Annals of Nuclear Energy 113 (2018) 118–121

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Analysis of delayed neutrons' contribution for the maximum to average flux ratio in an annular pulsed reactor by Finite Volume Method

Mário Augusto Bezerra da Silva *, Rajendra Narain

Nuclear Energy Department, Center of Technology and Earthsciences, Federal University of Pernambuco, Brazil

ARTICLE INFO

Article history:
Received 15 September 2017
Accepted 8 November 2017

Keywords:
Pulsed reactor
Reactivity modulation
Finite Volume Method

ABSTRACT

Generation of intense neutron sources is relevant for basic nuclear physics and for material testing and isotope production. Nuclear reactors have been utilized as sources of intense neutron fluxes, although the achievement of such levels is limited by the drawback to remove fission heat. Periodic pulsed reactors provide intense fluxes by a rotating reflector near a subcritical core. A concept for the generation of intense neutron fluxes that combines features of periodic pulsed reactors and steady state reactors was proposed by Narain (1997). This concept is known as Very Intense Continuous High Flux Pulsed Reactor (VICHFPR) and was analyzed by using one-group diffusion equation with moving boundary conditions and Finite Difference Method with Crank-Nicolson formalism, but did not consider the contribution of precursors. This research analyzed the flux distribution in the Very Intense Continuous Flux High Pulsed Reactor (VICHFPR) by using the Finite Volume Method and considered the contribution of delayed neutrons. The results showed that this contribution is not relevant for the maximum to average flux ratio, which is the most important characteristic of VICHFPR concept.

1. Introduction

Reactors with high neutron fluxes have been operating for a variety of applications in nuclear area. Once high fluxes give rise to a considerable heat generation, its dissipation becomes one of the main problems for this kind of reactor. The need for intense neutron fluxes originates from a desire to obtain high neutron fluence during a short time (Kapil, 1972). For instance, if it is intended to estimate the irradiation damage in reactor components, an average neutron fluence equal to 10^{22} neutrons/cm^2 must be provided so as to represent the whole *in-situ* fluence during the components' lifetime. Thus, the reduction of time testing can be accomplished by using more intense neutron fluxes: for example, if a flux equal to 10^{16} neutrons/cm^2 s is utilized, only a few weeks would be necessary for testing components. Another instance that shows the necessity of intense fluxes is the production of important transuranic nuclides, such as Cf^{252}, which is used as a neutron source.

The availability of enriched fuel and improvement in heat transfer for usage in research reactors offered a new dimension to the design of reactors. An example of these developments is the HFIR (High Flux Isotope Reactor), that has been under operation for more than fifty years and shall be able to operate until 2035. It is a tank type reactor, moderated and cooled by light water and uses beryllium as reflector, being capable to produce isotopes, perform engineering tests and basic neutron physics experiments with a flux equal to 5×10^{15} neutrons/cm^2 s.

Pulsed reactors can also be used in order to provide intense neutron flux levels (Ash, 1979; Long et al., 1976; Shabalin, 1979; Wimett, 1966). One of these reactors is GODIVA, that possesses 50 kg of enriched uranium disposed in two moving hemispheres for reaching supercritical state. Thermal pulsed reactors like TRIGA and TREAT have also been used for research and training, but cannot provide enough fluence for neither material testing nor isotope production. An important advance in pulsed reactors was obtained when the first Periodic Pulsed Reactor (PPR) named IBR was built, starting with average and peak powers equal to, respectively, 1 kW and 5 MW, and cooled by air. Subsequently, the average power was raised to 30 kW and using the same coolant as before. Some modifications were implemented, providing an average power equal to 2 MW, while the peak power reached 1500 MW (liquid sodium was used coolant).

A new concept for producing high neutron flux was proposed (Narain, 1997) by combining features of pulsed and stationary reactors. Such a concept, known as VICHFPR (Very Intense Continuous High Flux Pulsed Reactor), consists of an annular subcritical core pulsed by means of a rotating reflector. Prompt supercritical state is achieved in the neighborhood of the rotating reflector,

* Corresponding author.
E-mail address: mabs500@gmail.com (M.A.B. da Silva).

https://doi.org/10.1016/j.anucene.2017.11.019
0306-4549/

while the rest of the core remains subcritical. As the reflector is rotated, a neutron pulse is produced along the annular core. Thus, whether an irradiation sample moves synchronized with the rotating reflector, it will continuously be exposed to the peak flux, but the rest of the core will need cooling corresponding to the average flux.

This study intends to analyze the contribution of delayed neutrons to VICHFPR concept (if there is any) by using a numerical technique known as Finite Volume Method (FVM) and to compare the results with those obtained by Finite Difference Method (FDM) in the absence of delayed neutrons. According to Maliska (2004), the main advantage of using Finite Volume Method instead of Finite Difference Method or Finite Element Method is that the former is based on conservation balances in an elementary volume, while the other ones do not, dealing only with grid points, being non-conservative at a discrete level.

2. Theory

For the development of the theory, two subsections are considered. In the first one, the basic concepts of Finite Volume Method are presented, inasmuch they are necessary to discretize the main equations; some details of VICHFPR neutronics and the discretized equations are shown in the other subsection.

