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Original Article

Design and simulation of a blanket module with high efficiency cooling system of tokamak focused on DEMO reactor

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A B S T R A C T

In this study, the neutronic calculation to obtain tritium breeding ratio (TBR) in a deuterium-tritium (D-T) fusion power reactor using Monte Carlo MCNPX is done. In addition, by using COMSOL software, an efficient cooling system is designed. In the proposed design, it is adequate to enrich up to 40% ^{6}Li. Total tritium breeding ratio of 1.12 is achieved. The temperature of helium as coolant gas never exceed 687$^{\circ}C$. As regards the tolerable temperature of beryllium (650$^{\circ}C$), the design of blanket module is done in the way that beryllium temperature never exceed 600$^{\circ}C$. The main feature of this design indicates the temperature of helium coolant is higher than other proposed models for blanket module, therefore power of electricity generation will increase.

1. Introduction

The main purpose of breeding blanket in fusion reactors like DEMO and ITER is tritium production to complete fuel cycle. “Breeding blanket” within the fusion building blocks is a concept to develop the future power plants [1]. The breeding blanket is made up of parts of modules covering the interior of the fusion reactor vessel, receives a high heat load and an intense neutron flux [2]. Fusion reactions on earth have low cross sections for heavy nuclei to take place, but this is possible for light nuclei, in which two lighter atomic mass nuclei fuse to form a heavier nucleus. The candidate reaction in fusion area is deuterium-tritium (D-T) reaction that has high cross section to utilize in fusion devices. Tritium is a radioactive isotope of hydrogen. The half-life of tritium is 12.3 years. Although tritium occurs naturally in the environment, the amount is too small for practical recovery. Because of limitation in tritium storage, tritium is strategic fuel in nuclear fusion. The breeding blanket modules in the fusion reactor, contain lithium compounds. Fast neutrons from deuterium-tritium (D-T) reaction interact with blanket. As a result, tritium is produced [3]. The blanket as a key components of a fusion reactor generally has three functions:

1. Tritium breeding
2. Power exhaust
3. Radiation shielding

Design of breeding blanket has some important aspects that indicate tritium breeding rate (the ratio between the amounts of generated and burnt tritium) must bigger than one. In addition, low activation of materials, low tritium retention, good tritium confinement, high neutron fluence and high thermodynamic efficiency should be achieved [4]. The purposes of this paper are:

- Design and simulation of the tritium breeding blanket module and obtaining proper TBR by using MCNP code.
- Design and simulation of the efficient coolant system by using COMSOL Multiphysics software so that conversion efficiency of thermal power to electric power is higher compared to that of similar models.

2. Materials for the HCPB concept

A diversity of breeding blanket concepts has been considered. The major breeding materials made up of liquid breeders, mainly liquid metals. Recently some studies have been focused on FLiBe. A.R. Raffray et all [5], summarized the design and performances of

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recent breeding blanket concepts. They classified breeding blankets based on functional materials and coolants. There are several types of blanket concepts such as ceramic breeder + ferritic martensitic steel structure with separately water-cooled and helium-cooled concepts, Pb–17Li + ferritic/martensitic steel structure with dual-coolant blanket concept and water-cooled Pb–17Li blanket, self-cooled lithium + vanadium alloy structure concepts. SiC_f/SiC + liquid or ceramic breeders concepts like SiC_f /SiC + Pb–17Li. Other concepts recently receiving some degree of attention like blanket concept with tungsten alloy as structural material and heat extraction by lithium evaporation and FLiBe concepts with ferritic or other structural materials [5]. In this paper, the Helium-Cooled Pebble Bed (HCPB) blanket is used, because HCPB blanket has a reasonable efficiency, good safety characteristics and adaptability between coolant, structural and functional materials. These materials should have a number of properties, such as low electric conductivity, high mechanical resistance, high thermal stability, potentially high tritium generation and fast tritium release, to be considered as possible candidates for the tritium breeding blanket [6]. The major target of ceramic breeder materials led to the use of the breeder materials in the form of pebble beds. Three candidate pebble materials such as Li_4SiO_4, and two forms of Li_2TiO_3 for DEMO reactors have been considered. These materials will be tested in ITER [7]. The design temperature limit of lithium ceramic breeder, Li_4SiO_4 is 920 °C, which is about 100 °C lower than the melting point. In this paper we considered beryllium pebble beds of 1 mm diameter that are used in HCPB blanket as neutron multiplier, the volume of these pebbles is about 2–3 times larger than the Lithium ceramics. As we considered in our design, oxide dispersion strengthened (ODS) ferritic steels are promising blanket structural materials which can trap helium and hydrogen, strengthen the material and reduce creep under neutron bombardment [8]. Maximum design temperature of beryllium the HCPB concept is about 650 °C and the maximum temperature imposed by the ODS ferritic steel is about 750 °C.

