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A point kinetics model for dynamic simulations of next generation nuclear reactor

Mohamed S. El-Genk [a, b, c, d, *], Jean-Michel P. Tournier [a]

[a] Institute for Space and Nuclear Power Studies, The University of New Mexico, Albuquerque, NM, USA
[b] Nuclear Engineering Department, The University of New Mexico, Albuquerque, NM, USA
[c] Mechanical Engineering Department, The University of New Mexico, Albuquerque, NM, USA
[d] Chemical and Biological Engineering Department, The University of New Mexico, Albuquerque, NM, USA

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ABSTRACT

An accurate, fast-running and stable six-group, point kinetics (PK) model is developed and applied successfully to the dynamic simulation of the operation of the prismatic core, high temperature next generation nuclear plant (NGNP) reactor. The model is unrestricted by the size of the time step, which could be as much as several seconds, accounts for Doppler Broadening and the fuel and graphite temperature reactivity feedbacks, and includes an active neutron source for zero-power reactor startup. An efficient and robust numerical technique that approximates the exponential matrix using 7th order-accurate Padé(3,3) function with a discretization error on the order of $(\Delta t)^3$, solves the coupled nonlinear and stiff six-groups point kinetics equations. The PK model handles reactivity insertions in excess of a prompt critical, $\rho/\overline{\beta}>$ \$1.0, with unrestrictive time step size. Model results are successfully benchmarked using the Inhour solution for a step insertion of external reactivity. To simulate the transient response of the NGNP reactor following an external reactivity insertion and during a startup, the PK model is coupled to 84-nodes thermal-hydraulics model of the reactor, also developed in this work. With a 2 s time step, the error of predicting the reactor thermal power is ~0.001%, increasing exponentially to ~0.08% and ~1.5% with increased time step size to 5 and 8 s, respectively. The present PK model has been successfully incorporated into MELCOR-H_2 nuclear reactor analysis code to simulate transient operation of Very High Temperature Reactor (VHTR) for electricity generation, using a Closed Brayton Cycle turbomachinery, and the co-generation of hydrogen using Sulfur Iodine (SI) thermo-chemical processes.

1. Introduction

The Next Generation Nuclear Plant (NGNP) project was established in 2005 by United States Department of Energy (DOE), as required by Congress in Subtitle C of Title VI of the Energy Policy Act. The objective was to develop, license, build, and operate a prototype modular high temperature helium gas-cooled reactor (HTGR) plant for electricity generation at high thermal efficiency > 45%, the cogeneration of hydrogen using thermochemical processes, and the co-production of high-temperature process heat for energy-intensive industrial uses. The pre-licensing interactions for the NGNP began in 2006 and were suspended in 2013 after DOE decided in 2011 to cease detailed design and license application phases, citing impasses with the NGNP Industry Alliance on cost sharing arrangements for the public-private partnership required by Congress. Nonetheless, design development and construction activities of HTGRs for commercial applications continued in many countries around the world, notably China (Zhang et al., 2009). Licensing these reactors require developing and validating system codes, such as RELAP5-3D and MELCOR-H2, with transient analysis capabilities (Gauntt et al., 2000; Rodriguez et al., 2007; RELAP5-3D© Code Development RELAP5-3D Code Development Team, 2012). Due to the complexity of these codes, the time step for the transient simulations should not be restricted by the stability and accuracy of the solution of the reactor's six-group point kinetics equations.

In order to assess the effects of certain operation transients on the neutronics and thermal hydraulics parameters, and the

* Corresponding author. Founding Director, Institute for Space and Nuclear Power Studies, The University of New Mexico, USA.
E-mail address: mgenk@unm.edu (M.S. El-Genk).

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performance of a nuclear reactor, it is desirable to demonstrate robust capabilities for simulating these transients and performing complex safety analyses. This would require solving the six-group point kinetics equations, with the applicable reactivity feedback effects, as a function of space and time and integrating the solution in a system analyses code such as MELCO-H2 (Rodriguez et al., 2007, 2009) and RELAP5-3D (RELAP5-3D© Code Development RELAP5-3D Code Development Team, 2012). Such an approach is quite complex and would require huge computational capabilities.

An alternative approach couples the reactor thermal-hydraulics (TH) to the solution of the reactor's nonlinear point kinetics (PK) equations, with applicable values of the reactivity feedbacks, the neutron lifetime, and the concentrations and decay constants of the delayed neutron groups. These values are determined from separate neutronics analyses of the reactor type of interest. This approach is more practical and efficient to incorporate into large system codes, such as RELAP5-3D (RELAP5-3D© Code Development RELAP5-3D Code Development Team, 2012) and MELCOR-H2 (Rodriguez et al., 2007), but the time step for solving the point kinetics equations needs to be much less restrictive than that used by the thermal-hydraulics and safety analysis models in the codes.

The six-group point kinetics equations are a set of transient, stiff, nonlinear and coupled ordinary differential equations for calculating the fission power and the concentrations of the delayed neutron groups or precursors, in response to changes in the reactor temperatures and/or an external reactivity insertion during a reactor startup and following a reactivity insertion or a change in the operating thermal power of the reactor. For representative results, the values of the delayed neutron concentrations and decay constants, the neutron generation life time, and the various temperature reactivity feedbacks for the fuel, moderator, and coolant, and due to Doppler broadening need to be determined and incorporated into the solution of the point kinetics equations.

