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BEAVRS full core burnup calculation in hot full power condition by RMC code

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ABSTRACT

Monte Carlo method can provide high fidelity neutronics analysis of different types of nuclear reactors, owing to its advantages of the flexible geometry modeling and the use of continuous-energy nuclear cross sections. However, nuclear reactors are complex systems with multi-physics interacting and coupling. MC codes can couple with depletion solver and thermal-hydraulics (T/H) codes simultaneously for the "transport-burnup-thermal-hydraulics" coupling calculations. MIT BEAVRS is a typical "transport-burnup-thermal-hydraulics" coupling benchmark. In this paper, RMC was coupled with sub-channel code COBRA, equipped with on-the-fly temperature-dependent cross section treatment and large-scale detailed burnup calculation based on domain decomposition. Then RMC was applied to the full core burnup calculations of BEAVRS benchmark in hot full power (HFP) condition. The numerical tests show that domain decomposition method can achieve the consistent results compared with original version of RMC while enlarging the computational burnup regions. The results of HFP by RMC agree well with the reference values of BEAVRS benchmark and also agree well with those of MC21. This work proves the feasibility and accuracy of RMC in multi-physics coupling and lifecycle simulations of nuclear reactors.

1. Introduction

The Monte Carlo method, which is often taken as a benchmark method to validate deterministic methods, is receiving rising attention due to its irreplaceable advantages such as flexibility in geometry treatment, the ability to use continuous-energy pointwise cross-sections, the easiness to parallelize and high-fidelity of simulations.

Nuclear reactors are complex systems with multi-physics interacting and coupling. For examples, nuclides are generated or depleted during the lifecycle of reactors, and thermal-hydraulics has feedbacks on material temperature and density and thus nuclear cross sections. MC codes must be coupled with different solvers for high fidelity multi-physics simulations. In order to perform burnup calculations, MC codes are externally or internally coupled with a point burnup solver to figure out the nuclide densities in fuel during the depletion. It can also be coupled with thermal-hydraulics codes to obtain thermal-hydraulic feedback (Liu et al., 2015). When the burnup and TH feedbacks were taken into account simultaneously, it is known as "transport-burnup-thermal-hydraulics" multi-physics coupling, which is crucial for realistic reactors simulations and benchmarks calculations such as MIT BEAVRS benchmark (Horelik and Herman, 2012).

To consider the temperature effects on nuclear cross sections in high fidelity coupling calculations, recently, on-the-fly (OTF) techniques have been proposed in order to reduce the memory usage for both resolved resonance energy (Cullen and Weisbin, 1976; Yesilyurt et al., 2012; Yang et al., 2015; Forget et al., 2014) and thermal energy (Pavlou and Ji, 2014). To consider the distributed temperatures and coolant densities in the whole core, external and internal couplings are two traditional methods for neutronics/thermal-hydraulics (N-TH) coupling. External coupling is easily achieved but versatility is bad, however, internal coupling has good versatility but is more complex and needs a lot of code changes. Moreover, for three-dimensional pin-wise full core burnup calculations, the excessive memory demand is becoming a key obstacle for MC codes. To handle the memory problem, data parallel methods which include tally data decomposition (TDD)

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(Liang et al., 2014) and spatial domain decomposition (SDD) (Liang et al., 2016) have been proposed.

In this paper, a new hybrid coupling method has been developed to couple continuous-energy Monte Carlo code RMC (Wang et al., 2015) and the sub-channel code COBRA. In order to deal with the temperature dependence of cross sections in RMC code, the on-the-fly cross sections treatment has been developed for cross sections in resolved resonance region and thermal energy region. The spatial domain decomposition method based on nested MPI parallelism was developed to handle the memory problem of large-scale detailed full core burnup calculation. The "transport-burnup-thermal-hydraulics" coupling system was applied to burnup simulations of BEAVRS benchmark in hot full power condition.

The numerical tests show that domain decomposition can achieve the consistent results compared with original version. The results of HFP agree well with the reference values of BEAVRS benchmark and also agree well with those of MC21. This work proves the feasibility and accuracy of RMC code in multi-physics coupling and lifecycle simulations of nuclear reactors.

The remainder of this paper is organized as follows. Section 2 introduces the methodology, including on-the-fly cross sections treatment for resolved resonance region (RRR) and thermal energy region, coupling codes, the proposed hybrid coupling method, capability of varying materials during burnup calculations and spatial domain decomposition based on nested MPI parallelism. In Section 3, the accuracy and efficacy of spatial domain decomposition was tested with burnup calculations of a PWR assembly case and a two-dimensional PWR full core case. Then the modeling of BEAVRS benchmark was established and the coupling system was applied to BEAVRS full core burnup calculations in hot full power condition. Finally, the conclusions are presented in Section 4.