3. Breeder unit design description

Total surface area of the DEMO blanket is 1188 m^2 and the plasma facing surface area in our proposed design is 1.2m^2. Therefore 990 HCPB test blanket modules (TBM) are needed for the total area of the blanket. Each module has a number of different parts. The TBM is basically composed of breeder units (BU) and cooling channels. The BU contain lithium orthosilicate and beryllium pebble beds. A cooling tube is located inside of the breeder unit. Fig. 1 shows simulation of the proposed design of the module using COMSOL software. In addition, the configuration of the breeder units, module size and different parts of module are shown in Fig. 1.

Each sub-module has its own independent cooling channel and tritium purge gas circuits. Fig. 2 shows an illustration of the sub-module. The main characteristics of the HCPB-TBM and sub-module design are given in Table 1.

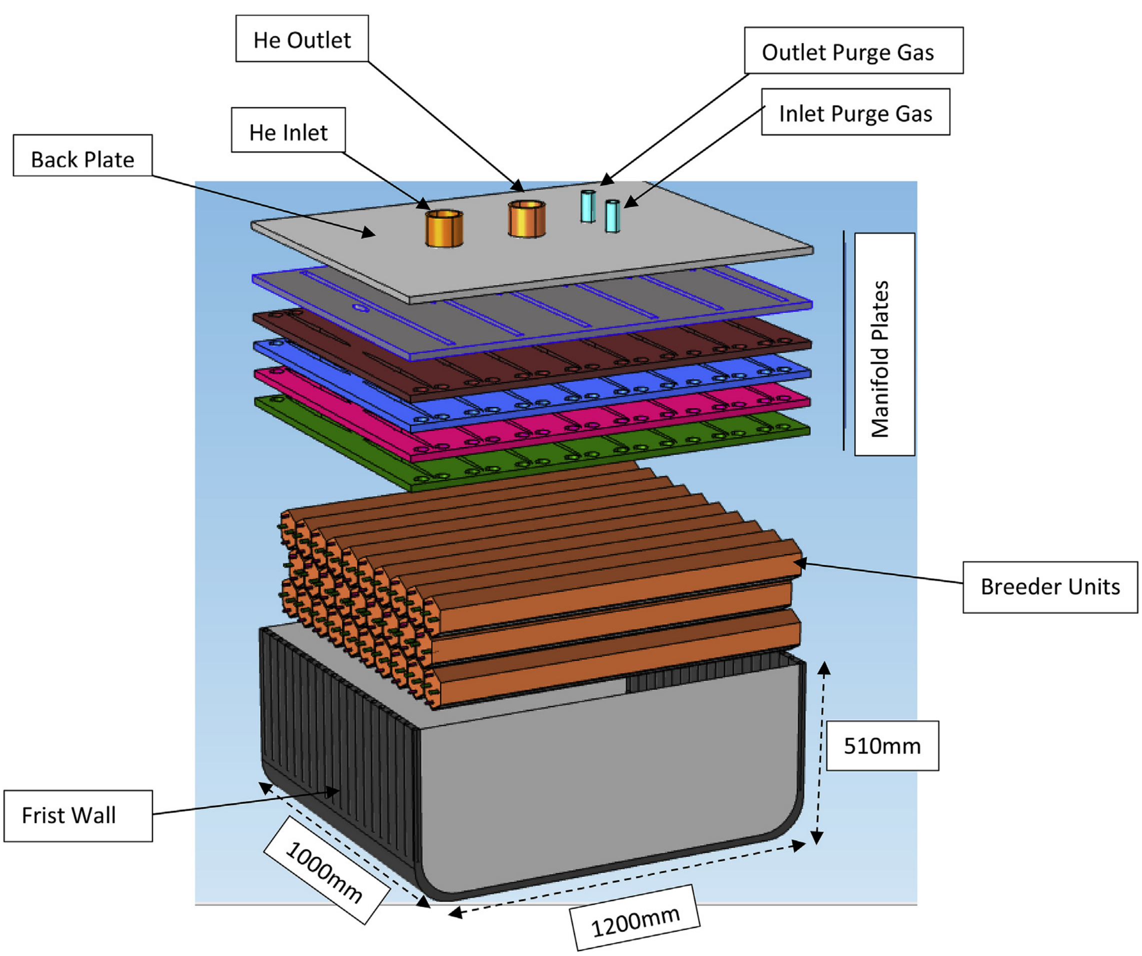

Fig. 1. The design of the HCPB-TBM.

