Progress in Nuclear Energy 103 (2018) 8–19

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

Conceptual design and comprehensive optimization analysis of a fusion-fission hybrid reactor water-cooled pressure tube blanket[☆]

Shijie Cui[a], Dalin Zhang[a,*], Xinli Gao[b], Wenxi Tian[a], G.H. Su[a], Suizheng Qiu[a]

[a] State Key Laboratory of Multiphase Flow in Power Engineering, Shaanxi Key Lab. of Advanced Nuclear Energy and Technology, School of Nuclear Science and Technology, Xi'an Jiaotong University, Xi'an, 710049, China
[b] Nuclear and Radiation Safety Center, Beijing, 100082, China

ARTICLE INFO

Keywords:
Fusion-fission hybrid reactor
Water-cooled pressure tube blanket
Conceptual design
First wall
Thermal-mechanical coupling

ABSTRACT

Fusion-fission hybrid reactor is believed to be a feasible implementation of fusion energy in a short time as it requires less advanced technology in fusion physics and engineering than pure fusion reactor. In this paper, based on the mature technology of pressurized water reactor (PWR) and existing fusion reactor blanket concepts, a new conceptual design scheme of water-cooled pressure tube blanket was proposed for hybrid reactor and both the material selections and the structure design were performed. In the blanket, a trapezoidal U-shaped first wall (FW) was adopted to decrease the gaps between blanket modules. Due to high heat flux from plasma and intense irradiation by high-energy neutrons, it's essential to conduct thermal-mechanical coupling analyses and optimizations of the FW to ensure reasonable temperature and stress distributions on it. In this work, CFX-Workbench coupling method was adopted to perform the simulation. The influences of different FW geometrical configurations and boundary conditions on the temperature and stress distributions were researched in detail to optimize the FW structure. Besides, the thermal and mechanical characteristics of the helium tanks, the cooling channels and the breeding zones were researched in this paper. The calculation results verified the reasonability of the conceptual design scheme preliminarily and could provide a meaningful reference for the further conceptual design, analysis and optimization of the hybrid reactor blanket.

1. Introduction

Fusion-fission hybrid reactor is a fusion reactor that contains thorium, uranium or transuranic elements in its blanket for fission (Dolan, 2013). This concept can take full advantages of both the fusion reaction in sufficient neutrons and the fission reaction in sufficient energy (Wu et al., 2013; Siddique et al., 2014), which make it possible to realize the combined functions of the two reactors as follows by installing an appropriate blanket: 1. Nuclear fuel breeding for fission reactor; 2. Nuclear waste transmutation; 3. Tritium breeding; 4. Energy production and transformation (Kotschenreuther et al., 2009; Wu et al., 2013; Cui et al., 2017). As a result, it can reduce the demand of advanced technology in fusion physics and engineering greatly than pure fusion reactor and is believed to be a feasible implementation of fusion energy in a short time (Liu et al., 2011).

Up to now, several conceptual design schemes of the fusion-fission hybrid reactor and their blankets have been proposed (Huang and Qiu, 1998; Feng et al., 2002; Mehlhorn et al., 2008; Kramer et al., 2009; Kotschenreuther et al., 2012; Reed et al., 2012) and a series of preliminary analyses have also been conducted to access their performances in various aspects (Zheng et al., 2012; Gao et al., 2013; Wu et al., 2013; Zu et al., 2013). However, most of the existing research work on the hybrid reactor blanket includes no detailed thermal-hydraulic and thermo-mechanical analyses, which are of great significance for the parameter optimization design of the blanket structure and improving the economic efficiency and safety. In addition, changing the geometrical structure will influence the neutronics performances of the blanket such as tritium breeding, radiation shielding and nuclear heating. As a result, it's essential to perform further intensive thermal-mechanical coupling analyses and optimizations for the preliminary blanket concept to evaluate the performances and obtain the optimal scheme.

In this paper, through sufficient investigation and reference on the mature technology of fission reactor like pressurized water reactor (PWR) (Zheng and Du, 2013) and extensive research and comparison on the existing fusion reactor blanket concepts (Liu et al., 2014, 2017; Chen et al., 2015; Ni et al., 2015; Feng et al., 2016; Cui et al., 2017), a new conceptual design scheme of water cooled pressure tube blanket

[☆] The 18th International Conference on Emerging Nuclear Energy Systems (ICENES2017) Hefei, Anhui, China, 24–27 April 2017.

[*] Corresponding author.
E-mail address: dlzhang@mail.xjtu.edu.cn (D. Zhang).

http://dx.doi.org/10.1016/j.pnucene.2017.11.002
Received 15 August 2017; Received in revised form 10 October 2017; Accepted 2 November 2017

was proposed for fusion-fission hybrid reactor. Firstly, by considering the operating requirements and design principles of the hybrid reactor water-cooled pressure tube blanket comprehensively, the coolant, structure and tritium breeding materials were all selected appropriately. Then, the preliminary structure design was performed, which mainly included the fission zone, tritium breeding zone, and first wall (FW). On these bases, thermal-mechanical coupling analyses and optimizations of the FW were performed by CFX-Workbench coupling method, in which the influences of different FW characteristics (eg. flow direction, front wall thickness, fillet radius, inlet velocity and cooling channel roughness, etc.) on both the temperature and stress distributions were researched in detail to obtain the optimal FW structure. It's essential to be noted that once the FW structure changed during the parametric sensitivity analyses, then we would change the neutronics model correspondingly and calculated the nuclear power deposition in it again. This real-time update would make the neutronics calculation results more accurate and conservative than those in the previously published work which adopted the assumption of uniform and constant heat source distribution in the FW structure. In addition to the above, the thermal and mechanical analyses of the helium tanks, cooling channels and breeding zones were also performed in this paper. All of the calculation results showed that they could satisfy the corresponding limits well, which verified the reasonability of the conceptual design scheme preliminarily.

