Modelica-Based Simulation of Step Reactivity Dynamic Response in TRIGA Research Reactor

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Date: 2025-06-10T19:56:10+00:00

Abstract

To satisfy the teaching and research demands for reactors in general universities, point reactor neutron kinetics, xenon and samarium poisoning, temperature feedback, and lumped-parameter thermal-hydraulic dynamic models for TRIGA (Training, Research, Isotopes, General Atomic) reactors—primarily utilized for training, research, and isotope production—were constructed based on the increasingly prevalent Modelica simulation technology. Simulations of pulse startup and emergency shutdown under large step reactivity perturbations, as well as power regulation under small step reactivity perturbations, were performed. Key dynamic response results, including pulse peak power, pulse released energy, pulse full width at half maximum, maximum xenon and samarium concentrations, and power variations, are essentially consistent with experimental or theoretical results. Consequently, the Modelica simulation model developed in this study can be employed to predict the fundamental dynamic characteristics of TRIGA research reactors, thereby providing support for reactor teaching and research.

Full Text

Abstract

To meet the teaching and research needs of ordinary universities for nuclear reactors, this study constructs point reactor neutron kinetics, xenon and samarium poisoning, temperature feedback, and lumped-parameter thermal-hydraulic dynamic models for the TRIGA (Training, Research, Isotopes, General Atomic) research reactor based on the increasingly popular Modelica simulation technology. Simulations of pulse startup and emergency shutdown with large step reactivity disturbances, as well as power regulation with small step reactivity disturbances, were conducted. Key dynamic response results including pulse peak power, pulse released energy, pulse full width at half maximum, maximum xenon and samarium concentrations, and power variations show good agreement with

experimental or theoretical results. Therefore, the Modelica simulation model established in this study can be used to predict the basic dynamic characteristics of TRIGA research reactors and provides support for reactor teaching and scientific research.

Key words TRIGA research reactor, Modelica, Dynamic response, Pulse, Power regulation

1.1 Neutron Kinetics Model

A point reactor neutron kinetics model with six delayed neutron groups is employed:

$$\frac{dn(t)}{dt} = \frac{\rho(t) - \beta}{\Lambda} n(t) + \sum_{i=1}^{6} \lambda_i C_i(t) + S$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} n(t) - \lambda_i C_i(t), \quad i = 1, 2, ..., 6$$

where $n(t)$ is the neutron density (m^{-3}), t is time (s), $\rho(t)$ is reactivity (pcm, i.e., 10^{-5}), β is the total delayed neutron fraction, Λ is the neutron generation time (s), λ_i is the decay constant of the i-th delayed neutron precursor group (s^{-1}), $C_i(t)$ is the concentration of the i-th delayed neutron precursor (m^{-3}), S is the external neutron source strength ($\mathrm{m}^{-3}\mathrm{s}^{-1}$), and β_i is the delayed neutron fraction of the i-th group.

Reactivity comprises several components:

$$\rho(t) = \rho_0 + \rho_{Xe}(t) + \rho_{Sm}(t) + \rho_f(t) + \rho_w(t)$$

where ρ_0 is the sum of excess reactivity at cold clean condition and reactivity introduced by control rods; $\rho_{Xe}(t)$ and $\rho_{Sm}(t)$ are the poisoning reactivity caused by fission products ^{135}Xe and ^{149}Sm, respectively; $\rho_f(t)$ and $\rho_w(t)$ are the reactivity changes due to fuel temperature variation and coolant temperature variation, respectively.

1.2 Xenon and Samarium Poisoning Model

Fission products ^{135}Xe and ^{149}Sm have strong neutron absorption capabilities and cause significant reactivity changes. Their dynamic models are as follows:

$$\frac{dN_I(t)}{dt} = \gamma_I \Sigma_f \phi(t) - \lambda_I N_I(t)$$

$$\frac{dN_{Xe}(t)}{dt} = \gamma_{Xe} \Sigma_f \phi(t) + \lambda_I N_I(t) - (\lambda_{Xe} + \sigma_{Xe} \phi(t)) N_{Xe}(t)$$

