long-term and short-term behavioral simulation models in the core have been developed, and this paper describes the short-term behavioral simulation model. The reactor behavior quickly changes when the reactivity is introduced into the core. The main purpose of developing a short-term behavioral analysis model is to visually confirm how the power of the reactor changes through the insertion of positive or negative reactivity. This can be implemented using a simple analytical model, the Point Kinetics. Since this model consists of only first-order differential equations, users unfamiliar with coding can easily implement it using the system dynamics method. In this paper, the Point Kinetics model was implemented on the system dynamics software platform, AnyLogic.

2. Governing Equations

In this section Point Kinetic Equations used to the short term behavior model are described. These equations are represented in two energy groups with separation energy of 0.625eV, i.e., 0~0.625eV for thermal and 0.625eV~20.0MeV for fast energy region, respectively.

2.1 2G Point Kinetics Equations

These deterministic time-dependent equations can be described by the two energy groups prompt neutron number density equations with 6 groups of delayed neutron precursors [2].

$$\frac{dn_1(t)}{dt}=\left(\frac{(\rho_1(t)-\beta)}{\Lambda_1}-\Sigma_{s12}v_1\right)n_1(t)+\frac{1}{\Lambda_2}(1-\beta)n_2(t)+\sum_{i=1}^{6}\lambda_i C_i(t), \quad (1)$$

$$\frac{dn_2(t)}{dt}=\frac{(\rho_2(t)-1)}{\Lambda_2}n_2(t)+\Sigma_{s12}v_1 n_1(t), \quad (2)$$

$$\frac{dC_i(t)}{dt}=\beta_i\left(\frac{1}{\Lambda_1}n_1(t)+\frac{1}{\Lambda_2}n_2(t)\right)-\lambda_i C_i(t), \quad (3)$$

$$\beta=\sum_{i=1}^{6}\beta_i, \quad (4)$$

where $n_1(t)$ and $n_2(t)$ are the fast and thermal neutron number densities, respectively, while $C_i(t)$ is the precursor concentration density of i^{th} group delayed neutrons. $\rho_1(t)$ and $\rho_2(t)$ are the reactivities induced by fast and thermal neutrons, respectively. β_i is the fraction of i^{th} group delayed neutrons. Λ_1 and Λ_2 are the fast and thermal neutron generation times, respectively. Σ_{s12} is the macroscopic scattering cross-section from fast group to thermal group and v_1 is the fast neutron average velocity. λ_i is the decay constant of i^{th} group delayed neutrons. The above equations can be summarized in a linear system as follows.

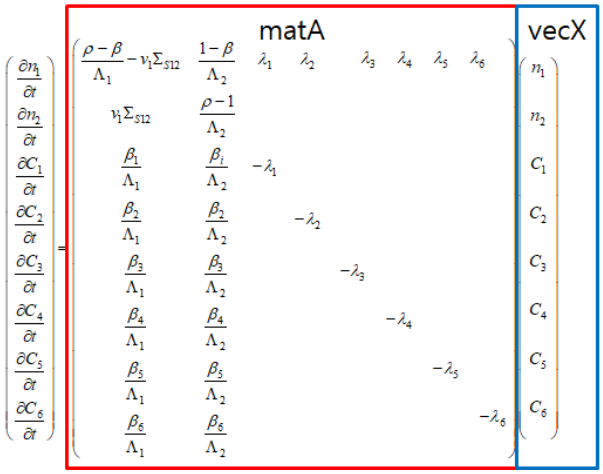

Fig. 1. The linear system of 2G Point Kinetics equations.

3. AnyLogic Analysis Model

The main screen of AnyLogic's analysis model was set up to accept input for reactor type, initial condition, and simulation time. In addition, this model includes other options that allow it to be calculated using the results of the existing long-term burnup calculations, as shown in Fig. 1.

