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XPZ: Development of a lattice code for HTR

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ABSTRACT

The XPZ code is developed for the lattice physics computation in the high temperature reactors (HTRs). This paper introduces the methodologies adopted in the XPZ code, including the resonance treatment, equivalent homogenization, transport calculation, and burnup calculation. Emphasis is put on the treatment of the double heterogeneity effect, which involves the following two strategies. Firstly, the Dancoff factor obtained from the double-heterogeneous model is used in the resonance treatment. Secondly, with considering the spatially self-shielding effect in dispersed particles, the fuel compact is equivalently homogenized into a homogeneous media so that the conventional transport calculation can be applied. The effectiveness and accuracy of the methodologies are examined against Monte Carlo solutions. Numerical results demonstrate that the XPZ code is promising for lattice physics computations in HTRs.

1. Introduction

The high-temperature reactor (HTR) is one of the candidates for next-generation nuclear power plants. According to the form of the fuel element, there are two main types of HTRs, i.e. the pebble-bed reactors and the prismatic-block reactors. In both type HTRs, the fuel element generally includes a fuel-free graphite shell and a special "fuel compact" that contains randomly dispersed fuel particles. The dispersion fuel has an important advantage of preventing or reducing the release of fission products in a very high temperature. From the aspect of lattice physics analysis, the dispersion fuel leads to the so-called double-heterogeneity problem. The first heterogeneity refers to the macro regions of the fuel element, and the second refers to the micro structure of the fuel particles in the fuel compact. The lattice code for use in HTRs has to carefully account for the double heterogeneity problem, otherwise it may cause dramatic errors.

There have been several computer codes that are capable of treating double heterogeneity, such as VSOP (Teuchert et al., 1980), MICROX (Mathews, 1997), DELIGHT (Nojiri et al., 2004), DRAGON (Marleau, 2013), and etc. In Institute of Nuclear Energy Technology (INET) in China, the VSOP code has played an important role in the physical design and licensing procedures for the HTR-10 (Wu et al., 2002) and HTR-PM (Zhang et al., 2006) reactors. Recently, a code package named HINT (HTR In-house Neutronics Tool system) is under development at INET. As one of the fundamental work, a lattice code named XPZ (Xs Processor for HTR cell/assembly Zone) has been developed. The XPZ code inherits some well proven methods from the legacy code VSOP, and meanwhile, it tries to implement some advanced approaches adopted by the modern lattice physics codes.

This paper introduces the methodologies and capabilities of the XPZ code. It covers the general contents in lattice physics computation, including the resonance treatment, transport calculation, and burnup calculation. Besides, emphasis is put on how to deal with the double heterogeneity effect. In XPZ, the double heterogeneity effect is treated in the following two steps. Firstly, in the resonance self-shielding calculation, the fuel escape probability is corrected by the Dancoff factor that is obtained from the double-heterogeneous model. Secondly, with properly accounting for the spatially self-shielding effect in dispersed particles, the fuel compact is equivalently homogenized so that the conventional transport calculation can be performed.

The remainder of the paper is organized as follows. Section 2 describes the calculation flow of the XPZ code. Section 3 introduces the theory and methodologies. In Section 4, numerical results of various test cases are presented for validation. Concluding remarks are provided in Section 5.

2. Calculation flow

Fig. 1 gives the calculation flow of the XPZ code, which consists of the following steps:

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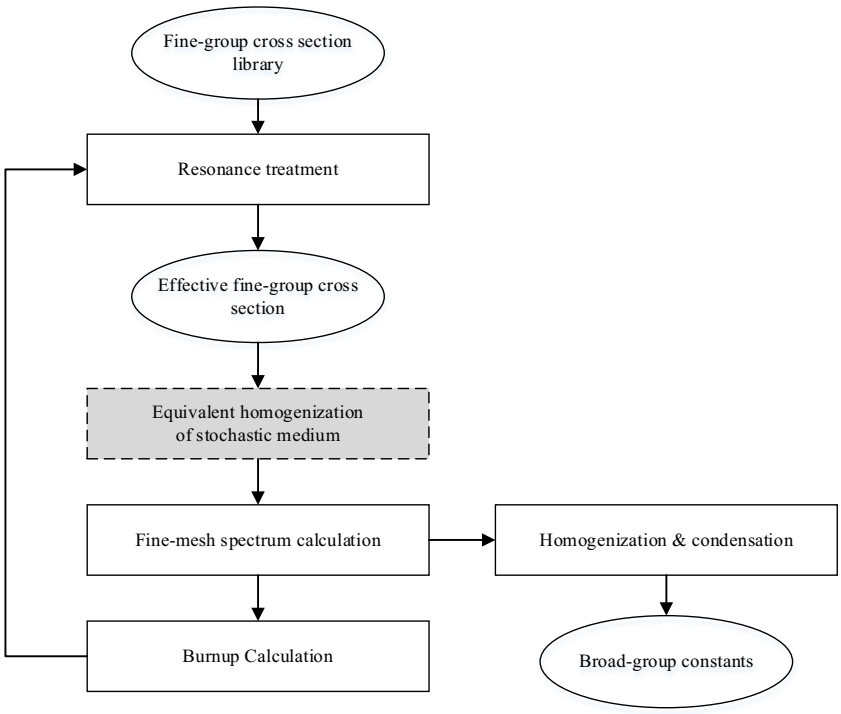

