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Photon transport effect on intra-subassembly thermal power distribution in fast reactor

Go Chiba *, Masashi Tsuji, Tadashi Narabayashi

Hokkaido University, Kita-ku, Sapporo, Hokkaido 060-8628, Japan

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ABSTRACT

In order to accurately predict intra-subassembly thermal power distribution in a fast reactor, neutron and photon transport calculations are carried out with a multi-purpose reactor physics calculation code system CBZ. All the fission fragment nuclide are treated explicitly during fuel depletion, and irradiation time-dependent energy spectra of delayed fission γ-rays emitted from all the fission fragment nuclides are precisely simulated. Time-dependent delayed β-ray emission and transmutations of fission fragment nuclide by neutron-nuclide reactions are also taken into account. A fuel subassembly model of Japanese prototype fast reactor Monju is used for numerical calculations, and their two-dimensional geometric feature is precisely modeled by a ray-tracing-based collision probability method implemented in CBZ. When the photon transport is considered, total thermal powers in fissile material regions are reduced by about 1.5% except at the beginning of fuel depletion.

1. Introduction

Accurate prediction of thermal power spatial distribution in a nuclear fission reactor core is essential for reliable and efficient reactor core designs. In addition to macroscopic spatial power distribution over a whole core required to allocate coolant flow in the core, a microscopic power distribution, *i.e.,* intra-subassembly thermal power distribution, is also important to determine nuclear fuel depletion, neutron irradiation of structure materials and temperature evaluations. In fast reactor core designs, a maximum fuel temperature is one of the most important design parameters and it sometimes restricts a feasible design range.

As well known, nuclear fission reactions release a large amount of energy with some different forms such as kinetic energy of fission fragments, prompt γ- and β-rays, delayed γ- and β-rays emitted from unstable fission fragments. In addition to fission reactions, γ-rays generated by several neutron-nuclide reactions such as (n, γ) and (n, n') reactions also contribute to thermal power generations. Energy given to nuclides by neutron scattering reactions is also not negligible. The simplest way to calculate thermal power distribution coming from these different forms is to determine an effective fission Q-value, Q_f. A thermal power can be obtained by multiplying total number of occurring fission reactions by Q_f. Historically this simple calculation method has been used with some improvement in fast reactor design studies. Its detail is well reviewed in a reference (Hazama and Yokoyama, 2013).

In this simple treatment, all the heats generated by a fission reaction are deposited to a medium in which the fission reaction occurs. Actually γ-rays generated by neutron-nuclide reactions and radioactive decay of unstable fission fragments transport in a core and deposit their energy to a medium which is different from a originating medium. This is referred to as a γ-ray (or photon) transport effect on thermal power distribution in the present paper.

Procedure of photon transport effect evaluation is quite simple; one has to calculate γ-ray sources from neutron-nuclide reaction rate distributions, and perform a fixed source photon transport calculation with a particle transport code. Thermal power distribution induced by photons can be obtained from photon flux distribution and the KERMA (Kinetic Energy Release in MAterials) factors of mediums consisting of a reactor core. A reference (Hazama and Yokoyama, 2013) reports that the photon transport effect increases heats in fast reactor blanket and shielding regions about 10%. The importance of the photon transport effect has been well recognized and this effect has been taken into consideration somehow in fast reactor core design studies.

Although the photon transport effect can be easily evaluated as above mentioned, there is a difficulty in calculating γ-ray sources originating from radioactive decay of fission fragments: so called the delayed fission γ-rays. Since a strength and energy spectrum of the delayed γ-rays depend on an irradiation profile, they cannot be uniquely determined. In actual calculations of the photon transport effect, however, fission fragment compositions are calculated by assuming an appropriate irradiation condition and a unique delayed γ-ray spectrum per a fission reaction is determined for each fissile nuclide. Then these γ-ray spectra are used commonly during fuel depletion to calculate γ-ray sources. Some have

* Corresponding author. Tel./fax: +81 10 706 6683.
E-mail address: go_chiba@eng.hokudai.ac.jp (G. Chiba).

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assumed an infinite irradiation since fission fragment compositions can be analytically calculated (Hazama and Yokoyama, 2013; Maeda et al., 2013). This infinite irradiation assumption, however, considers only nuclide transmutations by radioactive decay and cannot treat transmutations by neutron-nuclide reactions.

In the present study, we evaluate the photon transport effect on intra-subassembly thermal power distribution in a fast reactor. A notable point of this study is to rigorously simulate irradiation time-dependent delayed γ-ray sources by simulating explicitly nuclide transmutations of all the fission fragment nuclides by both the radioactive decay and the neutron-nuclide reactions.

2. Numerical calculation procedure

All the numerical calculations are performed with a multi-purpose reactor physics calculation code system CBZ, which is being developed at Hokkaido university. The CBZ code system has been well validated through a post-irradiation examination analysis (Kawamoto et al., 2012).