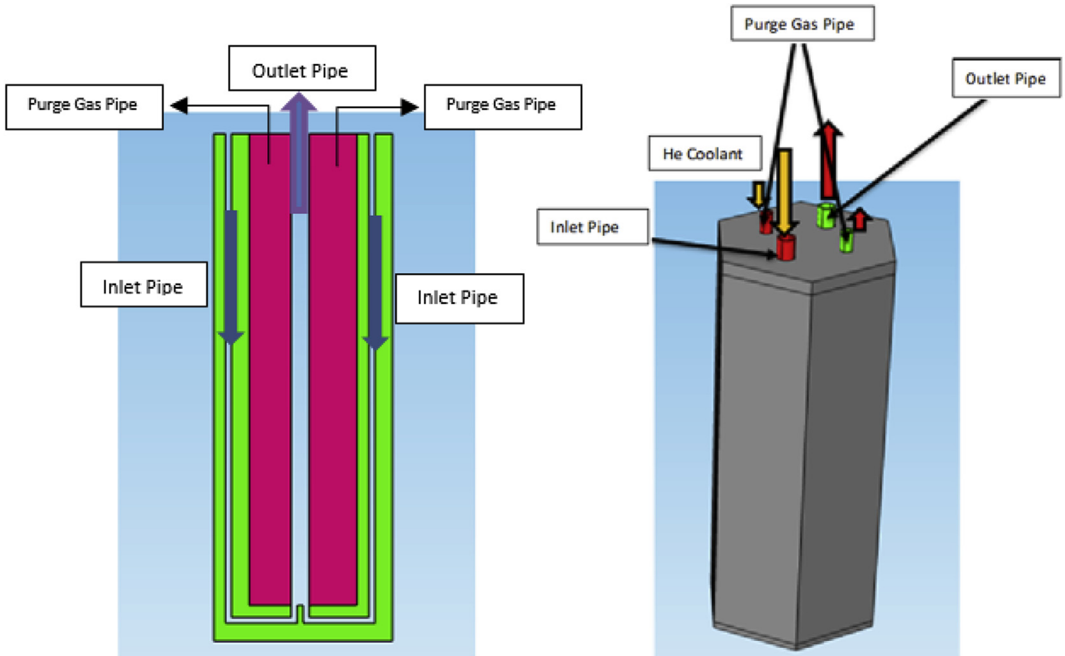

Fig. 2. Structure of breeder unit.

4. Neutronic analyses

Neutronic calculations have been done to determine where the instruments should be located in this design. The neutron energy deposited in the blanket containing lithium. Natural lithium contains 7.4% ^{6}Li and 92.6% ^{7}Li. The n-^{6}Li exothermic reaction has a large cross section for thermal neutrons, while the n-^{7}Li endothermic reaction has a smaller cross section for fast neutrons. ^{6}Li is the more useful one and can easily be enriched for use in a breeding blanket.

The feasibility of tritium breeding depends on the following two key functions:

1. Principles of physics
2. Engineering issues

The TBR is theoretically calculated using equation (1) [21]:

$$TBR \approx 1 + \frac{t_p}{n f_b t_d} \quad (1)$$

Where $t_p = 1$day is a mean time to recycle the tritium, $n = 0.5$ is improved efficiency of tritium injected into the plasma, $f_b = 1\%$ is tritium burnup fraction parameter and $t_d = 5yer$ is the period of time required to double the initial tritium, so the TBR value will be 1.12.

Neutronic calculations of the proposed blanket module are accomplished by using the Monte Carlo simulation MCNPX code. The amount of the produced tritium in the module is calculated by F4 Tally and MT card with interaction number 205. The achievable TBR depends on the thickness of the blanket. The primary analysis indicated that the TBR can be met with a total blanket thickness of 51 cm including 30 cm manifold region at the back, as shown in Fig. 3.

For better breeding, as calculated with the MCNPX code, it is proposed that the ^{6}Li enrichment in the ceramic breeder beds should be increased 20% for the front of the module and up to 40% for the back of it. Table 2 gives a summary of the main characteristics of the HCPB TBM neutronic analysis.

Table 1
Characteristics of the HCPB TBM and sub-module design [9–12].

