SIMULATION OF POWER MANEUVERING USING COUPLED ANALYSIS OF KINETICS AND THERMAL-HYDRAULICS IN A RESEARCH REACTOR

H. KIM*, S.K. PARK, C. PARK
Safety Analysis, KAERI
111 Daedeok-daero, Yuseong,
305-353 Daejeon-Korea

S.J. KIM, T.W. NOH
Applied Mathematics, Hongik Univ
94 Wausan-ro, Mapo-gu, 121-791 Seoul – Korea

*Corresponding author: hyeonilkim@kaeri.re.kr

ABSTRACT

An application using coupled kinetics and thermal hydraulics analysis is presented, which supports constructing and confirming the reactor design to maneuver the power operation in a research reactor. Whether the design can essentially cover the required stable and safe operation of power in an acceptable manner is confirmed by analyzing the behavior of the power during a transient state from inserted reactivity coming from the movement of the control absorber rod using a certain type of control logic. A simulation tool capable of handling transient behavior with coupled kinetics and thermal-hydraulics is a must-have kit through all design processes, especially at the starting phase of the design. Herein, a code able to catch the very physics with point kinetics and simplified thermal hydraulics within the incorporated core has been developed and programmed in modern MATLAB/SIMULINK, but originally written in FORTRAN. The tool was verified and tested through numerical experiments using the PARET/ANL code. A set of calculated results suggests the possibility of the code for its extension to a tool to prepare the guidelines for safe operation.

1. Introduction

The design of a research reactor starts from the very basic understanding of the balances of the reactor such as heat, mass, and controllability. It is of great importance to an effective and economic design to investigate various transient behaviors of the reactor with a coupled analysis of the neutronics and thermal-hydraulics from the early design stage. However, this takes a lot of time and effort in terms of a bulky code and engineering works. For this reason, a simple, fast, and reliable tool with super-flexibility is required as a preferred option in the system design of a research reactor. In this paper, a solution for simulation [2], the RRSSIM (Reactor Regulating System Simulation), using a coupled point-kinetics and thermal-hydraulics model in the environment, such as language and graphical user interfaces provided by MATLAB/SIMULINK [3], is presented along with simulation results for verification and application.

2. Mathematical Model

The dynamic models for the reactor simulation include neutron point kinetics, Iodine-Xenon behavior, reactor/thermal power from the core and reflector, and reactivity feedback. Hence, the individual component models of the reactor are incorporated into a simulation program of the RRSSIM.

Neutron Point Kinetics

To model a reactor containing material(s) of high photo-neutron yield, such as Be and heavy water, a model slightly modified from conventional point kinetics is selected to cover retarded photo-neutrons created by gamma rays in Be and heavy water [1][2][5]. Balance equations of neutron concentration, delayed neutron precursors, and photo-neutron precursors are expressed as [5][6]

$$\frac{dN(t)}{dt} = \frac{\rho(t) - \beta_C - \beta_D}{\Lambda} N(t) + \sum_{i=1}^{I} \lambda_{C_i} C_i(t) + \sum_{j=1}^{J} \lambda_{D_j} D_j(t) + S,$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_{C_i}}{\Lambda} N(t) - \lambda_{C_i} C_i(t),\ i = 1, \dots, I,$$

$$\frac{dD_j(t)}{dt} = \frac{\beta_{D_j}}{\Lambda} N(t) - \lambda_{D_j} D_j(t),\ j = 1, \dots, J,$$

Thermal Power and Primary Cooling System

Thermal power from neutron and gamma radiation in the core and reflector is considered as follows. The fuel element temperature is modeled by a simple energy conservation law as [6]

$$M_{FE} C_{FE} \frac{dT_{FE}}{dt} = \eta_F Q_C - H_F (T_F - T_C),$$

The coolant temperature passing through a core, T_c, is modeled as

$$M_C C_C \frac{dT_C}{dt} = (1 - \eta_F) Q_C + H_F (T_F - T_C) - W_C C_C (T_{CO} - T_{CI}),$$

.

Reactivity Feedback

The reactivity feedback is considered to be due to the variations in the fuel, coolant, reflector, and xenon load. In addition, an external reactivity insertion is modeled in the form of an arbitrary shape such as a step or ramp insertion.

3. Verification and Application

The result of the RRSSIM is compared with that of the PARET/ANL code, which was originally developed for the SPERT project and later modified by ANL with the aim of providing an analysis of plate-type research and test reactors, and extensively tested through the SPERT I and SPERT II experiments [7].

