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Resonance self-shielding treatment and analysis of resonance integral tables for Fully Ceramic Micro-encapsulated fuels with the Embedded Self-Shielding Method

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A resonance calculation method for Fully Ceramic Micro-encapsulated (FCM) fuels containing stochastically dispersed tri-structural isotropic (TRISO) coated fuel particles has been proposed in this research. The purpose is to obtain effective homogenized resonance cross sections representing the effect of double heterogeneity (DH). The Monte Carlo code MVP is used to solve the heterogeneity in the isolated FCM fuels pin, and to couple with the method of characteristic (MOC) to generate heterogeneous resonance integral (RI) tables for the following Embedded Self-Shielding Method (ESSM) based resonance calculation. The ESSM method is employed to treat the heterogeneity in the lattice (Dancoff effect). Heterogeneous RI tables based on different packing fraction may differ in relationship between background and self-shielded cross sections. Analysis of this distinction's impact on ESSM calculation has been conducted. Furthermore, resonance interference effect is neglected in ESSM because heterogeneous RI tables are developed for isolated resonant nuclide system. Therefore, Resonance Interference Factor (RIF) Method was applied to correct cross sections from ESSM. To obtain RIF, slowing-down equation need be solved twice for different homogeneous systems. Whereas, the cross section neglecting interference effect could be received by interpolating in homogeneous RI tables to improve efficiency. Evaluation of errors caused by interpolation in RIF method was performed with reference solutions from MVP. Numerical results show that the new method is proved effective in DH capability for resonance self-shielding calculation.

1. Introduction

Efforts have been made to achieve much safer, more reliable and economic nuclear power reactors since the accident at Fukushima. Thus development of nuclear fuels and claddings with enhance accident tolerance has been attracting attentions from all over the world. One of accident-tolerant fuel (ATF) proposed by Oka Ridge National Laboratory is the Fully Ceramic Micro-encapsulated (FCM) fuels adopting tri-structural isotropic (TRISO) particles at PWR conditions (Bragg-Sitton, 2014). TRISO particles which are stochastically dispersed throughout matrix comprise kernel fissile fuels and protective, shield cell shell materials. The advantage of this kind of fuel is capable of prohibiting fission products from releasing provided by the silicon carbide (SiC) shell of the TRISO particles. The dense, radiation-resistant SiC matrix where these particles are compacted also serves as the secondary safety boundary.

FCM fuels yield double heterogeneity in the aspect of geometry compared with typical cells of current PWR. The first heterogeneity refers to the heterogeneity of different cell in lattice. And the second heterogeneity comes from the heterogeneity of the dispersed particles and surrounding SiC matrix. The microscopic cross sections acquired from traditional homogenization method by volume weight fail to represent the influence of size of inclusions in the particle-dispersed media (Shmakov et al., 2000). Theoretically, Monte Carlo method has the ability of exactly modeling double heterogeneity problems. Shmakov's method obtained corrected point-wise effective microscopic cross sections based on a mixture of matrix with inclusions of random form. Toshihiro Yamamoto incorporated the improved Shamkov's method into Monte Carlo code MCNP to gain homogenized cross section representing DH effect (Yamamoto, 2006). Besides, Monte Carlo code MVP was applied directly to analyze neutronic DH effect (Akie and Takano, 2006). Nevertheless, Monte Carlo code requires for much computa-

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tional resources and could not be competent for time-dependent depletion calculation. Subgroup method was applied to resolve problems where coated TRISO particles with its surrounding matrix were homogenized as a one-dimensional sphere. And then cross sections were corrected with the infinite-medium Dancoff factor and the double heterogeneity Dancoff factor for fluoride salt-cooled high-temperature reactor (He et al., 2016). Cross section was predicted by the stochastic solution to calculate propagation through the media. Then new renormalized algorithm where MOC was directly implemented on stochastic problem was proposed to preserve the true stochastic propagation (Sanchez, 2004).

Recently, a fast resonance self-shielding method named as the Embedded Self-Shielding Method (ESSM) has been proposed (Williams and Kim, 2012). In the ESSM, the converged self-shielded cross-sections were obtained by iterating between transport calculation and interpolation in the heterogeneous resonance integral tables. The Dancoff effect was evaluated by performing fixed source transport calculation based on the real geometry of the analyzed system. In the traditional equivalence theory based method, the Dancoff factor was calculated outside the transport calculation using the collision probability method which is very time-consuming. Besides, the transport calculations in the ESSM are carried out for a whole energy group, which is different from subgroup method where the transport calculation is performed for each sub-group. Therefore, ESSM shows better calculation efficiency than equivalence theory method and subgroup method. However, the single-term rational approximation for the escape probability is used in the derivation of ESSM method. In order to reduce the error, problem dependent heterogeneous RI tables should be provided for the calculations. Recently, ESSM was applied to address DH problems (Kim and Gentry, 2016). In this research, Sanchez and Pomraning's method was used to originally estimate resonance self-shielded cross sections and to gain source term for initial fixed-source equation in ESSM. Although, the heterogeneous RI tables applied were generated for pressurized water reactors (PWR), the effect of DH was considered by Sanchez and Pomraning's method. In this paper, the heterogeneous RI tables were proposed to treat this effect. Monte Carlo code MVP (Mori et al., 1992) was implemented to solve realistic DH single cell problems and to obtain accurate self-shielded cross sections. Then fixed-source equation of single energy group was derived and to be solved by MOC code CART (Li et al., 2015) to gain scalar flux. Finally the corresponding background cross section could be achieved with accurate self-shielded and associated background cross sections.

