Development and Applications of Nuclear Design and Safety Assessment Program SuperMC for Fast Reactoron

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Abstract. Compared with the other reactor types, the neutron spectrum of fast reactors is hard, affecting the neutronics and safety performance, for which advanced nuclear simulation methods such as Monte Carlo method is necessary for the core design. Super Monte Carlo Program for Nuclear and Radiation Simulation (SuperMC) is a general, intelligent, accurate and precise program for the design and safety evaluation of nuclear system including fast reactors. The latest version of SuperMC can accomplish the n, γ transport calculation and depletion calculation, and is integrated with CAD-based automatic modeling, visualization and cloud computing framework. More than 2000 benchmark models and experiments have been duly verified and validated, including the nuclear analyses of fast reactor benchmarks BN600, IAEA-ADS, etc.

Key Words: SuperMC, nuclear design, safety evaluation, fast reactors, Monte Carlo

1. Introduction

It is generally believed that the development of fast reactors is one of the possible ways to achieve the Generation IV goal of sustainability and minor actinide (MA) burning capability. Compared with the other reactor types, the neutron spectrum of fast reactors is hard, affecting the neutronics and safety performance and brings new challenges for developing nuclear design and safety assessment tools.

To achieve its design goal, full-core high fidelity reactor simulation is becoming a research hotspot. Benefit from high simulation accuracy, continuous energy treatment and flexible geometry representation, the Monte Carlo methods have been broadly adopted in nuclear design and analysis, especially for advanced nuclear system such as fast reactors. However, for the full-core high fidelity reactor simulation, there are great challenges exist for the current Monte Carlo methods including the accurate modeling of complex geometries, slow convergence of complex calculation, memory limitation of transport-burnup coupled calculation etc.

Facing the challenges, Super Monte Carlo Program for Nuclear and Radiation Simulation (SuperMC) [1, 2] was developed by FDS team [3-5]. SuperMC is a general, intelligent, accurate and precise simulation software system for the nuclear design and safety evaluation of nuclear systems, and supports the comprehensive neutronics calculation, taking the radiation transport as the core and including the depletion, radiation source term/dose/biohazard, material activation and transmutation, etc. It supports multi-physics coupling calculation including thermo-hydraulics, structural mechanics, chemistry, biology, etc. Its functional architecture is shown in *FIG.1*. The main usability features include automatic modeling of geometry and physics, visualization and virtual simulation and cloud computing services. The latest version of SuperMC can accomplish the transport calculation of n, γ and depletion calculation, and can be applied for criticality and shielding design of reactors as well as analysis in medical physics.

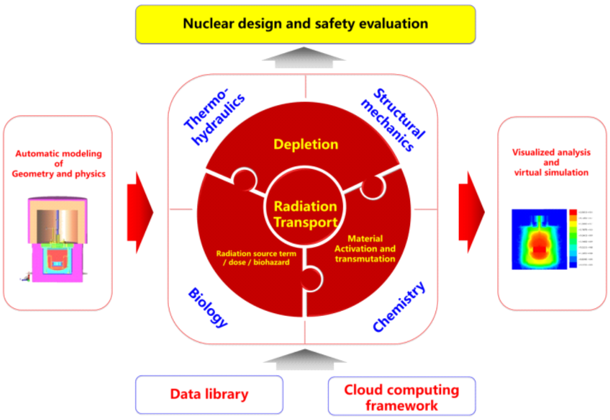

FIG.1 Functional architecture of SuperMC

2. Advanced Functions and Features

2.1. Advanced CAD-based Geometry and Physics Automatic Modeling Methods

To significantly reduce the manpower and enhance the reliability of calculation model, not only complex-configuration geometry, but also physical modeling including materials, sources, tallies, etc. has been developed.

An automatic and intelligent CAD-based modeling function in SuperMC is developed to enhance the reliability of calculation model [2]. CAD models represented by Boundary Representation method can be automatically converted to MC calculation geometry models which are represented in CSG based on primitive solids. Conversely, inversion from the calculation model to the CAD model for visualization to locate the defects and errors and further updates is also introduced to SuperMC. [3].

For generating high-fidelity full fission reactor modes easily, a new parameterized-based modeling method [6] was introduced. The approach could create or gather the geometries and physics parameters of fission reactor as well as the relations of different components of the models into a dedicated data structure, which called as Geometric Hierarchy Tree (GH-tree).

