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Improved resonance calculation of fluoride salt-cooled high-temperature reactor based on subgroup method

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ABSTRACT

The subgroup method is improved in several aspects to address challenges brought on by design features of the Fluoride salt-cooled High-temperature Reactor (FHR). Firstly, the Dancoff correction is applied to resolve the double heterogeneity arising from embedding TRISO fuel particles in the matrix of pebbles. Secondly, a fast Resonance Interference Factor (RIF) scheme is proposed to treat the resonance interference effect in the FHR. In this scheme, the heterogeneous system is converted into a homogeneous one according to self-shielded cross section conservation of the dominant resonant nuclide. The resonance interference effect is considered in the equivalent homogenous system by correcting the non-interfered self-shielded cross sections with RIFs which are obtained by solving the slowing down equation in hyper-fine energy group (~1M number of energy groups). Finally, the resonance elastic scattering effect becomes considerable due to high temperatures in the FHR. This effect is considered by substitution of the conventional Resonance Integral (RI) table with that generated by the Monte Carlo method. The Monte Carlo method is modified via the Doppler Broadening Correction Rejection (DBRC) method to implement the Doppler broadened scattering kernel. The numerical results show that the Dancoff correction can significantly reduce errors brought about by the double heterogeneity. The fast RIF scheme provides more accurate effective self-shielded cross sections than the conventional iteration scheme. In addition, the speedup ratio of the fast RIF scheme is ~3.3 compared with the conventional on-the-fly RIF schemes for TRU TRISO. The scheme to generate RI table can resolve the resonance elastic scattering effect encountered by the conventional scheme.

1. Introduction

The subgroup method (Nikolaev et al., 1971; Chiba and Unesaki, 2006; Hébert, 2009) has long been used for resonance calculations and is widely employed in neutron transport codes such as HELIOS (Stamm'ler, 2001), DeCART (Joo et al., 2004) and MPACT (Liu et al., 2013a) for its geometrical flexibility. In the subgroup method, the fluctuation of the cross sections is described by a probability table, including subgroup cross sections and the corresponding subgroup probabilities. The probability table is then used to formulate the subgroup fixed source problem (SFSP). The SFSP can be solved by multi-group transport methods such as the Method Of Characteristics (MOC) (Chen et al., 2008; Zhang et al., 2011) to obtain the subgroup flux which is then used to weight the subgroup cross sections and obtain the effective self-shielded cross sections.

The FHR is a novel reactor concept that combines High Temperature Reactor (HTR) fuel and flibe ($^7LiF–BeF_2$) coolant (Kim et al., 2003; Fratoni, 2008; Li et al., 2015). It is a promising concept to overcome the drawbacks of the Very High Temperature Reactor (VHTR) such as low power density and high pressure of coolant. However, the design of the FHR challenges the conventional subgroup method. Firstly, the pebble fuel element comprised of an outer fuel-free graphite spherical shell and a fuel zone is used in the FHR. In the fuel zone of a pebble, tens of thousands of TRISO particles are embedded in a graphite matrix. This system can be considered as a double heterogeneous system (Tsuchihashi et al., 1985) where resonance calculation methods such as equivalence theory and subgroup method cannot be directly applied. Secondly, the fuel enrichment of the FHR is typically higher than that of the Pressurized Water Reactor (PWR), which will introduce complex resonance interference effects (Wehlage et al., 2005). Besides, in recent study, the $TRUO_{1.7}$ fuel is used in the FHR to incinerate transuranic (TRU) elements including Plutonium, Americium, Neptunium, Curium and so on (Fratoni, 2008). This kind of fuel mixture has a complex composition and challenges the conventional method to treat resonance interference effects. Finally, the FHR features high temperatures up to 1000 °C which makes the

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resonance elastic scattering effect significant (Becker et al., 2009a). The conventional scheme, generating the Resonance Integral (RI) table by solving the slowing down equations over a range of background cross sections based on asymptotic scattering kernel (MacFarlane, 2000), will introduce considerable errors due to underestimation of neutron up-scattering at high temperatures (Ouisloumen and Sanchez, 1991). This paper will focus on these significant effects of double heterogeneity, resonance interference and resonance elastic scattering, for the FHR.

A pile of pebbles in FHR can be considered as a double heterogeneous system (Sanchez and Masiello, 2002). The first heterogeneity comes from the heterogeneity of the TRISO particle and the surrounding graphite matrix. The second heterogeneity is from the heterogeneity of the fuel zone and the graphite spherical shell. The Dancoff factor has long been used for consideration of the double heterogeneity effect in the HTR (Hyun et al., 2010; Kloosterman and Ougouag, 2007; Kloosterman et al., 2005). The typical Dancoff correction considers two steps. In the first step, the coated TRISO particle with its surrounding matrix is modeled as a one-dimensional sphere with its self-shielded cross sections calculated by the subgroup method. In the second step, the infinite-medium Dancoff factor and the double heterogeneous Dancoff factor are calculated. The Dancoff factors are used to correct the self-shielded cross sections obtained in the first step. The infinite medium Dancoff factor accounts for the probability that a neutron escaping from a fuel kernel enters another fuel kernel within an infinite-medium fuel zone without colliding with a moderator nucleus. The double heterogeneous Dancoff factor is the probability that a neutron escaping from a fuel kernel enters another fuel kernel within the same pebble or another pebble without colliding with a moderator nucleus. In this paper, the analytical scheme proposed by Bende (Bende and Hogenbirk, 1999) is applied to calculate the Dancoff factors.

