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Monte Carlo Simulation Software SuperMC 2.3 for Fusion and Fission Applications

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1. Introduction

The Monte Carlo (MC) methods have been broadly adopted in nuclear design and analysis of advanced nuclear energy systems. However, there are still great challenges in the current MC methods including the calculation modeling of complex geometries, simulation of deep penetration problem in radiation shielding, slow convergence of complex calculation, lack of experimental validation for new physical features, etc.

SuperMC [1] is a general purpose, intelligent and multi-functional program for the design and safety evaluation of nuclear systems. It is designed to perform 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. SuperMC2.3, the latest version, can accomplish the transport calculation of n, γ and can be applied for criticality and shielding design of reactors, etc.

2. Main Features

2.1 Geometry and Physics Automatic Modeling

An automatic and intelligent CAD-based modeling function in SuperMC is developed to significantly reduce the manpower and 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. During this process, automatic geometry fixing and high-order free surfaces simplification method are developed to make the CAD model standardized for conversion into high quality simulation models [3].

Hierarchical tree structure is adopted to describe the geometry and material and support geometry navigation during particles transport process. Through this hierarchical definition logic, the repeated structure can be easily specified by component and lattice. Additionally, a cuboid must be defined as a world volume and the root node of the geometry hierarchy to completely contain all components. Thus it is not needed to define all spatial areas such as cavity.

2.2 Hybrid Monte Carlo and Deterministic Transport Method Simulation

Three dimensional domain hybrid MC and discrete ordinates (SN) modeling and transport calculation method has been developed [4]. The whole model is divided into three parts: the complex region (for MC calculation using CSG geometry), the regular region (for SN calculation using mesh geometry) and coupling domain (for MC and SN calculation). Tally data of MC particle tracks crossing the specified surface should be mapped to discrete quadrature direction for calculating the angular flux distribution with SN method.

Hybrid MC–deterministic method based adaptive variance reduction technique for local tally was studied and implemented. Firstly, adjoint calculation with deterministic method was done, to get adjoint flux and response value. Then the importance parameters were acquired by adjoint flux and response value. Monte Carlo forward simulation with the importance parameters was done finally.

2.3 Advanced Acceleration Methods in Transport Calculation

The optimal spatial subdivision method [5] was employed to enhance the geometry navigation performance. The method used a recursive subdivision algorithm to subdivide a CSG model into non-overlapping grids, which were labeled as totally or partially or not occupied by CSG objects. The bounding box algorithm can be specifically customized and applied to accelerate the basic function of calculating the distance to volume boundary. A simpler check for ray intersection with the bounding box rather than the actual complex object will be done to eliminate unnecessary ray-object intersections. Since the calculation time increases almost linearly with the number of tallies, a massive tally scoring method based on hierarchical geometry tree was developed. In the recursive manner, the hierarchical tree can be constructed and allows a fast determination of what tally bins need to be scored.

2.4 Visualization and Virtual Simulation

The output data can be automatically and intelligently visualized by mixing with the input models according to users' interests, which simplifies information extraction from massive data [7]. Two innovative visual methods have been proposed. One is the data visualization coupled with calculation geometries. The other is the visualization of simulation process and real-time dose visualized assessment to test and evaluate the operational or maintenance tasks and assist the supervisors to plan better working activities.

3. Benchmarking

SuperMC has been verified by more than 2000 benchmark models and experiments. The handbook of International Criticality Safety Benchmark Evaluation Project (ICSBEP) and the Shielding Integral Benchmark Archive Database (SINBAD) were used to verify the correctness of SuperMC. The fusion reactor (ITER benchmark model, FDS-II), fast reactor (BN600, IAEA-ADS), PWR (BEAVRS, HM, TCA) and cases from the International Reactor Physics handbook Evaluation Program (IRPhEP) were employed for validating the comprehensive capability for reactor applications. As the supplementary of validation experiments of MC software for advanced nuclear energy systems applications, experiment for deep penetration problem in radiation shielding and neutronics integral experiment of fusion blanket are being particularly conducted.

The physical design and analysis of China Lead-based Research Reactor (CLEAR-I) was performed with SuperMC. For the physical design scheme of reactor core, power distribution, flux distribution, reactivity, dynamic parameters, depletion zone-wise, material-wise and total nuclide concentrations, masses, activities, decay heat, ingestion and inhalation toxicities, spontaneous fission rates and etc. were obtained. The shielding analysis of the reactor and proton beam-pipe, shut-down dose assessment of maintenance, design of temporary shielding of local part and etc. were performed.
The core of CLEAR-I was consisted with 136 fuel assemblies, 8 control-rod assemblies and containning 380 nuclides, as shown in Fig. 1. The representative results of keff was given in Table1 and neutron flux of assemblies in active region was in Fig.2.

Figure 1. Pin by pin core model of CLEAR-I

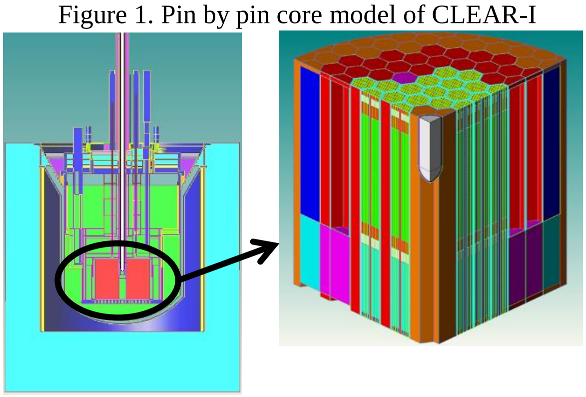
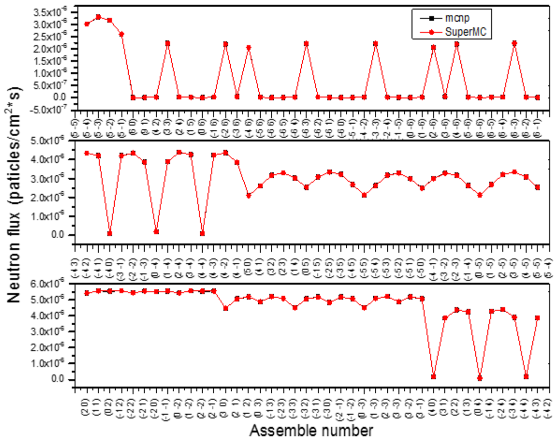


Table 1. The results of keff

	SuperMC	MCNP
k_{eff}	1.00035 (0.00010)	1.00025(0.00010)

Figure 2. neutron flux of assemblies in active region



4. Summary

SuperMC 2.3, the latest version, which can perform coupled neutron and photon transport calculation and is equipped with the functions of geometry and physics automatic modeling and visualization, has been developed. SuperMC2.3 owns the features including hybrid MC and deterministic transport method, advanced acceleration methods in transport calculation, visualization and virtual simulation. SuperMC has been validated by serials of benchmarks: some of the calculation results and calculation time of ITER benchmark model were given and compared with MCNP in this paper. The calculation results of SuperMC2.3 were in accordance with MCNP, while the calculation speed of SuperMC2.3 was faster.

Acknowledgements

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