The reference reactor modeled in this simulation is an open-pool type 5 MW research reactor. It is equipped with plate-type fuel assemblies and cooled using a forced convection flow during normal power operation.

3.1 Verification

The RRSSIM model is verified by comparisons to the simulation results of PARET for a heat transfer without kinetics, kinetics without reactivity feedback, and kinetics with reactivity feedback. The results show good agreement with the RRSSIM and PARET models.

Heat Transfer without kinetics (from 10-4% FP to 20% FP and vice versa)

Figure 1 shows the temperature responses at low power operation. While the RRSSIM model shows slightly lower temperatures than the PARET model, there is no noticeable difference during the transient. The maximum difference in the fuel temperature was about 0.07 ˚C at 20% FP.

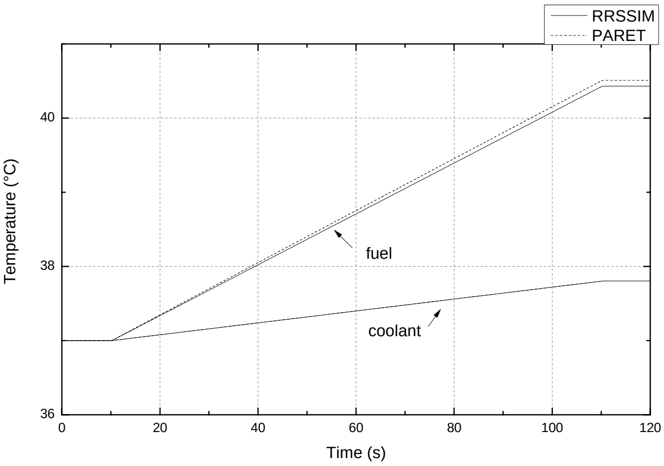

Figure 1. Temperature responses during a reactor power up from 10^{-4}% FP to 20% FP

Kinetics without reactivity feedback

Figure 2 shows the reactivity insertion transient without a reactivity feedback at full power operation. The RRSSIM model showed good agreement with the PARET model.

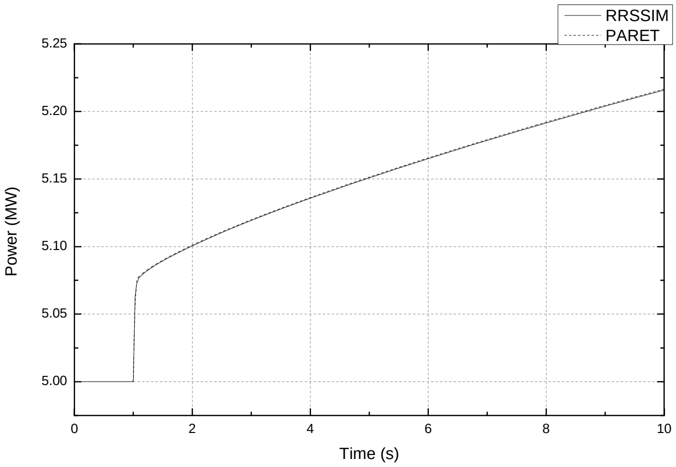

Figure 2. Reactivity insertion transient without reactivity feedback (step, +0.1 mk at 1 s)

Kinetics with reactivity feedback

Figure 3 shows the fuel temperature behavior during reactivity insertion (step, +0.1mk at 1 second) with feedback at full power operation. The RRSSIM model showed quite a good estimation with a very small difference from the PARET model.

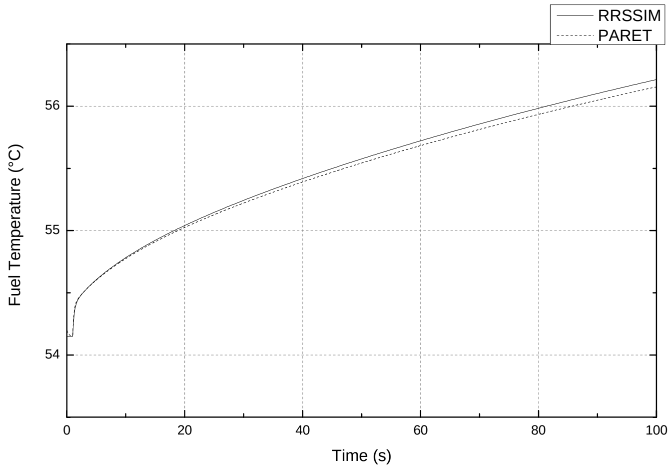

Figure 3 Fuel temperature during reactivity insertion transient with reactivity feedback (step, +0.1 mk at 1 s)

3.3 Application

Power maneuvering

Figure 4 shows the power up/down maneuvering operation with control logic [8] according to the demanded power over time. The simulation results showed that the reactor power can be controlled automatically in an acceptable manner using a designed controller.