To create and describe calculation model automatically and accurately according to the local problem, hybrid primitives and surfaces based constructive geometry was designed in SuperMC. Moreover, unstructured mesh was new applied to enhance the description capability of arbitrary shape and process the multi-physics coupling analysis by using the unstructured mesh results directly. A new speedup method called feature size tree was presented, to accelerate the unstructured mesh geometry processing and further reduce the memory consumption.

2.2. Variance Reduction Method Based on Coupled Global Weight Window and Uniform Fission Site Method

To improve the run-time performance of SuperMC, several novel acceleration methods were recently developed. The Global Weight Window Generator (GWWG) [7] was proposed in

SuperMC, to accelerate the convergence of globe map in Monte Carlo simulation, which gives hundreds of speedup for shielding problems. However the acceleration rate obtained is not very satisfactory for the full core fission reactor simulation.

A coupling variance reduction method based on GWWG and uniform fission site (UFS) method was newly developed to solve this performance pitfall. In the method, GWWG and UFS work simultaneously, with two mesh grids, one of which for UFS covering the fuel region where fission reactions happen, while the other one for GWWG covering the whole simulated region containing the fuel region. The UFS part decreases the weight as well as increase the number of the source particles near the boundary according to the source particle distribution in the fuel region, so that source particle weights are now compatible with the weight window bounds. Over-splitting of source particles now seldom occurs, thus the efficiency of the weight window is improved.

2.3.Built-in Depletion Calculation

Built-in depletion calculation has been newly developed in SuperMC, based on Chebyshev rational approximation method (CRAM) method. In order to judge and preload isotopes generated in burnup, a daughter nuclide searching method based on breadth-first algorithm has been developed. A bucket-sorting algorithm was introduced in energy searching process, which significantly reduced the memory consumption while keeping the calculation efficiency compared with the union-energy-grid method.

In the full-core high fidelity transport-burnup coupled simulation, commonly up to 1,000,000 burnup regions should be considered, memory limitation becomes one of the serious bottleneck problems. In SuperMC, to overcome this problem, parallel computing based on thread-level data decomposition method was implemented. Similar to the process-level data decomposition, the data is decomposed to different process. However, to improve performance, in each process, memory is not shared by all threads, but each thread only can operate the specific memory. Each thread could send data to corresponding thread in different process directly, also the same in receiving messages. By this way, conflict will not happens, and no need to consider thread synchronization and thread lock, which will observably enhance the parallel computing performance of transport-burnup coupled simulation.

3. Benchmarking

SuperMC has been verified by more than 2000 benchmark models and experiments including ICSBEP [8], SINBAD, etc. The fusion reactor (ITER benchmark model[9,10], FDS-II[11]), fast reactor (BN600[12], IAEA-ADS[13]), PWR (BEAVRS, HM, TCA) and cases from the handbook of IRPhEP were employed for validating the comprehensive capability for reactor applications. Furthermore, Several validation experiments are being conducted or planned to conduct, such as a shielding experiment of DFLL[11,14,15] mock-up is being particularly conducted to validate the deep penetration problem.

In this paper, two typical benchmarking, BN600 and IAEA-ADS model were selected to verify the capabilities of SuperMC, to be applied in fast reactors.

3.1.BN600

BN600 is Russia’s commercial fast reactor with thermal power 1470MW (electric power 600 MW) to validate, verify and improve methodologies and computer codes used for the calculation of reactivity coefficients in fast reactors. *FIG.2* shows the visualization of BN600 modeling. Nine parameters, including of k_{eff}; Doppler coefficients of fuel/stainless steel; density coefficients of Na, fuel, stainless steel, absorber; axial/radial expansion coefficients were calculated to prove the capabilities of SuperMC. The results were compared with MCNP and measurement data from different testing group, as shown in Table I. In all cases, the difference between the results of SuperMC and MCNP are within one standard deviation and within the range of values of results calculated by other institutes.