Fig. 1. Calculation flow of the XPZ code.

- It starts from a fine-group cross section library that is pre-produced by NJOY or some other data-processing codes. The data library contains a resonance integral table (RIT) at different background cross sections and temperatures for resonance isotopes. The RIT is calculated from a homogeneous system, but can be applied to heterogeneous systems according to the equivalence theory. It should be mentioned that the VSOP code has also utilized a resonance cross section library, which is tabulated versus various isotope densities and temperatures. But the library is obtained from a certain heterogeneous model, and thus it should not be used for other heterogeneous systems.
- The main task of the resonance treatment in XPZ is to evaluate the problem-specific background cross section, which is needed for the interpolation of resonance cross sections. In XPZ, the background cross section is formulated by the Bell factor and Dancoff factor. The Dancoff factor is calculated from the actual model in order to account for the double heterogeneity effect correctly.
- Compared with the typical lattice physics codes for light water reactors (LWRs), XPZ has a special process on the equivalent homogenization of the fuel compact, since it is a stochastic media containing dispersed fuel particles. Based on the rule of preserving the first-collision probabilities, the spatial self-shielding factors are calculated for the dispersed particles and the matrix. The self-shielding factors are then used to calculate the equivalently homogenized cross sections of the fuel compact.
- The next step is to calculate the flux distribution in energy and space by a neutron transport solver using the collision probability method. Besides, spatially homogenization and spectrally condensation are done to obtain the broad-group constants, which can be used for subsequent core physics computations.
- If required, the burnup calculation is performed for the current time step to update material compositions. A new round of the above calculation flow is then repeated for the next time step.

3. Methodologies

3.1. Resonance treatment

Starting from the neutron slowing down equation in a heterogeneous system, and applying the narrow resonance (NR) approximation and reciprocity theorem, the neutron flux in the fuel can be written as (Knott and Yamamoto, 2010):

$$\phi_f(E) = \frac{1}{E}\left[(1 - P_{f\to m}(E))\frac{\sum_{p,f}}{\sum_{t,f}(E)} + P_{f\to m}(E)\right] \tag{1}$$

where $\phi_f(E)$: neutron flux in the fuel, $\Sigma_{t,f}(E)$: macroscopic total cross section in the fuel, $\Sigma_{p,f}$: macroscopic potential scattering cross section in the fuel, $P_{f\to m}(E)$: fuel-to-moderator collision probability.

When the angular distribution of neutrons entering from the moderator region into the fuel is isotropic, the fuel-to-moderator collision probability in a lattice system is expressed as follows (Nordheim, 1961):

$$P_{f\to m}(E) = \frac{(1-C)P_e(E)}{1 - [1 - \Sigma_{t,f}(E)\bar{l}P_e(E)]C} \tag{2}$$

where $P_e(E)$ is the escape probability from the fuel, $\bar{l}$ is the mean chord length of the fuel, C is known as the Dancoff factor. By applying Wigner's rational approximation with the Bell factor, the fuel escape probability can be expressed as (Levine, 1963):

$$P_e(E) = \frac{\alpha_B}{\Sigma_{t,f}(E)\bar{l} + \alpha_B} \tag{3}$$

where α_B is the Bell factor.

By substituting Eqs. (2) and (3) into Eq. (1) and applying the well-known equivalence theory, the background cross section for the resonance nuclide r is given by:

$$\sigma_{b,r} = \frac{1}{N_r}\left[\sum_{k\neq r} N_k\sigma_{p,k} + g(C,\alpha_B)\Sigma_e\right] \tag{4}$$