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Parameter analysis of neutron point kinetics for nuclear reactors

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HIGHLIGHTS

- Five mathematical models describing the point reactor kinetics equations of nuclear power plants are investigated.
- Explicit solutions for the transients and safety analysis are introduced.
- Closed form expressions for reactivity are proposed.
- Comparison between both analytical and numerical solutions.
- Neutron flux density and reactor reactivity are analyzed under different circumstances.
- Efficient control is performed for Nuclear Power Plants.

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ABSTRACT

There is no one model can describe the neutron point kinetic formulation of reactor behaviors. This is due to that nuclear reactor operates in different time regions under different conditions. Therefore, we investigated in this paper several models to explain the performance of neutron point kinetic reactors according to time region of operation. These regions of operation represent the prompt neutron analysis, the delayed supercritical assessment and the transient behavior analysis. The first region of operation is described by neutron jump approximation model. The delayed supercritical one is evaluated by substitution model and combinational analysis model. The transient behavior includes prompt and delayed temperature feedback models. The obtained results are compared with published numerical models and validated using block diagram programming technique. The effects of initial power on the reactor performance are evaluated. Moreover, the influences of inserted positive and negative reactivity on the generated neutron flux density are introduced. The steady state operation of nuclear reactor is improved after step reactivity of $\rho_0 > 1\beta$. It is observed that the behavior of delayed neutron precursor increases after 40 s from cold start-up mode. Furthermore, optimum reactivity with step reactivity of $\rho = 2\beta$ is accomplished that introduces efficient handling of control rod within reactor core. Hence, the neutron dynamic behaviors under variation of control rod positions can be estimated. Thus, safety analysis and transient behaviors during start-up and shutdown of nuclear power plants can be optimized. Consequently, efficient nuclear protection level of nuclear power plant can be fulfilled.

1. Introduction

The neutron point kinetic is one of the most important reduced models of nuclear science and engineering (Ray, 2012). They have been included to countless studies and applications under neutron dynamics (Espinosa-Paredes et al., 2017; El_Tokhy and Mahmoud, 2014; Ray and Patra, 2012, 2013; Polo-Labarrios and Espinosa-Paredes, 2012a, 2012b). Neutron point kinetics express the time-dependence of neutron population and decay of delayed neutron precursors within reactor. The neutron point kinetics models are linear. These models describe the influence of reactor reactivity on the neutron population within nuclear reactor. The neutron point kinetics models are used for computation of neutron flux density. Also, they are used to determine delayed neutron precursor concentrations in the system of nuclear reactor (Ray and Patra, 2013). It is difficult to deal and manipulate these models due to their stiffness (Aboanber and Hamada, 2003). Moreover, the neutrons point kinetics are the most frequently solved models for reactor dynamics (Aboanber, 2003a).

For nuclear power plants, the variation of power during start-up and shut-downs depends on the inserted reactivity. On other hand, inappropriate reactivity insertion endangers the reactor (Chen et al., 2006). During the normal start-up, the control rod is uplift

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continuously. Subsequently, it moves step by step when the reactor is nearer to critical state (Li et al., 2010a). But, the rode position is kept fixed after withdrawing control rod until the nuclear reactor reached to stable state during the physical start-up. The reactor will arrive to the delayed critical by some similar steps (Li et al., 2010a). The continuous indication of the rate of change of neutron density is necessary for the secure start-up and functionality of nuclear reactors (Li et al., 2010b). Consequently, it is significant to analyze the change of neutron density in order to evaluate the relationships of neutron density response versus the speed of lifting the control rod (Zhang et al., 2008). Analysis of neutron point kinetics is useful when control aspects considered. It is necessary to develop accurate solution of the point kinetics equations (Li et al., 2007). Since, none of the presented numerical solutions can achieve the need for real-time and even super-time computation for the secure start-up and operation of reactors in practice (Li et al., 2010b).

An increasing interest in the task of searching for exact handling of linear and nonlinear problems by the scientific community has been noticed (Petersen et al., 2011). The compact explicit estimation gives better insight into the properties of the system. Also, it can be used to predict the behavior in limiting cases such as reactor kinetic approximations (Pazsit et al., 2012). The treatment of point kinetics equations in the presence of temperature feedback is useful for estimating the transient behavior of the reactor power and the parameters of the reactor core (Li et al., 2007; Tashakor et al., 2012). These models describe the neutron density with respect to the power level (Ray and Patra, 2013; Aboanber and Hamada, 2003). The nuclear reactor is the main part of nuclear power plants (Gonçalves et al., 2015). Neutron chain reaction occurs inside its core. Also, a nuclear reactor is a very complex system. It is made-up of various parts such as core, moderator, reactors, fuel bundles, control rods and coolant circulation system. The analysis, design and control of nuclear reactor depend on the precise knowledge of neutron flux distribution inside reactor core (Vyawahare and Nataraj, 2013).