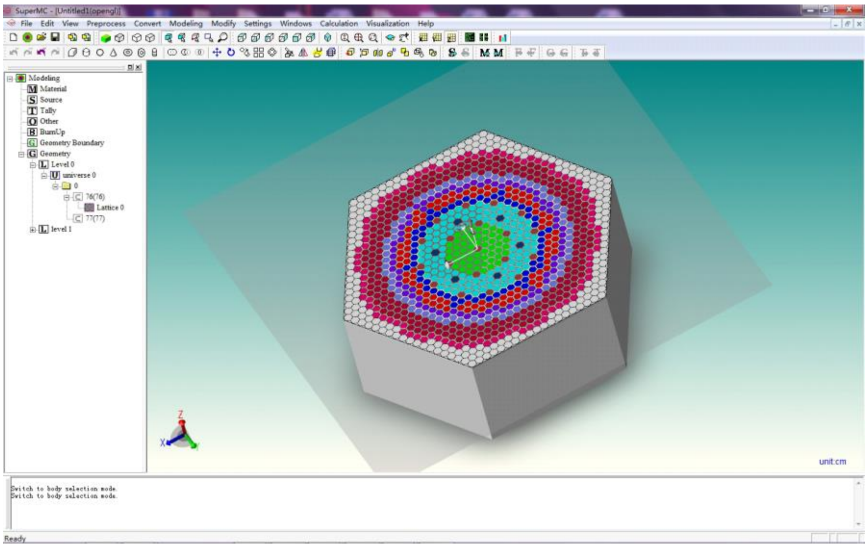

FIG.2 Modeling of BN600 in SuperMC

TABLE I: COMPARISON OF BN600 PHYSICAL PARAMETERS

		MCNP	SuperMC	Reference data				
				ANL	CEA/SA	IPPE	JNC	KAERI
k_{eff}		1.01709	1.01708	0.99802	1.02272	-	1.00967	1.01494
Doppler Coefficient	fuel	-0.00674	-0.00685	-	-0.00681	-0.00638	-0.00633	-0.00764
	SS	-0.00136	-0.00124	-	-0.00132	-0.0008	-0.00109	-0.00106
Density Coefficient	Na	0.0087	0.0126	-	0.00592	0.00206	0.00664	-
	fuel	0.3403	0.3499	-	0.3385	0.3438	0.3457	-
	ss	0.00194	-0.00097	-	-0.0073	0.0032	-0.0066	-
	Absorber	-0.0155	-0.0193	-	-0.0234	-0.0206	-0.0219	-
Expansion coefficient	axial	-0.1527	-0.1442	-0.1397	-	-0.1352	-0.153	-0.1514
	radial	-0.4921	-0.4942	-0.4605	-	-0.4822	-0.4814	-0.4679

3.2.Burnup Benchmarking with IAEA-ADS Model

The IAEA-ADS international benchmark model [15] was introduced as an example of burnup calculation benchmark. IAEA-ADS is a sub-critical benchmark released by IAEA to test the burnup calculation capability on sub-critical system. The model used 233U as fuel, 232Th as breeding material and Pb as reflect layer. In the calculation, the initial keff set as 0.94, and 15 burnup step was taken with 150 day per step. Figure 3 shows the result of keff variation along with burnup step. Since only the keff values were given in the reference [15], the keff results of this work were compared, as shown in *FIG.3*, which are agreed well with the reference results.

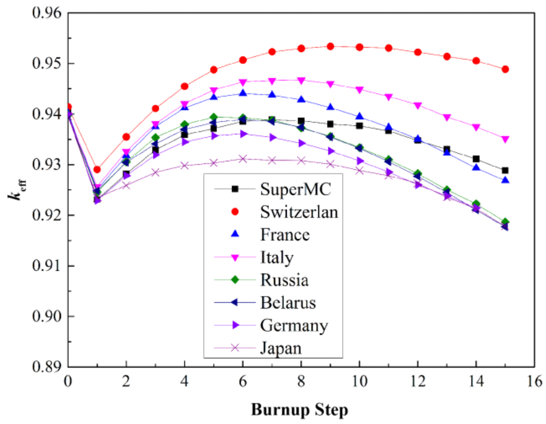

FIG.3 keff variation along with burnup step

4. Summary

SuperMC is designated to support the comprehensive neutronics calculation. The latest version of SuperMC can perform coupled n, γ transport calculation and depletion calculation, integrated with the functions of automatic modeling, visualization and cloud computing. Several advanced functions and features were introduced. SuperMC has been verified by more than 2000 benchmark models and experiments. In this paper, the benchmarking results of BN600 and IAEA-ADS were shown as examples, which indicates that SuperMC is capable to be applied into fast reactors for research and design behaviour[16], and has characteristics of high efficiency and more easy to use.

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