$$\frac{dN_{Pm}(t)}{dt} = \gamma_{Pm}\Sigma_f\phi(t) - \lambda_{Pm}N_{Pm}(t)$$

$$\frac{dN_{Sm}(t)}{dt} = \lambda_{Pm}N_{Pm}(t) - \sigma_{Sm}\phi(t)N_{Sm}(t)$$

where $N_I(t)$, $N_{Xe}(t)$, $N_{Pm}(t)$, and $N_{Sm}(t)$ are the concentrations of ^{135}I, ^{135}Xe, ^{149}Pm, and ^{149}Sm (m^{-3}), respectively; σ_{Xe} and σ_{Sm} are the microscopic absorption cross-sections of ^{135}Xe and ^{149}Sm (m^2); γ_I, γ_{Xe}, and γ_{Pm} are the fission yields; λ_I, λ_{Xe}, and λ_{Pm} are the decay constants (s^{-1}); Σ_f is the macroscopic fission cross-section (m^{-1}); and $\phi(t)$ is the core neutron flux density ($m^{-2}s^{-1}$), related to $n(t)$ by $\phi(t) = n(t)v$, where v is the neutron velocity (m/s). In equations (8) and (9), $\Sigma_f n(t)$ is approximated to be equal to the total core absorption cross-section.

The reactivity effects are given by:

$$\rho_{Xe}(t) = -\frac{\sigma_{Xe}N_{Xe}(t)}{\Sigma_a}$$

$$\rho_{Sm}(t) = -\frac{\sigma_{Sm}N_{Sm}(t)}{\Sigma_a}$$

1.3 Temperature Feedback Model

Both fuel temperature feedback and coolant temperature feedback are considered:

$$\rho_f(t) = a_f(T_f(t) - T_{f0})$$

$$\rho_w(t) = a_w(T_w(t) - T_{w0})$$

where a_f and a_w are the fuel and coolant temperature coefficients (pcm/°C), respectively; $T_f(t)$ and $T_w(t)$ are the average temperatures of fuel and reactor pool. For the TRIGA MARK II reactor, the fuel temperature feedback is negative ($a_f < 0$) while the coolant temperature feedback is positive ($a_w > 0$).

1.4 Thermal Model

Using the lumped parameter method, the fuel and coolant regions are modeled as:

$$C_f\frac{dT_f(t)}{dt} = P_n(t) - P_{fw}(t)$$

$$C_w \frac{dT_w(t)}{dt} = P_{fw}(t) - Q_{air}(t) - Q_{concrete}(t) - Q_{active}(t)$$

where C_f and C_w are the heat capacities of fuel and coolant (J/K); $P_n(t)$, $P_{fw}(t)$, $Q_{air}(t)$, $Q_{concrete}(t)$, and $Q_{active}(t)$ are the reactor power, heat transfer from fuel to coolant, heat loss from pool to air, heat transfer from pool to concrete wall, and active cooling power (W), respectively.

The heat transfer terms are calculated using empirical correlations. For $P_{fw}(t)$, the relationship from JSI is adopted:

$$P_{fw}(t) = hA(T_f(t) - T_w(t))$$

where h is the heat transfer coefficient and A is the heat transfer area. $Q_{active}(t)$ can be specified manually. For natural convection to air and concrete, the following correlations are used:

$$Q_{air}(t) = k_{air}(T_w(t) - T_{ambient})$$
$$Q_{concrete}(t) = k_{concrete}(T_w(t) - T_{ambient})$$

The reactor power is related to neutron flux by:

$$P_n(t) = \frac{\phi(t)}{v} E_f \Sigma_f V_c$$

where E_f is the energy per fission (J), V_c is the core volume (m^3), and other parameters are as defined previously.

1.5 Coupling Relationship Between Models

The various models are coupled to form a multi-physics system, as illustrated in Figure 1 [Figure 1: see original paper]. The neutron kinetics model couples with other models through reactivity and neutron density: changes in reactivity affect neutron density, which directly influences xenon and samarium poisoning and indirectly affects fuel and coolant temperatures through power. Conversely, changes in xenon/samarum poisoning, fuel temperature, and coolant temperature all affect reactivity. These models employ lumped parameter treatment of spatial variables, which limits simulation of spatial distributions but captures the fundamental dynamic behavior of the system, making them suitable for teaching, training, and basic dynamic analysis.

1.6 Determination of Steady-State Initial Values

When simulating from a steady-state condition, initial values must be determined. At steady state, with a given steady-state power P_0, all time derivatives are set to zero, yielding the neutron density and nuclide concentrations. For T_f, T_w, ρ_0, and P_n, the total reactivity ρ must be zero, leading to the following relationships:

$$\rho_0 + \rho_{Xe}(0) + \rho_{Sm}(0) + \rho_f(0) + \rho_w(0) = 0$$

$$P_n = \frac{\phi}{v} E_f \Sigma_f V_c$$

$$Q_{active} = P_{fw} - Q_{air} - Q_{concrete}$$

There are four unknowns but only three equations, requiring manual specification of one quantity. For example, by specifying the active cooling power Q_{active}, the remaining variables can be determined.