2. Computational methods

2.1. On-the-fly temperature-dependent cross section treatment

For thermal reactors such as PWR and HTGR, the temperature effects on nuclear cross sections at resolved resonance region and thermal energy region are significant. For resolved resonance region, Target motion sampling (TMS) method is a new on-the-fly temperature treatment which takes the thermal motion of target nuclei into account explicitly to model arbitrary temperatures with only 0 K continuous-energy cross sections. TMS method (Viitanen and Leppänen, 2012) was firstly developed in Serpent code based on Woodcock tracking which is the main tracking routine in Serpent.

TMS method was modified and developed in RMC code based on the ray tracking (Liu et al., 2016a). Moreover, TMS method was applied to reaction rate tally and depletion calculation for power generation feedback and nuclides densities evolutions. With TMS method, the reaction rates can be tallied with temperature feedback (Liu et al., 2016b). Temperature feedback in each burnup step can therefore be considered, so as to make the high fidelity ' 'transport-burnup-thermal-hydraulics" coupling calculation.

At thermal energies, the on-the-fly interpolation of thermal scattering data was developed in RMC to consider the thermal scattering and bound effect (Liu et al., 2016b). The S(α,β) data at the whole temperatures ranges are no longer needed to store, except for S(α,β) data at some reference temperatures.

With TMS method and on-the-fly interpolation of thermal scattering, RMC has the capability of high fidelity "transport-burnup-thermal-hydraulics" coupling for thermal reactors.

2.2. Coupling codes

2.2.1. Monte Carlo code RMC

RMC is a continuous-energy Reactor Monte Carlo neutron and photon transport code being developed by Department of Engineering Physics at Tsinghua University, Beijing. The code RMC intends to solve reactor analysis problems, and is able to deal with complex geometry, using continuous energy point-wise cross sections of different materials and temperatures. As one of new generation Monte Carlo codes, RMC is aimed at achieving full core calculations and analysis with high fidelity and efficiency by means of advanced methodologies and algorithms as well as high performance computing techniques.

RMC uses ACE format nuclear cross sections with S(α,β) and probability tables treatment in thermal and unresolved resonance energy ranges, adopts constructive solid geometry technique for flexible geometry modeling and employs ray-tracking method as main option for particle transport.

2.2.2. Thermal-hydraulics code COBRA

COBRA is a sub-channel analysis code which computes the flow and enthalpy distributions in nuclear fuel rod bundles or cores for both steady state and transient conditions. COBRA has two sub-channel models, for the PWR fuel assembly and PWR core analysis. RMC has been coupled with COBRA with fuel assembly model (Liu et al., 2015). In this paper, the PWR core model was used in which a whole fuel assembly and the associated coolant flow are treated as a single lumped-parameter channel.

2.3. Hybrid coupling method

Consider the advantages and disadvantages of external and internal couplings, a new hybrid coupling method (Guo et al., 2016) is developed. Hybrid coupling means transforming data via external files of thermal hydraulics code and managing all the useful data by internal memory in neutronics code, as is shown in Fig. 1.

RMC is based on ray tracking, in which neutron will stop at the boundaries between different cells. In N-TH coupling, different cell have different temperatures, and those cell filled by coolant have different densities. The fission power are generated in fuel pins which are surrounded by coolant, making up each individual pin cell. The pin cell will be further divided into axial meshes. Therefore, the whole geometry can be divided into three-dimensional meshes, and each mesh is an axial segment of each pin cell. The same mesh based geometry can be applied to both neutronics and thermal-hydraulics codes.

In this way, four three-dimensional matrixes are stored in RMC which are for fuel temperatures, coolant temperatures, coolant densities and fission power, respectively. The values of the matrix are stored according to their coordinates in the whole geometry. Two flags of cells are used to distinguish fuel and coolant. The user-defined temperatures are used for cells with no flags.

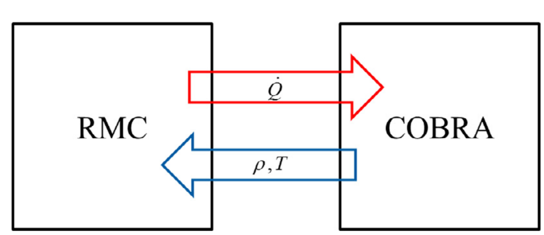

Fig. 1. Schematic diagram of hybrid coupling.