



The calculation of the reactivity by the telegraph equation



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ARTICLE INFO

Article history:

Received 13 January 2017

Received in revised form 6 June 2017

Accepted 9 June 2017

ABSTRACT

Reactivity is one of the most important quantities of a nuclear reactor because it is directly related to reactor core control. In a recent paper, Altahhan et al. (2016) derived a telegraph model of the point reactor kinetics equations considering variable separation and mono-energetic neutron approximation. In this paper the inverse point kinetics equation based on the telegraph model was obtained. The power history was calculated by the partial derivatives method as proposed by Diaz et al. In order to assess reactivity accuracy considering the approximations involved in this model, simulations were performed for different exponential power and relaxation time. The results for reactivity as obtained from the proposed inverse point reactor equation show that it has significant differences in a comparison with conventional formalism, being more pronounced as the relaxation time increases.

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1. Introduction

During the operation of a nuclear power plant it is necessary to monitor neutron behaviour in the reactor core (Aboanber and Mhlawy, 2009). The time-dependent behaviour of the neutrons in response to any change in the material composition is important for the safe operation of the reactor. Transient changes can take place during reactor start-up (Zhang et al., 2008) or shutdown or as a result of accidental disturbances in the operation of the reactor. They may result in the departure of the reactor from the critical condition. Therefore, it is very important to predict the time-dependent behaviour of the neutron population as induced by changes in the neutron multiplication (Chen et al., 2015), (Nahla and Zayed, 2010) and (Li et al., 2009).

Reactivity is one of the most important quantities of a nuclear reactor that represents the deviation from the condition of criticality, and in the design of a nuclear power plant this information may be used for a deeper investigation of the plant design bases that are related to reactor operation. Control systems and operational procedures are used to limit the rate of reactivity variation.

Transient events as seen in a nuclear reactor can be predicted only through the modification of the neutron flux and, as a result, it is possible to make a sufficiently precise forecast on the consequences of the transients. It is enough to relate the magnitude of the neutron flux, which varies in time, to the neutron population in the core of a nuclear reactor (Henry, 1975). Point kinetics equations relate these parameters and thus allow a study of the tran-

sient situations that may occur in a nuclear reactor, and their obtaining takes place from a sequence of approximations, done from the neutron transport equation. Their obtaining can be accomplished directly from the neutron transport equation, for the neutron diffusion equation, or through a heuristic procedure, according to Stacey (2007) and Henry (1975).

The reactivity can be predicted through the inverse point reactor kinetics model. This model results from the separation of the spatial dependence by assuming a time-independent spatial flux shape separated from a time-dependent amplitude function.

In practice, the use of point kinetics equations takes place in the so-called inverse kinetics where the reactivity is obtained from the nuclear power history (Duderstadt and Hamilton, 1976). There are only a few problems for which it is possible to obtain an exact analytical solution for neutron density, given a specific reactivity. Indeed, it is frequently more appropriate to invert the problem by calculating the reactivity that will determine the past behaviour for the neutron density expressed from a direct relation with the nuclear power. This procedure, according to Henry (1975), is more aligned with the nuclear reactor control methodology.

Many papers have been published with methods to determine the reactivity using the inverse point kinetics equation. Recently, Palma et al. (2016) derived such an equation from the neutron transport equation considering the time variation of the neutron density current in the P1-approximation. The kinetics parameters were consistently defined for a multi-group energy structure. In another paper Altahhan et al. (2016) derived a telegraph model of the point reactor kinetics considering a variable separation and mono-energetic neutrons approximation. The last is a very

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crude approximation that leads to very simple kinetics parameters definitions, with poor accuracy.

The goal of this paper consists of obtaining the inverse point kinetics equation based on the telegraph model as proposed by Altahhan et al. (2016) in order to evaluate the reactivity accuracy considering the approximations involved in this method.

2. Telegraph point reactor kinetics equations

The set of equations based on the telegraph model of point reactor kinetics (TPRK) as proposed by Altahhan et al. (2016) for a finite reactor can be written thus:

$$\begin{aligned} \tau_0 n^{(2)}(t) + \left[\frac{\tau(1-\rho) - \tau_0(1-\beta)}{\Lambda} + 1 \right] n^{(1)}(t) \\ = \left(\frac{\rho - \beta}{\Lambda} \right) n(t) + \sum_{i=1}^m \lambda_i C_i(t) + \tau_0 \sum_{i=1}^m \lambda_i C_i^{(1)}(t) + q(t) \\ + \tau_0 q^{(1)}(t), \end{aligned} \quad (1)$$

$$C_i^{(1)}(t) = \frac{\beta_i}{\Lambda} n(t) - \lambda_i C_i(t), \quad (2)$$

respecting the following initial conditions:

$$\begin{aligned} n(0) &= n_0, \\ n^{(1)}(t)|_{t=0} &= 0, \\ C_i(0) &= C_{i0} = \frac{\beta_i}{\Lambda \lambda_i} n_0, \end{aligned} \quad (3)$$

and where

$$\begin{aligned} \tau_0 &= \frac{3D}{v} \\ \tau &= \frac{\tau_0}{1+L^2 B^2}, \end{aligned} \quad (4)$$

are respectively the relaxation time for an infinite medium and a finite medium, and $(1+L^2 B^2)^{-1}$ is the non-leakage probability for neutrons, with all other parameters defined as follow: v is the neutron velocity, D is the neutron diffusion coefficient, B^2 is the reactor geometrical buckling, Λ is the neutron mean generation time, L^2 is the diffusion area, β is the total delayed neutron fraction of the fission neutrons, λ_i is the delayed neutron decay constant for the i th delayed neutrons precursor group, $C_i(t)$ is the neutrons precursor concentration in the i th group, ρ is the reactivity and $q(t)$ is the external source strength inside the reactor.

