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ORIGINAL RESEARCH

Impact Analysis of the Model on CFETR Neutronics Calculation

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Abstract Chinese Fusion Engineering Testing Reactor (CFETR) is a test tokamak reactor to bridge the gap between ITER and future fusion power plant and to demonstrate generation of fusion power in China. Fusion reactors have the characteristics of a strong anisotropic neutron flux distribution, wide range of neutron energy and spatial non-uniformity of the power density distribution caused by the external fusion neutron source. The different neutronics models were used in different research stage. The neutronics analyses of CFETR with helium cooled solid breeder blanket have been carried out to find out the effects of the 1D/2D/3D simplified geometric descriptions and 3D complex geometric descriptions for computational models. The tritium-breeding ratio, power density distribution and irradiation damage are calculated to evaluate the nuclear performance using the Monte Carlo transport code MCNP and nuclear data library FENDL-2.1. Comparison of the results shows that the value of TBR calculated by the 1D/2D/3D simplified model overestimates. The power density distribution and irradiation damage based on the 2D and 3D simplified models are similar since they all consider the effects of the axial components, but they are underestimated compared with the 3D complex models. So the simplified models of the fusion reactor for neutronics calculation are usually used at the beginning of the preliminary conceptual design. In order to obtain the accurate results, 3D complex geometric descriptions are needed.

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Introduction

Neutronics analysis plays an important role during the fusion reactor design process. To analyze the neutronics characteristics for fusion reactors, computational models of varying complexity have been used in the particle transport calculations [1–4].

Considering the geometrical complicacy of fusion reactor, a three dimensional (3D) detailed geometric description of fusion reactor is needed. However, the detailed design is devoid at the beginning of the preliminary conceptual design, then the simplified one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) geometry model are used in particle transport analyses usually. Such simple models may be useful for many aspects, such as the studies for the material fraction optimization, or for the blanket size optimization.

In this paper, in order to analyze the impact of the model on neutronics calculation, the helium cooled solid breeder blanket (HCSB) [5] of Chinese Fusion Engineering Testing Reactor (CFETR) [6] is used as a reference for 1D/2D/3D neutronics comparisons and analyses. The tritium-breeding ratio, power density distribution and irradiation damage are calculated to evaluate the nuclear performance using the Monte Carlo transport code MCNP [7] and nuclear data library FENDL-2.1 [8].

CFETR Design Parameters

Chinese Fusion Engineering Test Reactor (CFETR) is a testing tokamak reactor to bridge the gap between ITER and future fusion power plant and to demonstrate generation of fusion power in China [6]. The missions of CFETR include: addressing the Nuclear S&T issue for a reactor; testing materials and components in integrated fusion nuclear environment; demonstrating tritium self-sufficiency and demonstrating the physics issue for a reactor. The design goals were proposed as following: (1) the fusion power is 50–200 MW; (2) the duty cycle time is 0.3–0.5; (3) TBR is in the range of 1.1–1.2; (4) the engineering test stage is 8 years and the demonstration stage is 10 years [9]. The design configuration of CFETR superconducting tokamak option is shown in Fig. 1. And the main parameters for calculations of CFETR are shown in Table 1.

In order to select the most suitable blanket proposal for CFETR, the three blanket concepts (i.e. the helium cooled solid breeder blanket, the liquid LiPb blanket, and the water cooled ceramic breeder blanket) are under development and evaluation simultaneously. A helium cooled solid breeder blanket (HCSB) was proposed by School of Nuclear Science and Technology, University of Science and Technology of China, and its conceptual design has been carried out.

The detailed structure of HCSB as shown in Fig. 2, which is mainly composed of the FW, caps, stiffening plates (SPs), coolant plates (CPs), breeder units (BUs, including Be Zones and Li_4SiO_4 Zones), helium manifold and attachment systems. The FW is a U-shaped plate and the front wall is directly facing plasma. When the FW was removed, we can see that seven SPs are welded to the inner wall of the FW with the same interval to reinforce the blanket structure and to segment the BUs to 8 layers. Each BU layer consists of 4 beryllium (Be) zones and 4 Li_4SiO_4 Zones. The zones are made up by U-shaped CPs and closed by a wrap at the top and bottom respectively.