2.1. Multi-group neutron and photon libraries

Multi-group neutron and photon libraries are generated from JENDL-4.0 (Shibata et al., 2011) by the NJOY-99 code (MacFarlane and Kahler, 2010). The covered energy ranges and the numbers of energy groups are from 10^{-5} eV to 10 MeV and 70 for the neutron library, and from 1 keV to 50 MeV and 42 for the photon library. A lethargy width of all the energy groups except for the final one (from 10^{-5} eV to 0.322 eV) is 0.25 in the neutron library. The energy group structure of the neutron library has been utilized for fast reactor neutronics calculations in Japan. The energy group structure of the photon library is the same as the VITAMIN-J 42-group structure. Options for the weight function choice in NJOY-99 are set to iwt = 7 in the neutron library generation and iwt = 3 in the photon library generation. Self-shielding factor tables for the neutron library are generated using the narrow resonance approximation for neutron flux representation.

2.2. Treatment of fission fragment nuclide transmutation

Decay data of fission fragment nuclide such as decay constants, decay modes and their branching ratios, decay energy and delayed γ-ray spectra are taken from the JENDL FP Decay Data File 2011 (JENDL/FPD-2011) (Katakura, 2011). The delayed γ-ray spectrum is energy-integrated to the 42-group structure of the photon library. Fission yield data are taken from the JENDL FP Fission Yields Data File 2011 (JENDL/FPY-2011) (Katakura, 2011). We treat all the fission fragment nuclide explicitly in nuclide transmutation calculations. Neutron-nuclide reactions are also considered in the transmutation calculations for 406 nuclides to which the evaluation data are provided in JENDL-4.0. Although neutron-nuclide reaction data are not evaluated for extremely short-lived nuclides in JENDL-4.0, the neutron-nuclide reactions of such nuclides seems negligible in the present heating calculations. The neutron-nuclide reaction rates are obtained in multi-group neutron transport calculations described in the following subsection, and then nuclide transmutation calculations are performed with the matrix exponential method with the Chebyshev rational approximation (Pusa and Leppänen, 2010).

2.3. Neutron and photon transport calculations

We perform neutron and photon transport calculations for a two-dimensional fast reactor fuel subassembly model. The resonance self-shielding effect is evaluated by the method proposed by Tone (Tone, 1975). Whereas the numerical accuracy of this method is inferior to more advanced methods such as the subgroup method, it has been shown in the previous study that Tone's method can treat spatially-dependent intra-subassembly resonance self-shielding effect of a fast reactor subassembly well (Chiba, 2003). The resonance self-shielding effect is also taken into consideration in γ-ray production cross-sections; γ-ray production cross-sections are calculated by multiplying the self-shielded neutron-nuclide reaction cross-sections by γ-ray yield. The resonance self-shielding calculation is carried out only at the initial depletion step, and the same energy-averaged microscopic cross-sections are used in subsequent depletion steps.

After obtaining medium-wise multi-group neutron and photon cross-sections, neutron transport calculations are performed by a collision probability-based module of CBZ with an eigenvalue calculation mode. Collision probabilities are calculated by the ray-tracing method with the periodic boundary conditions. The maximum distance between two parallel neighboring rays is 0.01 cm and the azimuthal angle is divided to 48. γ-ray sources promptly emitted from neutron-nuclide reactions are determined from the calculated neutron flux and reaction rate distributions, and then the delayed γ sources emitted from radioactive decay of fission fragments are added to them. Finally a photon transport calculation is performed with the same collision probability-based module of CBZ. In both the neutron and photon transport calculations, the scattering anisotropy is considered by the transport approximation.

2.4. Power distribution calculations

We calculate the following component-wise power distributions.

- The kinetic energy of fission fragments and prompt β-ray energy. The sum of these energy per a fission reaction, E_{FR}, is given in evaluated data files. We use the evaluated data given in JENDL-4.0 for each fissionable nuclide. This power component can be calculated by multiplying total number of fission reactions by E_{FR} for all fissionable nuclides.
- The delayed β-ray energy. This component is calculated from β-ray energy per a radioactive decay, decay constants and number densities of all fission fragment nuclides included in fuel regions.
- The γ-ray energy. This component includes the prompt and delayed fission γ-ray and other neutron-nuclide reaction-induced γ-ray. This component is calculated by multiplying photon flux by the KERMA factor.
- Energy deposited to nuclides by elastic scattering reactions with neutrons. This component is calculated from neutron elastic scattering reaction rates.

In order to evaluate the photon transport effect on thermal power distribution, we also perform a thermal power distribution calculation without considering photon transport. In such calculations, all the γ-ray sources energy is deposited to a medium from which the γ-ray originates.

Note that only emitted γ-ray energy is taken into consideration in inelastic scattering reactions; energy deposited to nuclides by inelastic scattering reactions with neutrons is ignored in the present study.

3. Numerical results

3.1. Validation of nuclide transmutation calculation capability of CBZ

To show a validity of the CBZ capability for nuclide transmutation calculations with over 1000 fission fragment nuclides, we