This system can be solved to obtain the neutron density, the density of delayed neutron precursors, reactivity and temperature as function of time (Nahla and Zayed, 2010). The reactivity function and neutron source term are the parametric quantity of this essential system. The neutron density and delayed neutron precursor concentrations differ randomly with respect to time (Ray and Patra, 2013). Exact treatment of neutron point kinetics equations of nuclear reactor provides insight into the dynamics of nuclear reactor operation. They are useful in understanding the power fluctuations experienced during start-up or shut-down when the control rods are adjusted (Polo-Labarrios and Espinosa-Paredes, 2012b; Hamieh and Saidinezhad, 2012; Polo-Labarrios et al., 2014). Moreover, the neutron density and delayed neutron precursor concentrations determine the time-dependent behavior of the power level of nuclear reactor. The aim of this paper is to give a detailed and consistent presentation of the engineering features of the problem of the neutron kinetics, together with a discussion of the interpretation of the control phenomena involved. This paper is organized in the following manner. The basic assumptions and models description are described in Section 2. Then, the performance analysis of neutron point kinetic reactor is presented in Section 3. Discussions of the results are expressed in Section 4. Finally, concluding remarks are summarized in Section 5.

2. Basic assumptions and models description

The density of neutron flux and the delayed neutron precursor concentration determine the time-dependent behavior of the power level of a nuclear reactor (Hamieh and Saidinezhad, 2012). They are influenced by control rod position (Hamieh and Saidinezhad, 2012). The reactivity is one of the most important properties of nuclear reactors. It is directly related to the control of the reactor (Espinosa-Paredes et al., 2011). The reactivity will be inserted with lifting the control rods. Practically, the linear reactivity is introduced at certain period of time with each step of lifting the control rods. These control rods are lifted discontinuously. The length of each step is a time interval that assigned to the duration of a transitory. Therefore, the reactor can reach criticality in a slow and safety way (Espinosa-Paredes et al., 2011). However, uncontrolled control rods withdrawal or ejection is the most common type of initiator for a reactivity insertion accident (Espinosa-Paredes et al., 2011).

In this manuscript, one-group diffusion model is assumed. Therefore, it focuses the attention specifically on the spatial aspects. Also, the treatment of energy variable through multigroup approximation is important task of nuclear reactor kinetics. However, this aspect cannot be included in the present work due to additional complication introduced into the mathematical formalism (Corno et al., 2008). The effect of extraneous neutron resource is supposed to be neglected at steady output power. A generic reactor with negative temperature coefficient of reactivity is assumed. Since, the initial reactivity is less than the total fraction of delayed neutrons (Chen et al., 2013). From mathematical point of view, nuclear reactor is a very complex device with special emphasis of the kinetic effects on spatial basis throughout the reactor. The reactor is assumed to be simple entity. So, the performance of reactor portions is noted to be identical at the same time (Aboanber and El Mhlawy, 2009) that recently confirmed by many authors (Aboanber and El Mhlawy, 2009). The heat loss is assumed to be negligible under rapid transient. It is supposed for fuel temperature coefficient of reactivity. On other hand, various treatments to the point reactor kinetics equations can be obtained under simplified conditions. Since, there is being no extraneous neutron source. A prompt jump approximation (Yamoah et al., 2013) and constant neutron source are assumed. The reactor is in subcritical state. Thus, the external neutron source cannot be neglected during cold start-up. In this case, a lower average temperature of reactor core is considered. So, the power addition is supposed to be small. The presence of temperature feedback is assumed. It is useful in providing an estimate of the transient behavior of reactor power and other system variables in the reactor core that are fairly tightly coupled (Aboanber, 2009).

3. Neutron point kinetic reactor analysis

The neutron population and the delayed neutron precursor concentration are important parameters to be studied for safety analysis and transient behavior of the reactor (Yamoah et al., 2013; Arkani et al., 2016; Bortot et al., 2015; Aboanber et al., 2014; Nahla and Al-Ghamdi, 2012). Although, it is important to study the reactor kinetics equations as a function of space and time, some tightly coupled reactor can be analyzed with point kinetics equations (Nahla, 2010). Consequently, various models are presented and studied for describing neutron flux density, reactivity, average delayed neutron precursor concentration and temperature. The neutron point kinetics equations are nonlinear and rigid (Nahla and Zayed, 2010; Aboanber, 2009; Chen et al., 2007). The analytical solution for a set of differential equations can be obtained under very specific conditions. Recently, new analytic models and methods are brought forward in some pertinent literature. Their analytical solutions can be introduced (Chen et al., 2007). Moreover, different analytic models and solving methods are analyzed and compared. Therefore, this work introduces new methods to solve the coupled two point kinetic model of coupling reactor theory