In their paper, Altahhan et al. (2016) obtained Eqs. (1) and (2) in a different way to Niederauer PhD thesis (1967), which includes different variables definitions. The relaxation time was introduced to correct the drawback of the current, adjusted instantaneously to the gradient of the flux in Flick's Law. Relaxation time is the parameter specifying the rate of nuclear reactor returns to the state of equilibrium. Greater values for relaxation time mean that the nuclear reactor returns to the state of equilibrium very slowly.

In the paper by Altahhan et al. (2016) other variables are used, as related to mono-energetic neutrons and homogeneous medium approximations. They are:

$$\begin{aligned} L^2 &= \frac{D}{\Sigma_a} \\ v \Sigma_a &= \frac{1}{l(1+L^2 B^2)} \\ \rho &= \frac{k_{\text{eff}} - 1}{k_{\text{eff}}} \\ k_{\text{eff}} &= \frac{k_{\infty}}{(1+L^2 B^2)} \\ \Lambda &= \frac{1}{v \Sigma_a k_{\infty}} = \frac{l}{k_{\text{eff}}} = (1-\rho)l, \end{aligned} \quad (5)$$

where l is the neutron lifetime, k_{∞} is the infinite reactor multiplication factor and Σ_a is the macroscopic absorption cross section.

It is easy to see that when $\tau_0 \rightarrow 0$ and with no external neutrons source inside the reactor, Eq. (1) reproduces the conventional point kinetics equations well established in the literature (Duderstadt and Hamilton, 1976):

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

In the next section an expression for reactivity from the inverse TPRK will be obtained.

3. Calculation of reactivity from inverse kinetics

In this section an expression for reactivity, based on the telegraph inverse point kinetic equations, Eqs. (1) and (2), will be presented. Before, we will obtain the inverse kinetic equation derived from the conventional point kinetics equations, Eqs. (2) and (6). In all cases, a single effective delayed group was considered, that is:

$$\beta = \sum_{i=1}^m \beta_i, \quad (7)$$

$$\lambda = \left[\frac{1}{\beta} \sum_{i=1}^m \frac{\beta_i}{\lambda_i} \right]^{-1}, \quad (8)$$

with m being the number of the delayed neutrons precursor group.

3.1. Conventional inverse kinetics

From the set of conventional point kinetics equations, it is possible to write the following expression for the time variation of the reactivity in relation to the amplitude function (Díaz et al., 2007):

$$\rho_{\text{con}}(t) = \beta + \frac{\Lambda}{n(t)} n^{(1)}(t) - \frac{\lambda \beta}{n(t)} H(t), \quad (9)$$

where $H(t)$ is the power history of the reactor as follows:

$$H(t) = \int_{-\infty}^t n(t') e^{-\lambda(t'-t)} dt' = \frac{\langle n_0 \rangle}{\lambda} e^{-\lambda t} + \int_0^{\infty} n(t') e^{-\lambda(t'-t)} dt'. \quad (10)$$

The power history – Eq. (10) – will be calculated in this paper according to the method proposed by Díaz et al. (2007). It was demonstrated that, having integrated by parts, and in successive times, the integral in Eq. (10) it is possible to re-write it based on the 'n' order derivatives for amplitude function $n^{(n)}(t)$, as follows:

$$\begin{aligned} \int_0^{\infty} n(t') e^{-\lambda(t'-t)} dt' &= \frac{\lambda n(t) - n^{(1)}(t)}{\lambda^2 n(t) - n^{(2)}(t)} n(t) \\ &\quad - \frac{\lambda n(0) - n^{(1)}(0)}{\lambda^2 n(0) - n^{(2)}(0)} n(0) e^{-\lambda t}. \end{aligned} \quad (11)$$

In replacing Eqs. (10) and (11) one obtains the power history that appears in Eq. (9):

$$H(t) = - \frac{\lambda \beta}{n(t)} \left[\frac{\langle n_0 \rangle}{\lambda} e^{-\lambda t} + \frac{\lambda n(t) - n^{(1)}(t)}{\lambda^2 n(t) - n^{(2)}(t)} n(t) - \frac{\lambda n(0) - n^{(1)}(0)}{\lambda^2 n(0) - n^{(2)}(0)} n(0) e^{-\lambda t} \right]. \quad (12)$$

3.2. Telegraph inverse kinetics equation

The inverse telegraph point reactor kinetics equation will be obtained considering a single effective delayed group and no external source of neutrons. In this case, Eq. (1) can be simplified and written by:

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