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Analysis of BEAVRS two-cycle benchmark using RMC based on full core detailed model

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ABSTRACT

With the increasing demands of high fidelity neutronics analysis and the development of computer technology, Monte Carlo method is becoming more and more attractive especially in criticality analysis of initial core and shielding calculations, due to its advantages of flexible geometry modeling and use of continuous-energy nuclear cross sections. However, nuclear reactors are complex systems with different physics and feedback interactions and coupling. To perform the high fidelity multi-physics simulations of real reactors or benchmark calculations such as two-cycle BEAVRS benchmark based on measurement data of a practical nuclear power plant, several factors must be considered such as large scale detailed depletion, thermal-hydraulics feedback, on-the-fly nuclear cross section processing, criticality search and inter-cycle refueling. In this paper, the abilities mentioned above for multiple burnup cycles simulations in Hot Full Power condition of PWR full core have been developed in continuous-energy Reactor Monte Carlo neutron and photon transport code RMC, which is developed by Department of Engineering Physics at Tsinghua University, Beijing (Wang et al., 2015). RMC has the capacity for lifecycle simulations of nuclear reactor cores. The BEAVRS benchmark was selected as an example and RMC was applied to a full core, two cycle burnup calculation of BEAVRS. All of the parameters given in the BEAVRS benchmark have been calculated and compared with the measured values of BEAVRS benchmark. For other parameters such as pin power distributions, they are compared to the results of other codes. The results of RMC agree well with the measured values of BEAVRS benchmark and also agree well with those of other codes. This was the first time for a Monte Carlo code to perform the full core, two cycle calculation of BEAVRS. This work paves the way for Monte Carlo codes in life cycle simulations of nuclear reactor cores.

1. Introduction

With the increasing demands for high fidelity neutronics analysis and the development of computer technology, the Monte Carlo method becomes more and more important especially in critical analysis of initial core and shielding calculations, due to its 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. RMC is a continuous-energy Reactor Monte Carlo neutron and photon transport code being developed by Department of Engineering Physics at Tsinghua University, Beijing (Wang et al., 2015). 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.

However, nuclear reactors are complex systems with different physics and feedback interactions and coupling. For example, nuclides are generated or depleted during the lifecycle of reactors, and thermal-hydraulics has feedback effects on material temperature and density, and thus nuclear cross sections. Reactivity control systems such as soluble boron and control rods are adjusted during the operation of reactors to maintain the criticality of power plants. Moreover, when the concentration of soluble boron reach zero, the reactor should be refueled to proceed to the next burnup cycle. All

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of the factors mentioned above should be considered the high fidelity multi-physics simulations of real reactors or benchmarks calculations such as BEAVRS MIT BEAVRS benchmark (Horelik and Herman, 2012).

The calculations of BEAVRS benchmark can be divided into three stages. The first stage is the Hot Zero Power condition, the second is the Hot Full Power condition in cycle 1, and the third is the Hot Full Power condition in both cycles 1 and 2. Many codes have finished the first stage, including Monte Carlo codes such as OpenMC (Daniel et al., 2014), MVP (Suzuki and Nauchi, 2015), McCARD (Park et al., 2015), JMCT (Li, 2016), and deterministic codes such as Rattlesnake (Ellis et al., 2014). For the second stage, before RMC, MC21 (Daniel et al., 2014) is the only Monte Carlo code which has finished the HFP calculations of cycle 1, while cycle 2 has not been finished. Deterministic codes such as VERA-CS (Collins and Godfrey, 2015) and ARES of which few group cross sections generated by Serpent (Leppänen and Mattila, 2016) have also calculated the cycle 1 only. For the third stage, before RMC, no Monte Carlo code finished cycle 1 & 2, while deterministic codes such as nTRACER (Ryu et al., 2014),CASMO-SIMULATE (Smith, 2015) and COSINE (Shi et al., 2016) have calculated cycle 1 & 2.

In this paper, the abilities mentioned above for multiple burnup cycles analysis in the Hot Full Power condition for PWR full cores have been developed in RMC for life cycle simulations of nuclear reactor cores. The BEAVRS benchmark was selected as an example and RMC was applied to two cycle full core burnup calculation of BEAVRS. All of the parameters given in the BEAVRS benchmark will be calculated and compared with the measured values of BEAVRS benchmark. For other parameters such as pin power distributions, they are compared to the results of other codes such as MC21. The results of RMC agree well with the reference values of the BEAVRS benchmark and also agree well with those of other codes. This was the first time for a Monte Carlo code to perform the full core, two cycle calculation of BEAVRS. This work paves the way for Monte Carlo codes in multi-physics coupling and life cycle simulations of nuclear reactors.