2. Conceptual design of water-cooled pressure tube blanket

2.1. Design objectives of the blanket

Several main design objectives of the blanket concept were summarized as follows (Gao et al., 2013; Wu et al., 2013):

1) Thermal power = 3000 MW, fusion power = 500 MW;
2) Refer to the existing mature technology of fission reactor (PWR);
3) Meet the tritium self-sufficiency requirement;
4) Build the integrated cooling loops for both the fission and fusion zones;
5) Use as few structural materials as possible to reduce the nuclear power deposition in the fusion device;
6) Low pressure drop in the cooling channels;
7) Good compatibility between the selected materials;
8) Modularization, convenient for installation and maintenance;
9) As high economic efficiency as possible under the premise of safety.

2.2. Materials selection for the blanket

2.2.1. Coolant

Basic performance parameters of the commonly used coolants for fusion reactors were listed in Table 1 (Chen et al., 2015; Ni et al., 2015; Liu et al., 2017):

As the conceptual design of the blanket in this paper should be based on the existing mature technology of PWR, water with 15.5 MPa high pressure was chosen as the only coolant for fission zone as a matter of course (Zheng and Du, 2013; Liu et al., 2014). However, the excessively high operating pressure of the water would make it very difficult for the structure design of the FW, tritium breeding zone and sub-module cooling channels in the fusion zone, and it was also very difficult to extract the tritium from the water. As a result, high pressure water was inappropriate for cooling the fusion zone.

By extensive investigation and comparison on the existing fusion reactor blanket concepts, helium cooled solid breeder (HCSB) blanket was acknowledged as the most promising (Feng et al., 2012, 2016; Chen et al., 2015; Wan et al., 2016; Cui et al., 2017) as a result of its remarkable advantages in stable structure, easy realization, good compatibility between selected materials, and without Magneto Hydro Dynamics (MHD) effects (Li et al., 2013), in which the helium with 8 MPa pressure was commonly adopted as the only coolant to extract the deposited heat in the blanket components on account of its good stability and chemical inertness. Finally, high pressure helium was adopted as the only coolant for fusion zone.

Table 1
Main parameters of the commonly used coolants for fusion reactor.

Parameter	H_2O	Li	Pb (83%)-Li (17%) at 850 °C	FLiBe	He (8 MPa, 400 °C)
Density/kg·m^{-3}	960	450	8560	1840	5.6
Melting point/K	273	454	507–510	633–732	–
Specific heat/J·kg^{-1}·K^{-1}	4190	4200	185	2400	5195
Thermal conductivity/W·m^{-1}·K^{-1}	0.7	65	24.1	1.0	0.27
Dynamic viscosity/Pa·s	2.84E-4	2.5E-4	6.51E-4	3.0E-3	3.5E-5

2.2.2. Structural material

The structural materials used for fusion reactor, especially for the FW, suffered extreme working environment under intense radiation and huge energy deposition. In order to maintain the integrity of blanket structure under the coupling effects of the complex multi-physics fields, the structural materials were required to meet the following characteristics (Tavassoli, 2002):

1) Strong resistance to the radiation damage;
2) Can operate steadily under the high temperature and pressure condition;
3) Good compatibility with the other materials (coolants, breeders, etc.);
4) Can bear the huge thermal load;
5) Relatively low thermal expansivity and elasticity modulus and high thermal conductivity to reduce the temperature and stress distributions;
6) Relatively small expansion and creep deformation under the long term irradiation condition;
7) Low neutron activation and no long-lived radionuclide generation to reduce the decay heat.

The commonly used structural materials for fusion reactors at this stage included austenitic stainless steel (Eissa et al., 2016), Reduced Activation Ferritic/Martensitic (RAFM) steel (Eliniyaz, 2013), Vanadium alloy (Li et al., 2007), SiC and its composite (Zhao et al., 2008), etc. Their basic performance parameters were listed in Table 2.

By comparison on the above properties, China low activation

Table 2
Main parameters of the commonly used structural materials for fusion reactor.

Parameter	Austenitic stainless	RAFM	V alloy	SiC and composite
Density/g·cm^{-3}	7.9	7.8	6.1	2.7
Melting point/°C	1400	1420	1890	2800
Specific heat/kJ·kg^{-1}·K^{-1}	0.5	0.58	0.8	0.6
Thermal expansivity/10^{-6} K^{-1}	15.9	10.5	12.6	3
Thermal conductivity/W·m^{-1}·K^{-1}	16.3	35.3	27.7	10–35
Elasticity modulus/GPa	193	200	131	150
Ultimate tensile strength/MPa	515	760	420	500
Poisson ratio	0.3	0.27	0.36	0.2
Fracture toughness/kJ·m^{-2}	278	500	> 500	–