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# Coupled neutronics/thermal-hydraulics analysis of a full PWR core using RMC and CTF

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ABSTRACT

A hybrid coupled strategy was proposed for a coupled neutronics and thermal-hydraulics analysis of a full PWR core, using the continuous-energy Reactor Monte Carlo code (RMC) and the sub-channel code COBRA-TF (CTF). In the code system with hybrid coupling, CTF was invoked and controlled by RMC internally, without external interface. The On-The-Fly cross sections treatment of RMC was used to reduce the complexity of the coupled code as well as to reduce the memory requirement. The domain decomposition parallel technique was developed in CTF to improve the efficiency of full core sub-channel calculations, and the PWR preprocessor of CTF can reduce the complexity of full core modeling establishment. The coupled codes were applied to steady-state simulations of the Benchmark for Evaluation And Validation of Reactor Simulations (BEAVRS) in the hot, full power condition at the full-core level to reveal the effects of the coupling on the full-core power distribution in both axial and radial directions. The influences of other important parameters including the neutron population and the boron concentration were also investigated. The results proved the effectiveness and high fidelity of the coupled system. More systematic and detailed analyses can be performed based on realistic operating conditions of PWR full core with the coupled codes system.



## 1. Introduction

Reactor physics numerical calculations have been used for reactor design analyses, core power analyses and burn-up calculations, with both deterministic methods and the Monte Carlo method used in these calculations. The Monte Carlo method has the advantages of being a first-principle method and providing high fidelity calculations. The Monte Carlo method can provide high fidelity neutronics analyses of different nuclear reactor designs owing to its flexible geometric modeling and the use of continuous-energy nuclear cross sections. Massively parallel algorithms significantly reduce the computational costs of Monte Carlo codes.

Many factors need to be considered in reactor analyses, such as the fuel pin temperature, coolant temperature and density, and void friction. These thermal parameters that can be predicted by reactor thermal hydraulics codes strongly influence the reactor operations and safety. The single channel method and sub-channel method are two traditional approaches for analyzing the coolant flow and heat transfer in the reactor core with many codes using such models to accurately model the thermal hydraulics process, such as RELAP5 (SCIENTECH Inc., 1998), COBRA-EN (Basile et al., 1999), and CTF (CASL, 2015). Unlike single channel codes, sub-channel codes provide more accurate modeling of the full reactor core or a single assembly taking the mixing flow into account. Detailed pin-by-pin sub-channel modeling of a full core also needs to be run in parallel to reduce the huge computational costs.

The model accuracy requirement for design and safety analyses of current and future nuclear reactors is continuously increasing, so high fidelity numerical reactor simulations are needed that include all the important reactor physics. The interplay between the neutronics and the thermal-hydraulic effects in a nuclear reactor core plays an important role in the reactor design, safety analyses and long term efficiency. To achieve the high fidelity solution with neutronics and thermal-hydraulics (N-TH), the neutronics code can be deterministic code or Monte Carlo code. Compared with the deterministic code, the Monte Carlo code has the greater advantages of accurate geometry and neutron energy treatment, which provides the most important foundation for full-core pin by pin level resolution through one-step direct transport calculations. While traditional deterministic codes based on three-step or two-steps homogenization methods have difficulties to predict the pin level power distributions precisely.

The sub-channel code and the computational fluid dynamics (CFD) code are two kinds of commonly used thermal-hydraulics

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codes. The CFD code can provide high accuracy calculation results but costs too much time especially for full core problems, while the highly efficient sub-channel code can accomplish the pin by pin level sub-channel resolution for full core problem.

There have been many previous studies of N-TH coupling using various combinations of different kinds of coupling codes mentioned above. For example, the deterministic code MPACT (Kochunas et al., 2013) and sub-channel code CTF has been coupled by CASL (Kochunas et al., 2014) in VERA-CS (Clarno et al., 2014). The Karlsruhe Institute of Technology (KIT) in Germany (Hoogenboom et al., 2011) has well achieved the coupling between MCNP (Briesmeister, 2000)/TRIPOLI4 (Brun et al., 2011) Monte Carlo codes and FLICA4 (Aniel et al., 2005)/SubChanFlow (Sanchez et al., 2010) thermal-hydraulics codes. It should be mentioned that the Monte Carlo code RMC (Wang et al., 2015) developed by REAL group of Tsinghua University in China, has been coupled with CFD code CFX (Marchisio et al., 2003) by Li et al. (2012), and Liu et al. (2015) has coupled RMC with the sub-channel code COBRA-EN. Besides, there are still many coupling work between Monte Carlo codes and thermal hydraulics codes being done by different research groups of many countries, which indicates that the N-TH coupling based on Monte Carlo code is an important research trend.