Ceramic breeder	**Li_4SiO_4 pebble bed**	**Value**
	Pebble size [mm]	**0.25–0.63**
	Thermal conductivity [$wm^{-1}k^{-1}$](500–900 °C)	**1–1.2**
	Maximum allowable temperature [^{0}C]	**920**
Neutron multiplier	**Beryllium pebble bed**	
	Pebble size [mm]	**2**
	Thermal conductivity [$wm^{-1}k^{-1}$](500,600,700)	**5.4, 8.8, 10.6**
	Maximum allowable temperature [^{0}C]	**650**
Structural material	**ODS low activation steel**	
	Thermal conductivity [$wm^{-1}k^{-1}$]	**29**
	Maximum allowable temperature [^{0}C]	**750**
Parameters	**HCPB(TBM)**	
	Dimension (toroidal × radial × poloidal) [m3]	**1.2 × 0.51 × 1**
	Maximum wall load (MW/m2)	**5**
	Surface heat flux	**0.5**
	Breeder Unit	
	Dimension (toroidal × radial × poloidal) [m3]	**0.1 × 0.1 × 1**

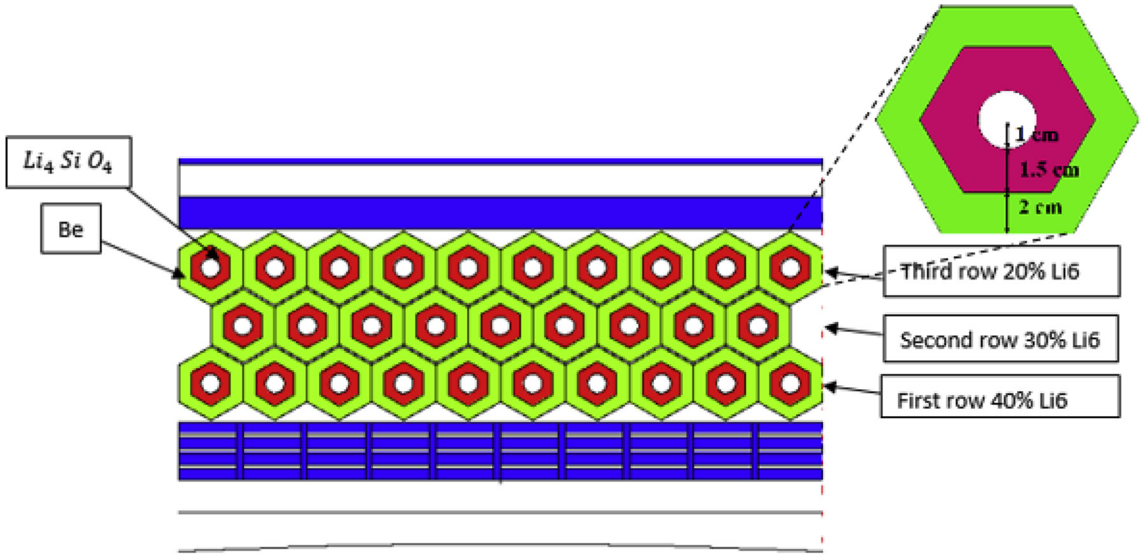

Fig. 3. Cross sectional figure of arrangement of the breeder units in the blanket.

Table 2
Characteristics of the HCPB TBM neutronic analysis.

	Li_4SiO_4 pebble bed and Be		Value
Ceramic breeder and neutron multiplier	First row	Be thickness	2 cm
		(Li6 20%) Li_4SiO_4 thickness	1.5
	Second row	Be thickness	2 cm
		(Li6 30%) Li_4SiO_4 thickness	1.5
	Third row	Be thickness	2 cm
		(Li6 40%) Li_4SiO_4 thickness	1.5
Tritium breeding ratio	1.12		

5. Cooling system

The pebble beds are contained and cooled by cooling plates with internal channels through which helium flows with temperatures approximately between 327 °C and 687 °C. The temperature of helium as coolant gas never exceed 687°*C*. As regards the tolerable temperature 650°*C* of beryllium, the design of blanket module is done in the way that beryllium temperature never exceed 600°*C*. The coolant helium flows into the first wall and the breeding area at 8 MPa pressure and high temperature in small channels, whenever a low pressure helium flow purged the beds [12,13]. This purge flow separately removes the tritium produced in the beds, transfers it to a tritium extraction system and makes the tritium partial pressure to be low at the interface with the cooling channels that prevents increasing the permeation flow to the major cooling system. Thermal mechanical calculations for the modular blanket are accomplished by using COMSOL software.