Numerous approximate analytical and numerical solutions of the point kinetics equations have been reported (Kinard and Allen, 2004; Quintero-Leyva, 2008; Nahla and Zayed, 2010; Mamieh and Saidinezhad, 2012). They are either oversimplified, to speed up the transient analyses of nuclear reactors and/or require using a very small time steps for accuracy and solution stability. Recently, Ganapol (2013) has introduced a unique contribution to solving the PK equations using a semi-analytical method, based on a piecewise constant approximation and accounting for the reactivity feedback effect. The demonstrated results were quite accurate for a time step of as large as 0.01s.

The objective of this paper is to develop an accurate, fast-running and stable 6-point kinetics model for simulating the transient response of the prismatic core, high temperature NGNP reactor (MacDonald et al., 2003), with unrestrictive time step size. The developed point kinetics (PK) model accounts for the effects of Doppler broadening and the fuel and graphite temperature reactivity feedbacks, and includes an active neutron source for zero-power reactor startup. The coupled six-groups point kinetics equations are solved using an efficient methodology that approximates the exponential matrix using 7th order-accurate Padé(3,3) function, with a discretization error on the order of $(\Delta t)^3$ and an unrestrictive time step. The PK model results are successfully benchmarked using those of the Inhour analytical solution for step reactivity insertions in excess of a prompt critical, $\rho/\overline{\beta}>$ \$1.0.

To simulate the transient response of the NGNP reactor, following an external reactivity insertion and during a reactor startup, the PK model is coupled to 84-nodes thermal-hydraulics model of the NGNP reactor. The PK model detailed in this paper has been incorporated into the MELCOR-H_2 nuclear reactor analysis code (Rodriguez et al., 2007, 2009) to simulate operation transients of Very High Temperature Reactor (VHTR), for electricity generation, using a closed Brayton Cycle turbomachinery, and the co-generation of hydrogen using Sulfur Iodine (SI) thermochemical processes. This PK model could also be applied to other reactor types, after incorporating the applicable reactivity feedbacks and kinetics parameters.

1.1. Point kinetics equations

The governing equations in the present PK model are expressed in terms of the reactor's thermal power, P, and the delayed-neutron precursors, $\{Y_i\}$, as:

$$\frac{dP}{dt} = \frac{\rho - \overline{\beta}}{\Lambda} \times P + \sum_{i=1}^{6} \lambda_i Y_i + S_o, \tag{1}$$

$$\frac{dY_i}{dt} = \frac{\beta_i}{\Lambda} \times P - \lambda_i Y_i, \quad \text{i} = 1 \text{ to } 6. \tag{2}$$

The total reactivity, ρ, is expressed in terms of the effective multiplication factor, k, as:

$$\rho = \frac{k-1}{k} = 1 - \frac{1}{k}. \tag{3}$$

The neutron generation time(s), $\Lambda = (v\nu\Sigma_f)^{-1}$, and the thermal power (W) generated by the ith group of the delayed-neutron precursors is given as:

$$Y_i = Q_f VOL \times \frac{C_i(t)}{\nu\Lambda}, \tag{4}$$

The rate of thermal power generation by the active neutron source (W/s) in Equation (1) is expressed as:

$$S_o = Q_f \times \frac{s'_o}{\nu\Lambda}. \tag{5}$$

The coupled set of stiff and nonlinear, first-order differential equations (1) and (2), is solved subject to the initial conditions:

$$P_{(t=0)} = P_o, \; Y_{i(t=0)} = Y_i^o, \text{ where i} = 1 \text{ to } 6. \tag{6}$$

Assuming an initial equilibrium at $t = 0$, then$dY_i/dt = 0$, where $i = 1$ to 6, and$(dP/dt) = 0$, reducing Equation (2) to simple form:

$$Y_{i(t=0)} = Y_i^o = \frac{\beta_i}{\lambda_i \Lambda} P_o, \text{ where i} = 1 \text{ to } 6. \tag{7}$$

When an active neutron source is present ($s'_o > 0$), a small negative external reactivity, $\rho_o < 0$, needs to be inserted in equation (1) to ensure equilibrium, thus:

$$\rho_o = -\frac{\Lambda S_o}{P_o}. \tag{8}$$

With no active source present ($s'_o = 0$), a zero external reactivity, $\rho_o = 0$, ensures equilibrium. In this case, the reactor becomes critical at any thermal power, P_o, where those powers generated by delayed neutron precursors are related to P_o by Equation (7). For transients simulations of the NGNP reactor, the total reactivity in Equation (1), ρ, is the sum of the external reactivity, ρ_{ext} (active control), and the fuel Doppler reactivity feedback, ρ_D, the fuel temperature reactivity feedback, ρ_f, and the graphite temperature reactivity feedback, ρ_G, thus:

$$\rho = \rho_{ext} + \rho_D + \rho_f + \rho_G. \tag{9}$$