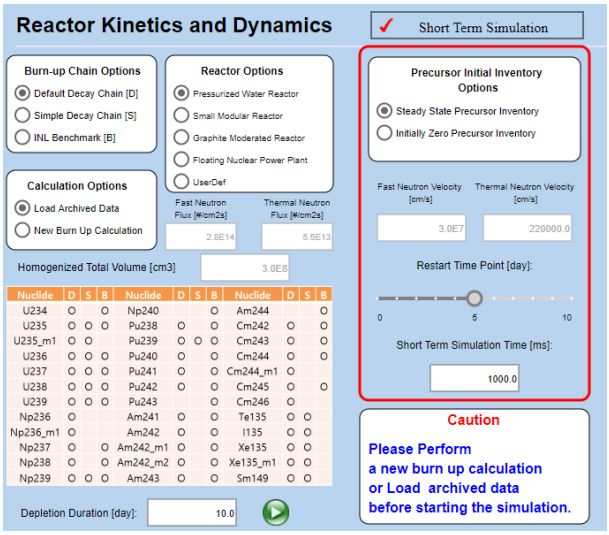

Fig. 2. Short term simulation main screen.

The linear system shown in Fig. 1 was implemented as a model as shown in Fig. 3 using the System Dynamics tool provided by AnyLogic. Each variable corresponding to vecX was implemented using AnyLogic's stock tool, and the amount of time change of each variable was implemented using the flow tool.

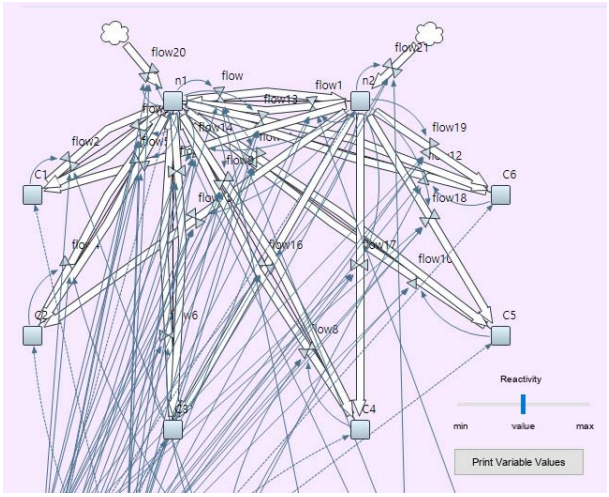

Fig. 3. System dynamics model of 2G point kinetics equations.

4. Execution Results

A calculation is performed in short-term behavioral analysis by retrieving data from the result file at a specific point in time for the nuclide inventory, neutron flux, and delayed neutron generation fraction of each nuclide generated in the long-term behavior simulation. The behavior of neutron flux and delayed neutron precursors was simulated for 1000 ms in these calculations, and it was confirmed that the same results were derived from the model created on the AnyLogic platform through comparison with separately written code results.

The values of the macroscopic ν -fission cross section and the average neutron velocity used to calculate the neutron generation time, and neutron generation time calculated during the short-term behavior simulation are summarized in Table I.

Table I: Values of Main Variables

energy group	macroscopic ν -fission XS [cm^{-1}]
1	0.004
2	0.048
-	neutron generation time Λ[s]
1	2.241e-5
2	3.871e-5
-	neutron average velocity ν [cm/s]
1	2.0e7
2	2.5e5

Fig. 4 shows the change in neutron flux over time when a positive reactivity of 500 pcm is inserted at 300 ms followed by a negative reactivity of 500 pcm is inserted again at 600 ms. When positive reactivity is inserted, it is confirmed that a prompt jump occurs due to the decay of delayed neutron precursors with short half-lives, and it is confirmed that they are then affected by delayed neutron precursors with long half-lives.

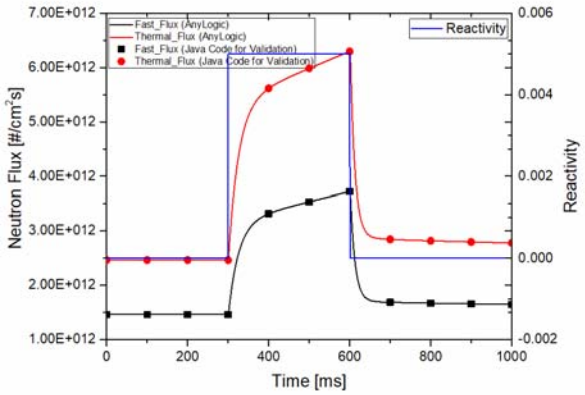

Fig. 4. Neutron fluxes variation over time (Case 1).