The remainder of this paper is organized as follows. Section 2 introduces the methodology, including the proposed hybrid coupling method with on-the-fly cross section treatment, layered parallelism based on MPI/OpenMP parallel model for full-core detailed burnup calculation, critical boron concentration searching, adjoint-weighted dynamic parameter calculations, inline equilibrium xenon method, Monte Carlo refueling capacity, and restart capacity for burnup calculations. In Section 3, the results of HZP are compared to the benchmark references. In Section 4, RMC coupled with thermal-hydraulics, depletion, critical search and refueling is applied to the two cycle burnup calculation of BEAVRS. The results are compared to the benchmark references and also the results of MC21. Finally, the conclusions are presented in Section 5.

2. Computational methods

There are three stages of BEAVRS benchmark calculations, including Hot Zero Power condition, Hot Full Power condition in cycle 1 and Hot Full Power condition in both cycle 1 and 2. These three stages of calculations request three levels of capabilities and algorithms of a Monte Carlo code, as shown in Fig. 1. For the HZP condition, some basic capabilities of Monte Carlo codes are necessary, such as detailed geometry modeling, neutron collisions physics, reaction rate and flux tally, and MPI parallel. For the cycle 1 calculation in HFP, many different algorithms must be developed. On-the-fly (OTF) temperature dependent cross sections treatment for resolved resonance region and thermal region, and full core neutronics/thermal-hydraulics coupling are needed to consider thermal-hydraulic feedback. Large-scale and detailed burnup

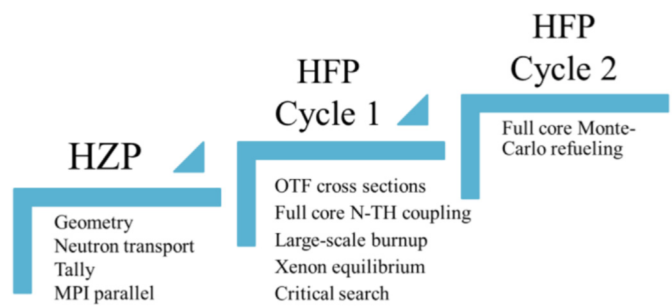

Fig. 1. Three stages of BEAVRS calculations.

calculations can treat each fuel rod as an individual burnup region with decomposed or shared memory strategies, while xenon equilibrium method can make the power distributions of large-scale burnup calculations more stable. The turning point from HFP cycle 1 to cycle 2 is full core Monte Carlo refueling, which is very different from the refueling routine of deterministic codes.

The key algorithms for the second and third stages will be introduced with more detail in the remaining parts of this section. In each sub-section of this section, a brief introduction was given for each method with corresponding references. The validation, standalone testing and discussions of these methods developed in RMC can be referred to the corresponding references.

2.1. Hybrid coupling method with on-the-fly cross sections treatment

RMC was coupled with the sub-channel code COBRA (Basile et al., 1999.), equipped with on-the-fly temperature-dependent cross section treatment to consider the thermal-hydraulic feedback and temperature effects on nuclides cross sections.

For on-the-fly temperature-dependent cross section treatment, the Target motion sampling (TMS) method based on the ray tracking (Liu et al., 2016a) is used for resolved resonance region and on-the-fly interpolation of thermal scattering data was developed in RMC to consider the thermal scattering and bound effect (Liu et al., 2016b).

For thermal-hydraulic coupling, considering the advantages and disadvantages of external and internal couplings, a new hybrid coupling method is developed (Guo et al., 2016). Hybrid coupling means transforming data via external files of the thermal-hydraulics code and managing all the useful data by internal memory in neutronics code. The hybrid coupling method can reduce the difficulty of modeling and improve the versatility of coupling by managing all the useful data by internal memory in neutronics code, while making good use of existing thermal-hydraulics codes.

2.2. Layered parallelism based on MPI/OpenMP parallel model

Huge memory consumption is the bottleneck of full-core detailed burnup calculations of a PWR. Therefore, several methods have been proposed to solve the memory problem, such as domain decomposition, data decomposition and layered parallelism based on MPI/OpenMP parallel model. On the other hand, future computer platforms will move toward a larger numbers of nodes and processor cores per node coupled with lower memory available, as shown in Fig. 2. These new architectures encourage a hybrid parallel algorithm in Monte Carlo simulation. Therefore, layered parallelism based on MPI/OpenMP parallel model was developed (Yang et al., 2016) and applied to the burnup calculations of BEAVRS, as shown in Fig. 3.