ARTICLE IN PRESS

Fusion Engineering and Design xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Advanced geometry navigation methods without cavity representation for fusion reactors

Bin Wu[a], Shengpeng Yu[a], Lijuan Hao[a], Jing Song[a], Longfeng Shen[b,*], Pengcheng Long[a,*]

[a] Key Laboratory of Neutronics and Radiation Safety, Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, Hefei, Anhui, 230031, China
[b] Huaibei Normal University, Huaibei, Anhui, 235000, China

ARTICLE INFO

Keywords:
ITER
Particle transport
Without cavity description
SuperMC
Geometry

ABSTRACT

Particle transport simulations of models comprising large numbers of complex and irregular geometrical shapes is a great challenge in neutronics design and analysis of fusion reactors. All the space in the particle transport universe should be described including cavity in MCNP which is the most common deployed tool in fusion reactors. The quality of the cavity directly affects the calculation accuracy and efficiency. In view of the difficulty in describing the cavity and the instability of calculation efficiency, a new geometry representation method without cavity description was formed in Super Monte Carlo Program for Nuclear and Radiation Simulation (SuperMC). Advanced geometry navigation was developed in SuperMC to get high performance for particle transport in fusion reactors. The ITER benchmark model, a validation model released by ITER International Organization, was used to verify the accuracy and efficiency of geometry representation and navigation methods in SuperMC. The results in SuperMC showed consistency with MCNP. Besides, the computation speed was 10% faster than MCNP, while it brought more convenience without cavity representation for fusion reactors.

1. Introduction

One of the great challenges in the particle transport of fusion systems is the highly detailed and reliable geometry models consisting of a large number of complex and irregular geometrical shapes [1,2]. Due to the capacity of realistic representation of arbitrarily complex geometry, Monte Carlo methods are suitable for particle transport in fusion systems. Along with the opportunities of complex geometry, it also increases difficulty to get high performance through Monte Carlo methods for fusion systems from the point of view of geometry representation and geometry navigation.

Firstly, complex and irregular geometry makes the geometry description of calculation model more difficult. The solids can be described by a common geometry description method Constructive Solid Geometry (CSG) which was used in most Monte Carlo codes, such as MCNP [3], Serpent [4], MC21 [5], Geant4 [6], MCBEND [7], et al. According to the geometry characteristic of fusion systems, surface-based CSG description is often used for the analysis of fusion systems, and MCNP is the most common deployed tool for particle transport in fusion systems. In MCNP, all the space in the particle transport universe should be described including the space between the solids which is called cavity in this paper. With the help of automatic CAD interface codes, such as SuperMC/MCAM [8,9], McCad [10] and Geomit [11], it is feasible to convert the CAD model to Monte Carlo calculation model with both solid and cavity. But if the solids are complex or the model has specific boundary condition (such as reflecting boundary, white boundary, etc.), the cavity description cannot be generated well by automatic generating algorithms and need some manual operations, which increases the modeling difficulty.

Secondly, complex and irregular geometry makes the particle tracking more difficult. Geometry navigation directly affects the run-time performance of the Monte Carlo particle transport simulation. Some previous researches indicate that geometry navigation typically accounts for 30–80% of total run-time, especially for large scale complex and irregular fusion systems [12,13]. Flexible and effective geometry navigation plays an important role to Monte Carlo particle transport simulation. In MCNP, due to the description of cavity, particle always tracks in certain cell (solid with material or cavity with vacuum). The major accelerator method for MCNP's geometry navigation in particle transport simulation of fusion systems is Neighbor List (NL) to reduce the run-time of geometry navigation. But the effect of neighbor list acceleration method is depended on the number and complexity of cavity. If the solids are complex, the complexity of the cavity will increase, which necessitates splitting the cavity into a large number of simpler cells, increasing the cavity cell count. At the meantime, average neighbor cells for per surface would be also

* Corresponding authors.
E-mail addresses: longfengshen521@126.com (L. Shen), pengcheng.long@fds.org.cn, wubinhjj@sina.com (P. Long).

http://dx.doi.org/10.1016/j.fusengdes.2017.08.008
Received 24 January 2017; Received in revised form 19 July 2017; Accepted 8 August 2017

increased.

In view of the difficulty in describing the cavity and the instability of the neighbor list acceleration method in MCNP, a new geometry representation method without cavity description was formed in Super Monte Carlo Program for Nuclear and Radiation Simulation (SuperMC) [14–17]. And advanced geometry navigation was developed in SuperMC to get high performance for particle transport in fusion reactors. The structure of this paper is as follows. Section 2 describes the geometry representation of fusion systems. The process of geometry navigation is presented in Section 3. The results and discussion from ITER benchmark application between SuperMC and MCNP5 are showed in Section 4. Section 5 is left for the conclusion.

