Resonance treatment using pin-based pointwise energy slowing-down method

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ABSTRACT

A new resonance self-shielding method using a pointwise energy solution has been developed to overcome the drawbacks of the equivalence theory. The equivalence theory uses a crude resonance scattering source approximation, and assumes a spatially constant scattering source distribution inside a fuel pellet. These two assumptions cause a significant error, in that they overestimate the multi-group effective cross sections, especially for ^{238}U. The new resonance self-shielding method solves pointwise energy slowing-down equations with a sub-divided fuel rod. The method adopts a shadowing effect correction factor and fictitious moderator material to model a realistic pointwise energy solution. The slowing-down solution is used to generate the multi-group cross section. With various light water reactor problems, it was demonstrated that the new resonance self-shielding method significantly improved accuracy in the reactor parameter calculation with no compromise in computation time, compared to the equivalence theory.

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1. Introduction

Equivalence theory has been widely used for resonance treatment methods [1,2]. The equivalence theory gives a reasonable solution within a short computation time. Because of this many lattice physics codes adopt the equivalence theory to generate the effective cross-section (XS) [3,4]. There have been a lot of research into equivalence theory to improve the accuracy of multi-group effective XS and the applicability for general geometry [1,5,6].

Recently, Cao reported that the multi-group ^{238}U absorption XS from the equivalence theory tends to be overestimated [7]. He concluded that the flux from the narrow resonance (NR) approximation in the equivalence theory is problematic, and suggested an improved resonance treatment method using a pre-generated look-up table of integrated flux like the multi-group effective XS. Yamamoto focused on the reaction rate preservation between the ultrafine group calculation and the multi-group effective XS calculation with multi-term rational approximation, and suggested an improved derivation [8]. The two researches were performed to correct an overestimation of ^{238}U absorption XS.

The overestimation of the ^{238}U effective XS is addressed in this paper. This work figures out that resonance scattering causes the overestimation. In the equivalence theory, the resonance scattering source is approximated by the intermediate resonance (IR) approximation, and the resonance scattering XS is usually neglected in the resonance treatment process. However, for the nuclides (i.e., ^{238}U) which have very large resonance scattering XSs, the equivalence theory causes a significant error in the effective XS because of the following reasons. First, the expression for the effective XS is derived

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from the multi-term rational approximation along with the NR or IR approximation. The derivation is formulated based on the IR approximation, but the final effective XS is calculated as a linear combination of the effective XSs generated from multiple dilution systems. This discrepancy between the derivation and usage of the XS look-up table can cause an error in the effective XS. Second, the equivalence theory cannot treat the spatial distribution of the effective XS inside the fuel pellet. Since the theory is based on the averaged effective XS of the fuel lump, the spatial self-shielding and spatial distribution of the scattering source cannot be considered properly. There are several methods which can consider spatial self-shielding inside the fuel pellet [9–11]. However, as the methods are based on the pellet-averaged effective XS [10] or the pellet-averaged escape probability approximation [9,11] with the IR approximation, the resonance scattering source cannot be accounted for accurately.

This paper suggests a new resonance self-shielding method using the pointwise energy slowing-down solution in order to resolve the two problems described above. The new method computes the collision probabilities inside the fuel pellet as a function of the total XS, and then solves pointwise energy slowing-down equations based on the pin-cell. The shadowing effect correction factor and fictitious moderator are introduced to derive a realistic pointwise energy slowing down equation. The multi-group effective XS is calculated using the pointwise flux spectrum. The new method is verified with various light water reactor (LWR) problems and shows significant improvements in the accuracy of the effective XS and the multiplication factor.

2. Overestimation of ^{238}U cross sections

The conventional equivalence theory is summarized in Section 2.1, and numerical test results are described in Section 2.2 to show the overestimation of ^{238}U XS with the equivalence theory. From Section 2.3 to Section 2.5, further tests are performed with the pointwise energy approaches to find reasons of the overestimation ^{238}U XS.

2.1. Equivalence theory

A transport equation with collision probabilities for the two-region problem is

$$\Sigma_{t,F}(E)\phi_F(E)V_F = P_{FF}(E)V_F Q_{s,F}(E) + P_{MF}(E)V_M Q_{s,M}(E), \tag{1}$$

where

$$
\begin{cases}
Q_{s,F}(E) = \displaystyle\sum_{r\in F} N^r \int\limits_{E}^{E/\alpha^r} \sigma_s^r(E')\phi_F(E')\frac{1}{1-\alpha^r}\frac{dE'}{E'} \\[2em]
Q_{s,M}(E) = \displaystyle\sum_{r\in M} N^r \int\limits_{E}^{E/\alpha^r} \sigma_s^r(E')\phi_M(E')\frac{1}{1-\alpha^r}\frac{dE'}{E'}
\end{cases}, \tag{2}
$$

and F is the index of fuel; M is the index of moderator; $\Sigma_{t,F}(E)$ is the total XS of fuel; $\phi_F(E)$ is the flux in fuel; V_F is the volume of fuel, $P_{FF}(E)$ is the first flight fuel collision probability (or fuel-to-fuel collision probability); $P_{MF}(E)$ is the collision probability from M to F; N^r is the number density of nuclide r; $\sigma_s^r(E)$ is the scattering XS of nuclide r; $\alpha^r = (1-A^r)^2/(1+A^r)^2$; and A^r is the mass of nuclide r.

The scattering source from the nuclide in the fuel material is written with the IR approximation as follows:

$$\int\limits_{E}^{E/\alpha^r} \sigma_s^r(E')\phi_F(E')\frac{1}{1-\alpha^r}\frac{dE'}{E'} \approx \lambda^r\sigma_p^r\frac{1}{E} + \left(1-\lambda^r\right)\sigma_s^r(E)\phi_F(E), \tag{3}$$

where λ^r is the IR parameter; and σ_p^r is potential XS of the nuclide r.

The scattering source from the nuclide in the non-fuel material (or moderator) is approximated as follows:

$$\int\limits_{E}^{E/\alpha^r} \sigma_s^r(E')\phi_M(E')\frac{1}{1-\alpha^r}\frac{dE'}{E'} \approx \lambda^r\sigma_p^r\frac{1}{E}. \tag{4}$$

Although the IR parameter is introduced to approximate the resonance scattering source, the IR parameter considers the average energy loss in the collision as well as the width of resonance peak in the practical lattice physics calculation [1]. This is why the IR parameter is used in approximating the scattering source of the moderator, even though the moderator does not usually have a resonance. Eq. (1) is rewritten by using the approximate scattering source and a reciprocity theorem in Eq. (6) as follows:

$$\Sigma_{t,F}(E)\phi_F(E) = P_{FF}(E)\left[\lambda_F \Sigma_{p,F}\frac{1}{E} + (1-\lambda_F)\Sigma_{s,F}(E)\phi_F(E)\right] + P_{FM}(E)\Sigma_{t,F}(E)V_F\frac{1}{E}, \tag{5}$$