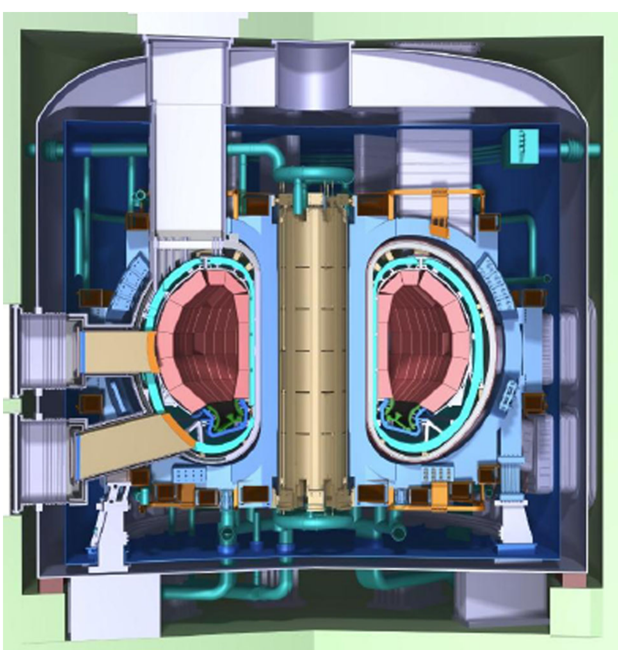


Fig. 1 Design configuration of CFETR

Table 1 Main parameters of CFETR for calculations

Fusion power (MW)	200
Major radius (m)	5.7
Minor radius (m)	1.6
Plasma elongation	(1.8–2.0)
Plasma current (MA)	(8–10)
Toroidal field on axis (T)	5
Neutron yield (n/s)	7.09×10^{19}
Neutron wall load (MW/m^2)	(average) (0.35)
Surface heat load (MW/m^2)	0.2
Duty cycle time	0.5

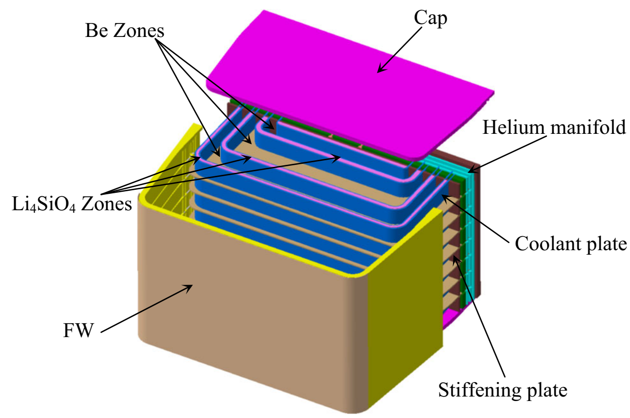


Fig. 2 The structure of helium cooled solid breeder blanket

Computational Model

1D/2D/3D neutronics calculations are performed using the Monte Carlo code MCNP along with nuclear data based on FENDL-2.1 evaluation. A CAD/MC interface code named McCad [10] is used to create CAD models and convert the models from CAD to the MCNP input file. Since the CFETR is driven by fusion neutron, the 14 MeV neutron source is described in 1D, 2D and 3D modeling in the plasma region. Based on the CFETR design configuration, the different ways are used to CFETR design configuration and convert CFETR CAD modeling to 1D, 2D and 3D neutronics models.

The 1D simplified model (1D-S) is the simplified one-dimensional spherical geometry model in which the inner blanket (IB) and outer blanket (OB) extend in the poloidal direction (no divertor). Figure 3 is a schematic diagram of 1D model.