2. Geometry representation

The Constructive Geometry (CG) is a widely used geometry representation method in many Monte Carlo codes. Based on CG representation method, each geometry volume is constructed using a CG tree by the Boolean operation (union, intersection and complement) of surfaces or predefined primitives. The Constructive Surface Geometry volumes are defined by first- and second-degree surfaces and fourth-degree elliptical tori. The Constructive Solid Geometry volumes are defined by simple and regular primitives, such as box, cylinder, sphere, torus, etc. In SuperMC, both Constructive Surface Geometry volumes and Constructive Solid Geometry volumes are supported, as shown in Fig. 1. Different volumes can be composed of surfaces or solids by Boolean operation, and four combinations of volumes have been supported. Lattice Geometry is suitable for Pressurized Water Reactor (PWR) and Fast Reactor (FR) with irregular arrangement volumes. Nest Geometry is mainly used for High Temperature Gas cooled Reactor (HTGR) with random distributed particle fuel. Cluster Geometry can describe the repeated structure of Heavy Water Reactor (HWR). And other geometry models can be described by General Geometry. Not limited to the geometry representation, but also have specific geometry navigation methods for Constructive Surface Geometry and Constructive Solid Geometry, respectively. Thus, different representation method can be handled in the same calculation model by SuperMC. These characteristic allows that SuperMC can be widely used for arbitrary and complicated geometry models.

Due to the complex and irregular geometrical shapes for fusion reactors, Constructive Surface Geometry representation and General Geometry were chosen in SuperMC. In view of the difficulty in describing the cavity and the instability of the neighbor list acceleration method in MCNP, the calculation model without cavity description would be converted by SuperMC/MCAM. Because there is no cavity representation generated, all solids were put in a vacuum box cell called "WorldBox" in SuperMC whose size is equal to the bounding box of entire fusion model.

In additional, all the reference models for parties to perform analyses [18] released by ITER International Organization are 40°sector of vessel extending from the major axis to the bioshield, entered on an equatorial port and bounded by reflecting planes. Thus, the set of reflecting planes is needed. Users can choose the reflecting planes interactively and mark the bounding conditions by SuperMC/MCAM. Finally, the calculation model with boundary condition would be generated completely without cavity description.

3. Geometry navigation

Multi-level geometry hierarchy structure has been supported in SuperMC. It provides an effective method to track particle trajectory in geometry volumes including hierarchy relationship. "WorldBox", as the root node of the structure, is used to describe the calculation models without cavity representation. Furthermore, this structure is also suitable for actual engineering fusion reactor calculation models that every component includes many detailed parts. In SuperMC, particle location and distance calculation in geometry navigation are all operated on the Multi-level geometry hierarchy structure. In addition, several acceleration methods, including Bounding Box method (BB) [19] and Optimal Spatial Subdivision method (OSS) [20], were applied in SuperMC to improve geometry navigation efficiency. These acceleration methods were depended on each solid's bounding box which was generated by automatic modeling tool SuperMC/MCAM along with the calculation model. The role of the principle of these acceleration methods is to reduce the geometry volumes which would be involved in the distance calculation and particle location.

3.1. Distance calculation

Distance calculation operation is to compute the distance to the volume boundary along the particle trajectory when the particle is inside a certain volume. To calculate actual distance (AD) which means the minimum distance to all boundaries along the particle trajectory is a time-consuming process. Safety Distance (SD) which means the

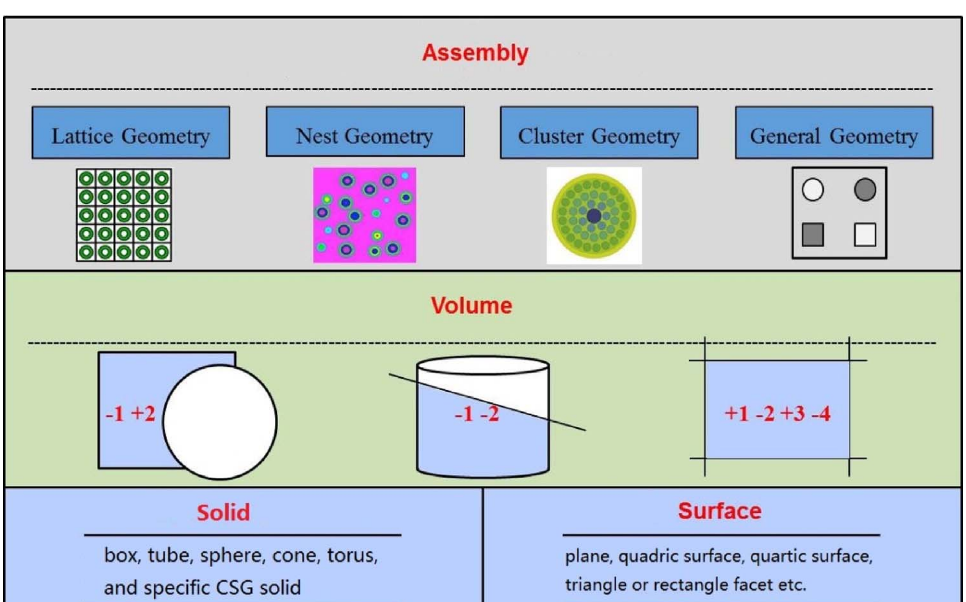

Fig. 1. Geometry representation in SuperMC.