COMSOL software potentially is used in many application areas such as simulation of different components of fusion reactor and fusion reactions [14–19]. In this paper, a cooling system is designed and simulated using this software. The modules “NON - ISOTHERMAL PIPEFLOW” and “HEAT TRANSFERIN SOLIDS” are applied in order to simulate helium flow with cooling tubes and heat transfer physics, respectively. Accordingly, both modules simultaneously are coupled and the simulation model ran for a simulated time of 24000 s.

Figs. 4 and 5 show the descriptive of the cooling system and results of the COMSOL software simulation. Table 3 depicted the cooling system parameters of the HCPB TBM.

According to Figs. 4 and 5, the maximum temperature values of

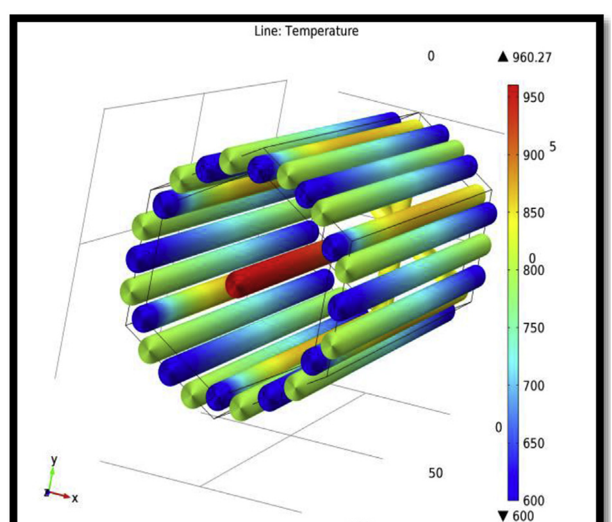

Fig. 4. Simulation of He inlet/outlet temperature.

ceramic breeder beds, beryllium and steel are 710°*C*, 600°*C* and 720°*C*, respectively. These temperatures are lower than the temperatures which are mentioned in Table 1. The heat load on the first wall, the maximum tolerable temperature of applied materials in the blanket and also the outlet temperature of coolant are the major parameters to determine conversion efficiency of thermal power to electric power [11,20]. A.R. Raffray et all [11], indicated that the power efficiencies are 36% and 44% at temperatures of 550°*C* and

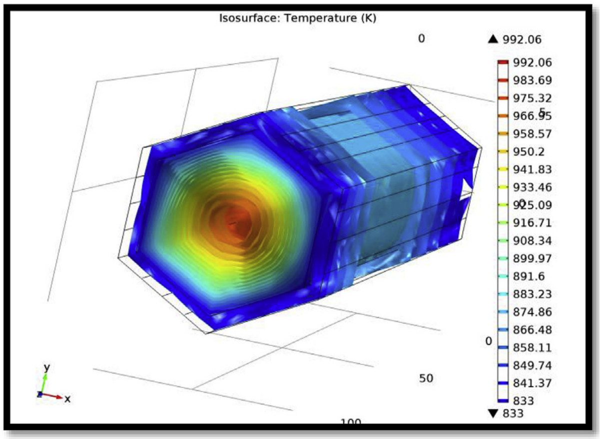

Fig. 5. Distribution of temperature in breeder unit.

Table 3
Characteristics of cooling system of the HCPB TBM.

Cooling system	Value
Inlet temperature[^{0}C]	327
Outlet temperature[^{0}C]	687
He pressure[Mpa]	8
He purge flow pressure[Mpa]	0.4
Channel diameter[mm]	13
Number of cooling tube in one breeder unit	13
He velocity in channel[m/s]	75

700°*C* respectively. In the present paper, the temperatures of all used materials never exceed the maximum allowable temperatures. In addition, the power efficiency tends to its maximum value.

6. Conclusion

In this paper tritium breeding ratio was calculated using MCNPX code. Beryllium is an excellent neutron multiplier, which can multiply neutron through the Be (n, 2n) reaction. Furthermore, the cooling system of the blanket was simulated by COMSOL Multiphysics and the distribution of temperature in TBM was obtained. Finally, we achieve these obvious results:

1. In the proposed model, blanket module with enriched Li_4SiO_4 up to 40% ^{6}Li was considered.
2. TBR in the proposed model was 1.12 which is convenient for future self-sufficient fusion reactors.
3. The temperature of helium as coolant gas never exceeded 687 °C.
4. As regards the tolerable temperature of beryllium (650°*C*), the design of blanket module is done in the way that beryllium temperature never exceed 600°*C*.
5. The main feature of this design indicates the temperature of helium coolant is higher than other proposed models for blanket module, therefore power of electricity generation will increase.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2019.07.019.

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