The 2D simplified cylindrical model (2D-C) is needed to properly account for the poloidal heterogeneity, especially for the divertor. In the model, the divertor region is simplified as three compositions which are w armor, Cu armor and divertor with homogeneous material (RAFM: 25 %, He-gas: 75 %). The coolant for divertor is helium gas under 8 MPa pressure. Both IB and OB regions are modeled simultaneously to account for the toroidal effects. Since the minor radius of CFETR is 1.6 m and the plasma elongation is 2, a 320 cm (radial thickness) × 640 cm (poloidal thickness) circle core is described in 2D modeling. The stereogram drawing of 2D model is shown in Fig. 4.

Because of its symmetry, only a 22.5° sector (1/16 of toroidal length) is modeled in 3D simplified cylindrical model (3D-C) with reflecting boundaries, shown in Fig. 5. The model is used considering the effects of upper port and mid-plane port. The toroidal dimension of upper port is 11.25°, the radial dimension is 96 cm and the poloidal dimension is 149 cm from plasma zone to shielding zone. The mid-plane port was segmented two parts and distributed in both sides in toroidal dimension. Each part is 5.625° in toroidal dimension and 96 cm in poloidal dimension and 149 in radial dimension from plasma zone to shielding zone.

In order to obtain the more actual neutronics results, a 3D detailed model (3D-D) based on simplified CAD design was modeled, including the main components by a 22.5° sector as follows: Blanket, Shielding bulk, Vacuum Vessel, Divertor cassette, Magnet System (TFCs, PFCs and Center Solenoid), Upper Port and Mid-plane Port, shown in Figs. 6 and 7. The blanket modules are composed of the