Furthermore, the full-core pin by pin sub-channel resolution is also a great challenge for the traditional thermal-hydraulics codes, but the new generation sub-channel code CTF can well solve the problem by the developed advanced techniques of domain decomposition for parallel computing and preprocessor for simplifying the geometry and power input for users.

Thus, with the great support of the super computer, the Monte Carlo code and sub-channel code CTF can match well for the coupling of full-core pin by pin resolution simulation, and can obtain the high fidelity results with the precise modeling of the full core.

This paper describes a coupled code using the continuous-energy Monte Carlo code RMC, and the sub-channel code CTF. The coupling codes are used to simulate the steady-state BEAVRS benchmark at the hot, full power condition. The temperature dependence of the cross sections in the Monte Carlo code were modeled using the on-the-fly cross section treatment in RMC, which will also be used for the coupled neutronics and thermal-hydraulics analyses in this work.

The simulation results show the necessity of the coupling as well as the significance of key coupled factors, including the neutron population and the boron concentration. The results also show the high efficiency and accuracy of the code. This coupling code provides a powerful tool for coupled steady-state and transient analyses.

This paper is organized as follows: in Section 2, two coupled computer codes are introduced in brief, including the Monte Carlo code RMC and sub-channel code CTF. Section 3 presents the coupling scheme in detail including the proposed hybrid coupling method, the approach to solve the temperature dependence, the principle of mesh mapping and the setting up of convergence criteria. Section 4 describes the modeling details of BEAVRS benchmark and the following coupling results and further discussion about the influence parameters on coupling. Finally, the conclusions and future work are presented in Section 5.

## 2. Computer codes

### 2.1. Monte Carlo code RMC

The Monte Carlo transport code, RMC, developed by the Department of Engineering Physics at Tsinghua University, is a continuous-energy Reactor Monte Carlo neutron and photon transport code (Wang et al., 2015). This new generation Monte Carlo code solves reactor analysis problems in complex geometries using continuous energy point-wise cross sections for various materials and temperatures. RMC can now do criticality calculations and burnup calculations with parallel processing using on-the-fly calculations of cross-sections as functions of temperatures with the source convergence acceleration for full-core hybrid calculations (Liu et al., 2017). RMC also has advanced methods to accelerate calculations (Liu et al., 2011; She et al., 2011, 2012).

RMC is being used for full core analyses with accurate, efficient results using advanced algorithms together with high performance computing techniques.

### 2.2. Thermal-hydraulics code CTF

CTF, a thermal–hydraulic simulation code designed for light water reactor (LWR) vessel analysis, is the shortened name given to the version of COBRA-TF (Coolant Boiling in Rod Arrays-Two Fluid) being developed by the Consortium for Advanced Simulation of Light Water Reactors (CASL) and the Reactor Dynamics and Fuel Management Group (RDFMG) at Pennsylvania State University (PSU) (CASL, 2015). CTF uses a two-fluid, three-field modeling approach and can solve detailed full-core models in parallel using the domain decomposition method (Salko et al., 2015). CTF has both sub-channel and 3D Cartesian forms of the 9 conservation equations for LWR modeling.

CTF stems from the original COBRA code, which was developed by Pacific Northwest Laboratory in 1980 and has been used and modified by several institutions, resulting in a series of COBRA codes, such as COBRA-EN and COBRA-IV. In the last decade, CTF has been improved and validated for both pressurized water reactor (PWR) and boiling water reactor (BWR) analyses. Improvements include additional models, enhanced computational efficiency, a PWR preprocessor to simplify the geometry input, and the ability to generate code documentation. CTF has been extensively used throughout the nuclear industry due to its powerful functions and rapid development.

## 3. Coupling scheme

For the full core pin-by-pin sub-channel calculations coupled with Monte Carlo code, many important aspects and details in the coupling process should be considered. Firstly, the most important aspect is the coupling method, which deals with how the data were transferred in coupling process. The second part introduced how the coupling process takes the advantages of some advanced feathers of CTF, including the domain decomposition and PWR preprocessor. The third part is about the temperature dependence treatment of cross sections developed in RMC. Besides, the mesh mapping strategy and the convergence criteria will also be explained in this section.

### 3.1. Hybrid coupling method

Traditional neutronics and thermal-hydraulics coupling methods include external or internal coupling. External coupling simply transforms the data in external files produced by the two coupled codes, while internal coupling transforms the data in memory between the two codes. External coupling is easily achieved but is not as versatile and slows the computations. Internal coupling is more versatile but is more complex and needs extensive code changes. Thus, a hybrid coupling method is used here.

The hybrid coupling was introduced in this paper, which transforms the data in the external files of the thermal hydraulics code while managing all the useful data in memory by the neutronics