The resonance interference effect is caused by the overlap of the resonance peaks of different nuclides. Nuclide data in homogeneous or heterogeneous RI tables are developed for each single resonant nuclide system neglecting resonance interference effect. Therefore, this effect cannot be directly treated by the resonance calculation methods based on RI tables such as ESSM and subgroup methods. Resonance Interference Factor (RIF) method (Williams, 1983) was proposed to account for resonance interference for the above mentioned methods. RIF could be achieved by comparing two sets of self-shielded cross sections. One set is from isolated single resonant nuclide system. And the other set comes from entire resonant nuclides fuel mixture systems. Homogeneous geometry rather than heterogeneous one was used to gain these two sets of cross sections because interference between resolved resonances was not sensitive to the environment and it could realize higher efficiency (Kim and Williams, 2012). Recently, it was pointed out that the evaluation of background cross sections and approximate equivalent relationship between heterogeneous and homogeneous systems were two main sources of errors in the RIF method (Zu et al., 2016). The conclusions were derived based upon assumption that the RI tables were detailed enough. Note that effective cross sections are generated from various diluted isolated resonant nuclide system and stored in form of homogeneous RI tables. And the denominator of RIF is calculated from an isolated resonant nuclide system neglecting resonance interference. In view of the two facts mentioned above, the denominator of RIF came from interpolating in homogeneous RI tables rather than being solved on the fly was applied (Liu et al., 2013). This method is identified as simplified RIF (sRIF) method in this paper. Meanwhile, the method obtaining the denominator of RIF still by solving slowing-down equation is named as full RIF (fRIF) method. In RIF method, the background cross sections from inverse interpolation are implemented to derive the homogeneous systems used to calculate numerator and denominator of RIF. Two sources of errors might be introduced to interpolation procedures above. One is that the models of solving slowing-down equation for generating homogeneous RI tables and RIF are inconsistent. The other is that the intervals of homogeneous RI tables are not narrow enough. In this paper, the source and effect have been evaluated. Approach to avoiding interpolating errors is suggested based on sensitivity analysis.

In this study, ESSM utilizing heterogeneous RI tables developed by Monte Carlo code MVP and MOC code CART was proposed to treat resonance self-shielding of DH problems. The impact of double heterogeneity on MG cross sections was considered by new RI tables. Resonance interference effect was neglected in the heterogeneous RI tables and assumed to be treated by RIF method.

The organization of this paper is as follows. The model of ESSM, method for generating the heterogeneous RI tables and coupling ESSM with RIF method are introduced in Section 2. In Section 3, the proposed method is tested against some DH problems. Some conclusions are given in Section 4.

2. Theory Description

2.1. Introduction and application of Embedded Self-Shielding Method

The collision form of neutron slowing-down equation can be expressed as follows:

$$V_F\Sigma_{t,F}(u)\phi_F(u) = V_F P_{F\to F}(u)Q_F(u) + \sum_{J\in M} V_J P_{J\to F}(u)Q_J(u), \tag{1}$$

where M is denoted as other materials other than fuels and u is lethargy. V_F, $Q_F(u)$, $Q_J(u)$, $\Sigma_{t,F}(u)$ and $\phi_F(u)$ are the volume, source term of fuel region, source term of materials J other than fuel, macroscopic total cross section and scalar flux of the fuel respectively. $P_{F\to F}(u)$ and $P_{J\to F}(u)$ are the first flight collision probability from fuel to fuel and from material J to fuel.

In the resolved resonance energy range, the source terms are conventionally simplified by the following three assumptions: (1) the scattering source is isotropic; (2) neglect up-scattering source; (3) neglect the direct fission source. For the non-fuel materials, $Q_J(u)$ can be further simplified with Narrow Resonance (NR) approximation. Finally, the $Q_J(u)$ is written as:

$$Q_J(u) = \sum_{iso\in J}\Sigma_{p,J,iso}, \tag{2}$$

where subscripts p is potential scattering cross section and iso is isotope in material J. With the reciprocity relation $V_x P_{x\to y}\Sigma_{t,x} = V_y P_{y\to x}\Sigma_{t,y}$, and assumption of $\Sigma_{p,J,iso} = \Sigma_{t,J,iso}$,

Eq. (1) can become:

$$\frac{\sum_{iso}\Sigma_{t,F,iso}(u)\phi_F(u)}{1-P_{esc}(u)} = Q_F(u) + \frac{P_{esc}(u)\sum_{iso}\Sigma_{t,F,iso}(u)}{1-P_{esc}(u)}, \tag{3}$$

where the escape probability that neutron escape from fuel and has its first collision in materials other than fuel is defined as