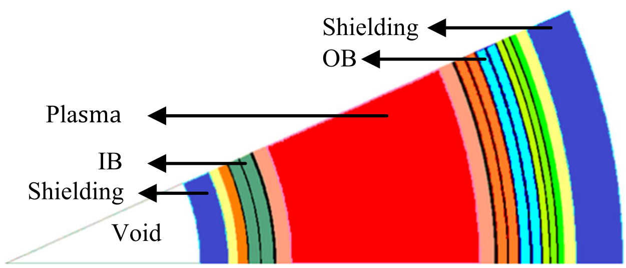


Fig. 3 The schematic diagram of 1D-S model

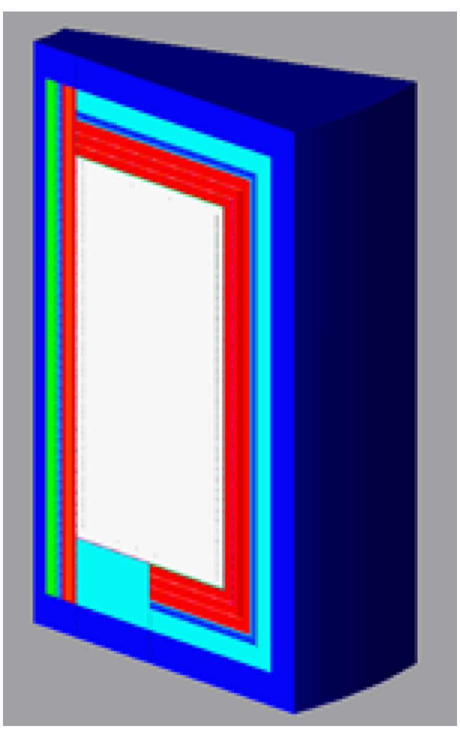


Fig. 4 The 2D-C simplified cylindrical model in McCad

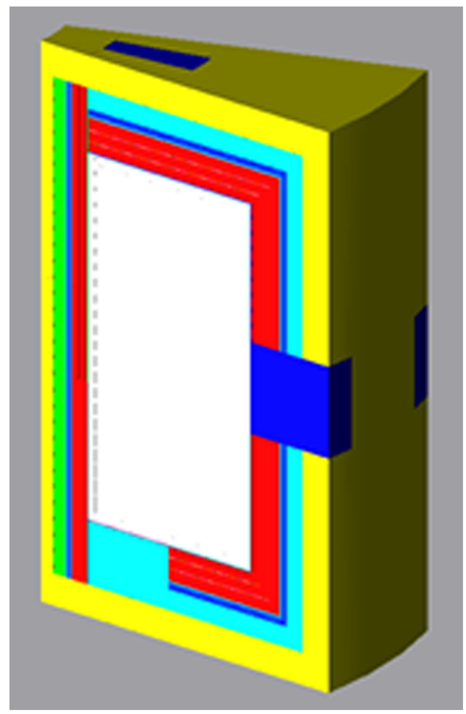
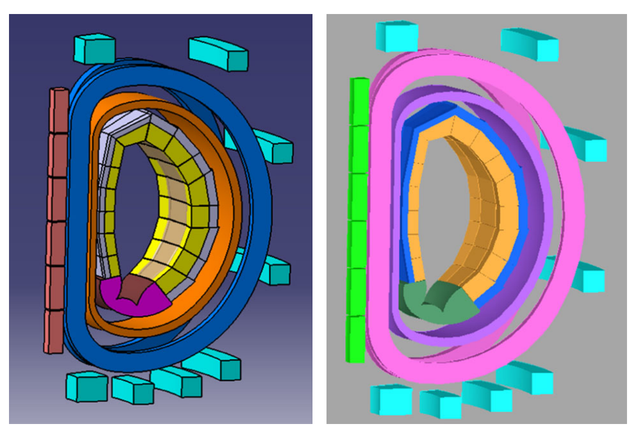


Fig. 5 The 3D-C simplified cylindrical model in McCad



(a) (b)

Fig. 6 3D-D model shown in CATIA (**a**) and McCad (**b**) first wall (FW), homogenized breeder units (BUs), caps and homogenized helium manifold.

Considering the influence of the blanket detailed structure on neutronics results, the outboard blanket located in the mid-plane was used the detailed 3D engineering model to replace the simplified model for the exact evaluation.

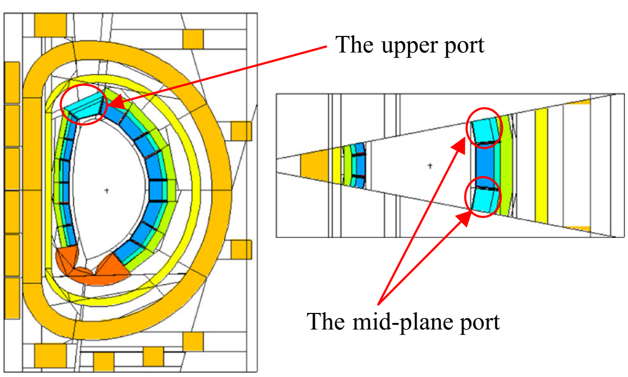
Figure 8 shows the cross-section view of the detailed blanket module and the homogenized blanket modules in the whole CFETR 3D model (3D-DB) which was plotted by MCNP. The main dimensions and material compositions of HCSB are shown in Table 2.

Comparison Analysis

Tritium Breeding Ratio

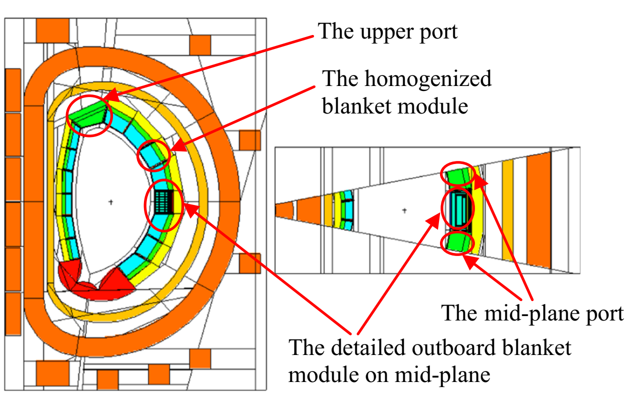
A fusion reactor must be self-sufficient with respect to tritium breeding. Previous study has shown that the typical design targets of the global TBR were in the range of 1.05–1.15 [11, 12]. Table 3 lists the TBR calculated in the different models. Li_4SiO_4 with a lithium enrichment of 90 % Li-6 is used in tritium-breeding zone. Comparing the TBR based on 1D, 2D and 3D calculations indicate that the 1D-S/2D-C/3D-C calculation overestimates the TBR. 3D-D model calculations yield a TBR 1.11 which is in the range of 1.05–1.15.