2.1. The Finite Volume Method (FVM)

The conservative form of continuity, momentum and energy equations for a compressible and Newtonian fluid, including equations for scalar quantities such as pollutant concentration and temperature, may be written in the following form (Versteeg and Malalasekera, 2007) by using a general variable, φ, in which u, t, ρ, S and Γ represent velocity, time, density, source term and diffusion coefficient, respectively:

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla \bullet (\rho u \phi) = \nabla \bullet (\Gamma \nabla \phi) + S_\phi \quad (1)$$

For transient problems, the terms must be considered in the finite volume integration over a control volume (CV). By performing an integration of Eq. (1) and using Gauss' divergence theorem, one obtains:

$$\int_{CV}\left(\int_t^{t+\Delta t}\frac{\partial(\rho\phi)}{\partial t}dt\right)dV + \int_t^{t+\Delta t}\left(\int_A n \bullet (\rho u \phi)\, dA\right)dt = \int_t^{t+\Delta t}\left(\int_A n \bullet (\Gamma\nabla\phi)\, dA\right)dt + \int_t^{t+\Delta t}\int_{CV} S_\phi dV\, dt \quad (2)$$

The first step in the Finite Volume Method (FVM) is to divide the domain into discrete control volumes, whose boundaries are positioned mid-way between adjacent nodes. For one-dimensional analysis, a control volume surrounds each nodal point (node). As it is shown in Fig. 1 (Silva and Narain, 2013), P identifies a general nodal point, W and E identify its neighbors, the nodes to the west and east, respectively. The west and east side faces of the control volume are referred to by w and e, respectively.

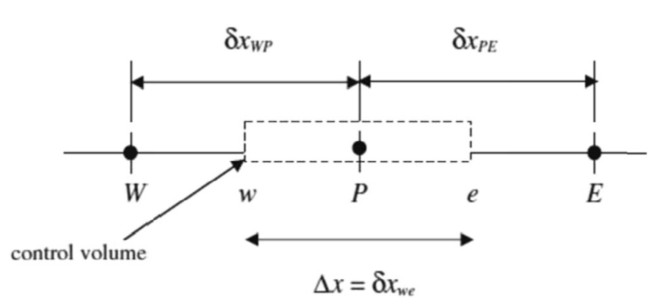

Fig. 1. Grid generation (Silva and Narain, 2013).

2.2. Characteristics of VICHFPR

VICHFPR concept consists of an annular high leakage subcritical core pulsed by means of a rotating reflector, as can be seen in Fig. 2 (Silva and Narain, 2012). In the region near the reflector, a prompt supercritical state is achieved, although the remainder of the core stays subcritical. As long as the reflector is rotated, the pulse is generated continuously along the core, thus giving rise to a rotating pulse in the annular core.

Due to some drawbacks related to time dependence of moving boundary conditions and annular geometry, a modeling for the core is developed by opening up the ring so that the system is approached to a parallelepiped whose length is equal to perimeter of the ring. Besides, a change to a coordinate system that moves with the reflector is adopted (x direction). Further details can be found in Narain (1997).

3. Methodology

The basic equations considering only monoenergetic neutrons and one effective delayed neutron group are (Lamarsh and Baratta, 2001):

$$\frac{1}{v}\frac{\partial\phi}{\partial t} = D\nabla^2\phi + (\nu\Sigma_f(1-\beta) - \Sigma_a)\phi + \lambda C \quad (3)$$

$$\frac{\partial C}{\partial t} = \beta\nu\Sigma_f\phi - \lambda C \quad (4)$$

By using a transverse buckling, B_t^2, for the y and z directions, Eq. (3) turns to Eq. (4):

$$\frac{1}{v}\frac{\partial\phi}{\partial t} = D\frac{\partial^2\phi}{\partial x^2} + (\nu\Sigma_f(1-\beta) - \Sigma_a - DB_t^2)\phi + \lambda C \quad (5)$$

The elimination of time dependent boundary conditions is accomplished by a change of variable space x, which is transformed to x', that is, to a coordinate system that moves with the reflector according to Eq. (6) in the x direction, where V represents the velocity of the reflector. The temporal coordinate remains the same, i.e., $t' = t$.

$$X' = x - Vt \quad (6)$$

After some algebraic manipulations (Silva, 2003), Eqs. (3) and (4) can be written as:

$$\frac{1}{Dv}\frac{\partial\phi}{\partial t} = \frac{\partial^2\phi}{\partial x^2} + B\frac{\partial\phi}{\partial x} + A\phi + \frac{\lambda}{D}C \quad (7)$$

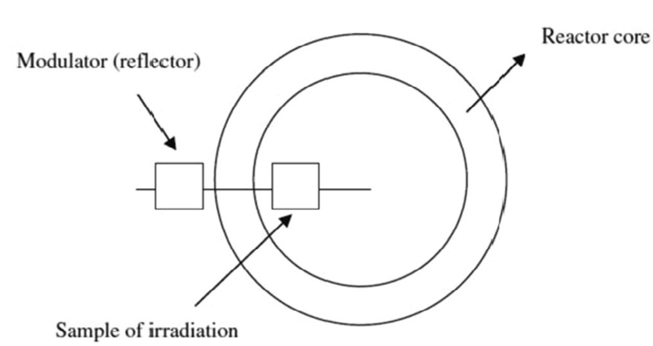

Fig. 2. VICHFPR display (Silva and Narain, 2012).