2 Simulation Results and Discussion

Based on the above models, the governing equations were coded in the open-source Modelica platform OpenModelica, which automatically couples and solves the system using the default DASSL solver with implicit high-order multi-step characteristics, enabling multi-physics dynamic simulation.

2.1 Verification of Point Reactor Kinetics Equation Solution

Reactivity is a crucial parameter measuring the deviation of a nuclear reactor from criticality, and reactivity response simulation relies on solving the point reactor kinetics equations, which are inherently stiff. The solution accuracy of OpenModelica was first verified. Using identical parameters, the simulated and analytical values for different reactivity disturbances are presented in Table 1 , showing good agreement. This demonstrates that solving stiff point reactor kinetics equations with OpenModelica is feasible, and the computational accuracy is not significantly affected by step size.

2.2 Pulse Startup

Pulse startup simulations were performed based on the JSI TRIGA MARK II reactor with a simulation step size of 0.001 s. The specific model parameters for this reactor are listed in Table 2 , and the model diagram is shown in Figure 2 [Figure 2: see original paper]. During simulation, a large step positive reactivity greater than the total delayed neutron fraction was introduced to simulate control rod ejection, causing a prompt supercritical transient where power increases

rapidly but then decreases quickly due to strong negative fuel temperature feedback, forming a pulse. The main pulse parameters, including pulse peak power, pulse released energy, and pulse full width at half maximum (FWHM), vary with the magnitude of introduced reactivity. The simulated and experimental values are compared in Figure 3 [Figure 3: see original paper], where pulse energy is defined as the total energy generated while power exceeds 1% of the peak power. For pulse peak power, simulation and experimental values show consistent trends and close agreement. For pulse released energy and FWHM, deviations are small at large reactivity insertion but larger at small reactivity insertion. In addition to model errors, this is primarily because at small pulses, the power shape is asymmetric and the pulse energy is small compared to measurement resolution, resulting in larger measurement uncertainties.

2.3 Emergency Shutdown

Using the same model parameters as Section 2.2 with a simulation step size of 1 s, all variables were initialized to steady-state values at 200 kW power. After 10 hours, a -5000 pcm reactivity insertion was introduced for emergency shutdown. The simulated concentrations of ^{135}Xe and ^{149}Sm are shown in Figure 4 [Figure 4: see original paper]. The ^{149}Sm concentration gradually approaches the theoretical stable value of 2.2×10^{21} m^{-3}, while the ^{135}Xe concentration first increases then decreases, creating an "iodine well." The maximum concentration matches the theoretical prediction of 2.9×10^{20} m^{-3}, and the time of occurrence (9.2 h after shutdown) agrees with theoretical formulas, which is shorter than the 11.2 h typical for large reactors due to the lower steady-state neutron flux density (10^{13} cm^{-2}s^{-1}) in this reactor.

2.4 Power Variation

Model parameters were set to match the TRIGA MARK II reactor at the University of Pavia (Table 2) with a simulation step size of 1.0 s. All variables were initialized to steady-state values at 50 kW power, and an 89 pcm step reactivity was introduced at 50 s. The simulated and experimental power values are compared in Figure 5 [Figure 5: see original paper], showing good agreement. After introducing positive reactivity, power gradually increases, reaching a peak of approximately 75 kW after about 30 s, then gradually decreasing to a new power level of approximately 70 kW.

Conclusion

A dynamic model for the TRIGA research reactor was constructed using Modelica simulation technology, incorporating point reactor neutron kinetics, xenon and samarium poisoning, temperature feedback, and lumped-parameter thermal-hydraulic models. Simulations were performed for various step reactivity insertion scenarios. Under pulse, shutdown, and power variation conditions, key simulation results show good agreement with experimental or theoretical

values, demonstrating that Modelica can accurately and conveniently perform dynamic simulations of TRIGA research reactors. The dynamic model developed in this paper captures the fundamental dynamic physical characteristics of TRIGA research reactors and provides valuable reference for teaching, training, and basic dynamic characteristic analysis of TRIGA reactor physics and operation.

Author Contributions XU Zhitao was responsible for drafting the article, guiding and implementing the overall research. NIU Aijun was responsible for article revision, data analysis, and material support. LV Yufan was responsible for implementing preliminary multi-physics research. ZHOU Chuangye was responsible for implementing point reactor neutron kinetics research.

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Note: Figure translations are in progress. See original paper for figures.