Compared with homogenized blanket modules, the detailed geometry description of BUs will reduce the value of TBR. In order to obtain the reduction rate, the local TBR of the outboard blanket module on mid-plane was evaluated based on 3D-D and 3D-DB models respectively. The calculated results are showed in Table 4. When the



(a) (b)

Fig. 7 Section view of the 3D-D model of OXZ (**a**) and OXY (**b**) plane in MCNP



(a) (b)

Fig. 8 Section view of the 3D-DB model of OXZ (**a**) and OXY (**b**) plane in MCNP

Table 2 Material composition of the blanket module

	Composition (vol%)	Thickness (cm)
Detailed blanket module		
Armor	Tungsten 100 %	0.2
FW	RAFM steel 77 %, helium 23 %	2.8
Be-1	Beryllium 80 %, helium 20 %	2
Li_4SiO_4-1	Li_4SiO_4 64 %, helium 36 %	1.5
Be-2	Beryllium 80 %, helium 20 %	12
Li_4SiO_4-2	Li_4SiO_4 64 %, helium 36 %	2.5
Be-3	Beryllium 80 %, helium 20 %	20
Li_4SiO_4-3	Li_4SiO_4 64 %, helium 36 %	2.5
Be-4	Beryllium 80 %, helium 20 %	9
Li_4SiO_4-4	Li_4SiO_4 64 %, helium 36 %	3
CP	RAFM steel 69 %, helium 31 %	0.5
SP	RAFM steel 69 %, helium 31 %	0.8
Cap	RAFM steel 95 %, helium 5 %	2.8
Side wall	RAFM steel 64.5 %, helium 35.5 %	2.8
Manifold	RAFM steel 57.5 %, helium 42.5 %	21
Homogenized blanket module		
Armor	Tungsten 100 %	0.2
FW	RAFM steel 77 %, helium 23 %	2.8
BUs	Beryllium 58.02 %, Li_4SiO_4 9.69 %, RAFM steel 8.52 %, helium 23.77 %.	56
Cap	RAFM steel 95 %, helium 5 %	2.8
Side wall	RAFM steel 64.5 %, helium 35.5 %	2.8
Manifold	RAFM steel 57.5 %, helium 42.5 %	21

Table 3 The comparison of TBR

1D-S	1.65
2D-C	1.64
3D-C	1.46
3D-D	1.11

Table 4 The reduction rate of local TBR

Homogenized geometry	4.3246E−03
Detailed geometry	3.7756E−03
Reduction rate	12.70 %

reduction rate was used for the global TBR based on 3D-D, the value was reduced to 0.97 from 1.11. So, in order to obtain the reliable value of TBR, the detailed modeling of breeding blanket is necessary.

Power Density Distribution

The power density is an important parameter for designing a fusion reactor and its components. The calculated nuclear power density distributions in the HSCB blanket components are shown in Fig. 9 as a function of the distance from the front of the first wall. The maximum power density in 2D-C, 3D-C and 3D-DB model which occurs in tungsten armor is 0.88, 0.93 and 6.93 MW/m^3, respectively. The simplified cylindrical models underestimate the power density in blanket. Figure 10 gives the neutron flux distribution in Li_4SiO_4-1. It shows that neutron flux distribution in 2D-C and 3D-C computational model is close, but the neutron flux in 3D-DB model is larger than in 2D-C and 3D-C model, and the power density distribution also presents the same development trend.