The change in the number of delayed neutron precursors over time is shown in Fig. 5, and it was discovered that the change in the number of delayed neutron precursors due to the insertion of positive or negative reactivity was not sensitive to the change in reactivity.

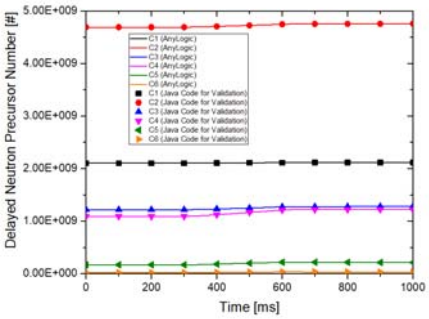

Fig. 5. Delayed neutron precursor inventory over time.

The neutron flux variation is shown in Fig. 6 when a positive reactivity of 500 pcm is inserted at 300 ms, a negative reactivity of 1000 pcm is inserted at 500 ms, and a positive reactivity of 500 pcm is inserted again at 700 ms. The rate at which the neutron flux multiplies differs significantly depending on the current critical state, despite the same amount of reactivity being inserted at 300 ms and 700 ms. For example, the thermal neutron flux is approximately 2.43 times multiplied from 2.47e12 #/cm^{2}s at 300 ms to 5.99e12 #/cm^{2}s at 500 ms, whereas 1.54e12 #/cm^{2}s at 700 ms to 2.59e12 #/cm^{2}s at 900 ms. The multiplication is only 1.54 times as can be seen.

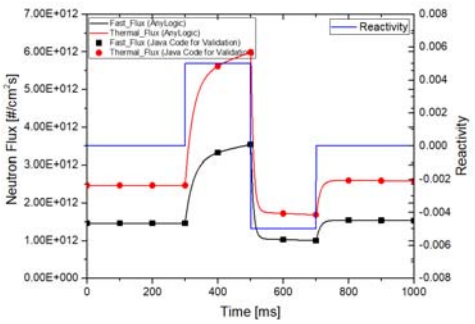

Fig. 6. Neutron fluxes variation over time (Case 2).

In the case of Fig. 7 and 8, more changes were made to the reactivity insertion and the results were confirmed.

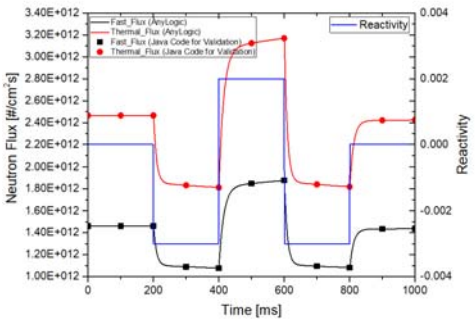

Fig. 7. Neutron fluxes variation over time (Case 3).

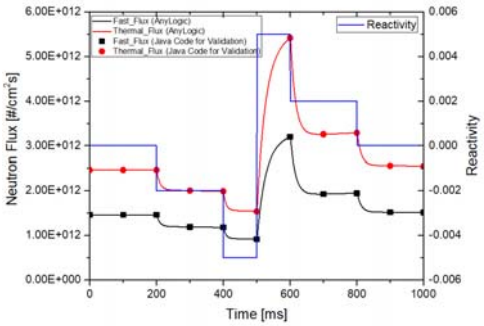

Fig. 8. Neutron fluxes variation over time (Case 4).

It was confirmed that there was no additional singularity, showing the same trend as in the previous cases.

3. Conclusions

By utilizing AnyLogic, one of the System Dynamics Platforms, a short-term reactor behavior analysis model was developed and validated. The linear system composed of first-order differential equations could be solved more quickly and accurately using the tools provided by AnyLogic, and it was confirmed that the results were compared with the analysis results using independent codes, indicating appropriate analysis results.

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