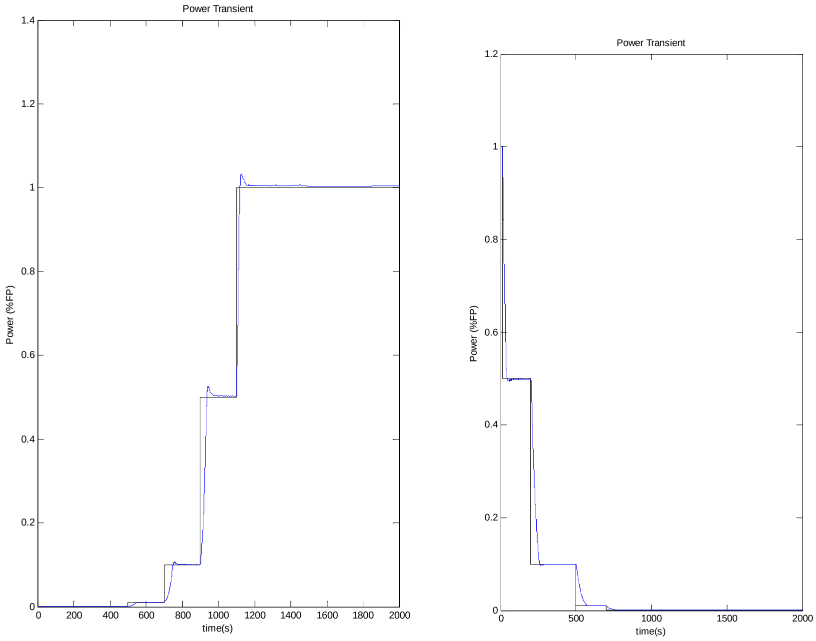

Figure 4 power maneuvering

Disturbance to reactivity such as moving target

Figure 5 shows the variations of the reactivity, temperature, and reactor power during a 4mk reactivity insertion transient, which may be caused by an insertion or withdrawal of some targets such as experimental devices and radioisotope production facilities in research reactors.

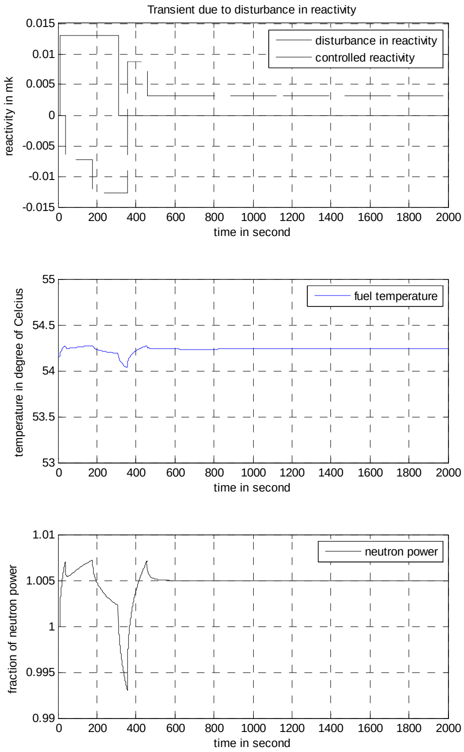

Figure 5 Reactor transient from disturbances in reactivity (4mk in 300 seconds)

4. Summary and Conclusions

A tool capable of analyzing the somewhat simple but essential coupled neutronic and thermal-hydraulic behaviors of research reactors was verified through numerical experiments using the PARET/ANL code. The results showed that the tool is able to simulate the reactivity transient from the loading of a target as well as maneuvering power.

In addition, a possible extension of the code is expected as a tool to prepare the guidelines for safe operation when handling targets for radioisotope production and irradiation tests inside a nuclear reactor. A future of the code is expected to be a fast, flexible, easily approachable design tool with a friendly graphical user interface for use in research reactors.

5. References

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