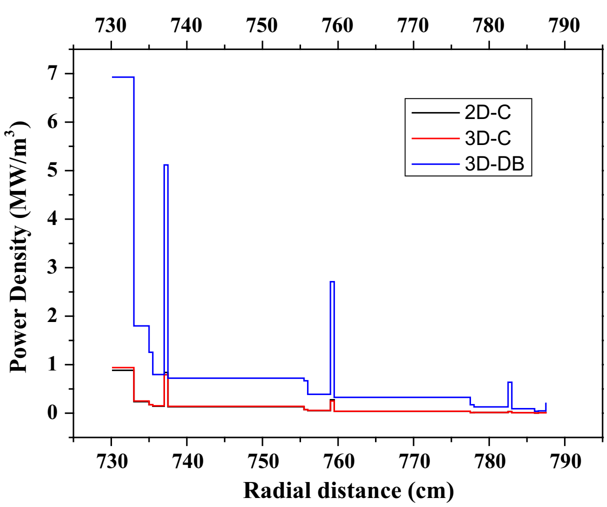


Fig. 9 The nuclear power density distribution

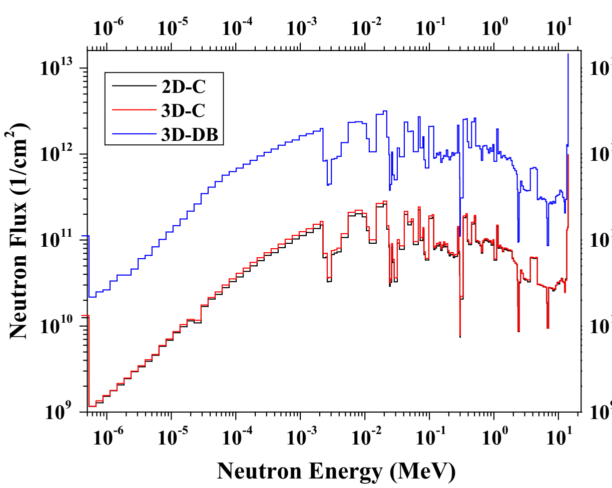


Fig. 10 The neutron flux distribution in Li_4SiO_4-1

Table 5 The irradiation damage of steel in FW

	2D-C	3D-C	3D-DB
dpa	1.11	1.14	9.14
Helium production rate (appm)	12.29	12.66	104.76
Hydrogen production rate (appm)	44.76	46.04	381.06

Irradiation Damage

As it is well known, the levels of the atomic is placement and of helium and hydrogen production have the most severe impact among the neutron-induced effects in the structure materials, such as steels. The lifetimes of the structures are determined by the displacement per atom (dpa) levels attainable during operation. The maximum dpa limit for CFERT is 10 dpa in 8 years' engineering test stage [11]. The precise distribution of neutron wall loading was calculated and the peak was 0.473 MW/m^2 on the outboard blanket module at equatorial plane [12]. The peak damage rate of the FW appears at the same blanket module. After 8 years' neutron radiation with 0.5 duty cycle time, the irradiation damage of steel in FW is shown in Table 5. It shows that the results of irradiation damage in 2D-C and 3D-C computational model is close, but it in 3D-DB model is larger than in 2D-C and 3D-C model.

Conclusion

Based on a helium cooled solid breeder blanket for CFETR superconducting tokamak option, the effects for neutronics analysis in different models are carried out. The models include 1D spherical geometry (1D-S), 2D cylindrical geometry (2D-C), 3D cylindrical geometry (3D-C), 3D detailed model with homogenized blanket (3D-D) and 3D detailed model with detailed outboard blanket (3D-DB) model which are created by McCad. The neutronics calculation was carried out by the Monte Carlo N-Particle transport code MCNP.

The global TBR is determined to be 1.65, 1.64, 1.46, 1.11 and 0.97 based on 1D-S, 2D-C, 3D-C, 3D-D and 3D-DB models, respectively. The 1D-S, 2D-C and 3D-C calculations overestimate the TBR very much. The maximum power density in 2D-C, 3D-C and 3D-DB model which occurs in tungsten armor is 0.88, 0.93 and 6.93 MW/m^3, respectively. The dap of steel in FW are 1.11, 1.14 and 9.144 based on 2D-C, 3D-C and 3D-DB model, respectively. The simplified cylindrical models underestimate the power density and irradiation damage in blanket.

So, the simplified models of the fusion reactor for neutronics calculation are usually used at the beginning of the preliminary conceptual design. In order to obtain the accurate results, 3D complex geometric descriptions are needed.

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