The resonance interference effect is caused by the fact that the multi-group nuclear data is prepared for each nuclide ignoring the overlap of the resonance peaks of different nuclides. The interference effect is conventionally treated by iteration, where, when the present resonant nuclide is treated, all the other ones are assumed to be without resonance peaks (Askew et al., 1966). However, there exist two shortcomings in this scheme. Firstly, the iteration procedure is time-consuming especially when there are numerous resonant nuclides due to burn-up. Secondly, the results of iteration cannot converge to the true value (Williams, 1983). To speed up the iteration procedure, a Resonant Nuclide Grouping (RNG) scheme was proposed (Stamm'ler, 2001). In this scheme, numbers of resonant nuclides are grouped into a small number of categories according to their resonance features. Although this scheme can improve the calculation efficiency, it suffers from loss of precision. To gain higher precision, a RIF scheme was developed (Wehlage et al., 2005; Williams, 1983). The RIF is the quotient of two sets of self-shielded cross sections, that is, the self-shielded cross sections with a single resonant nuclide and the self-shielded cross sections with the mixture of all nuclides. These self-shielded cross sections are calculated in continuous energy or hyper-fine energy groups. Then the RIF is applied to the self-shielded cross sections without resonance interference obtained by the subgroup method. The RIFs can be calculated in priori and tabulated (Kim and Hong, 2011; Peng et al., 2013), or be generated on-the-fly (Kim and Williams, 2012; Liu et al., 2013b) for each resonant nuclide. However, this scheme increases the storage of nuclear data and the conventional on-the-fly scheme increases the computation time. In this paper, in order to treat resonance interference effect efficiently and accurately, a fast RIF scheme is proposed. For each resonance group, the dominant resonant nuclide is selected. The self-shielded cross sections of the dominant resonant nuclide without resonance interference are calculated by the subgroup method. Then the heterogeneous system is converted to a homogeneous one by preserving the self-shielded cross section of the dominant nuclide. Finally, the self-shielded cross sections of all the resonant nuclides with resonance interference are obtained by solving the homogeneous slowing down problem.

In the subgroup method, the probability table is generated by fitting Resonance Integral (RI) tables. Methods such as the hyper-fine energy group method and the Monte Carlo method are often used to solve the slowing down problems over a range of background cross sections to generate the RI tables (Joo et al., 2009; Kim and Hong, 2011; Kim et al., 2003). For the hyper-fine energy group method, the asymptotic elastic scattering kernel assuming that the target nucleus is at rest is adopted (Ishiguro and Takano, 1971; Leszczynski, 1987; MacFarlane, 2000). For the Monte Carlo method, the scattering kernel without Doppler broadening assuming that the scattering cross sections at zero temperature are constant in energy is adopted (X-5 Monte Carlo Team, 2003). However, when the neutron energy is in the vicinity of the elastic scattering resonance peaks in the epithermal energy range, the thermal motion of the target will considerably influence the elastic scattering reaction and increase neutron capture in the resonance peaks. As a consequence, the eigenvalue and the Fuel Temperature Coefficient (FTC) are affected. This effect is the so-called resonance elastic scattering effect (Lee et al., 2008). Recent works have demonstrated that the resonance elastic scattering effect on eigenvalues is ~200 pcm at hot full power for light water reactor (LWR) (Lee et al., 2008) and ~400 pcm for Very High Temperature Reactor (VHTR) (Becker et al., 2009b). It is also shown that the Fuel Temperature Coefficients (FTC) are affected by ~10% for LWR (Ono et al., 2012). To take into account this effect in the deterministic method, Lee et al. utilized Monte Carlo method, which considers resonance elastic scattering effect via Weight Correction Method (WCM), to generate RI tables (Lee et al., 2008). Ono et al. implemented the simplified resonance elastic scattering model in the GROUPR module of NJOY (Ono et al., 2012). Mao et al. combined the RIF method and the Improved Méthode Direct (IMD) method to treat the resonance interference effect and the resonance elastic scattering effect simultaneously (Mao et al., 2015). In this paper, to introduce Doppler broadened scattering kernel for the multi-group deterministic method, the scattering kernel of the Monte Carlo code OpenMC (Romano and Forget, 2013) is modified via DBRC to generate RI table. The improved RI table is combined with the subgroup method to recover the resonance elastic scattering effect in the FHR.

The above improvements are implemented on a subgroup method based code named SUGAR (Cao et al., 2011; He et al., 2014). The theory and model of the subgroup method, the Dancoff correction for double heterogeneity, the schemes for treating resonance interference effect and the resonance elastic scattering correction are described in Section 2. The numerical results and analysis are provided in Section 3. The summations and conclusions are given in the last section.

2. Theory and model

2.1. Subgroup method

As illustrated in Fig. 1, subgroups are defined according to the magnitude of the cross section rather than the energy in a broad energy group. The energy range of a subgroup is defined by

$$\Delta E_{g,i} \in \{E|\sigma_{g,i} < \sigma(E) \leqslant \sigma_{g,i+1}\} \tag{1}$$

where g is the energy group index and i is the subgroup index.