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Fusion-based hydrogen production reactor and its material selection

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ABSTRACT

The fusion-based hydrogen production reactor (named FDS-III), one of the series of fusion system design concepts developed in China, is designated to exploit the fusion energy advanced application for the production of hydrogen. In this paper, a conceptual design of FDS-III is presented, including the design of plasma core, high temperature blanket, divertor and related auxiliary systems. In particular, an innovative high temperature liquid blanket (named HTL) concept with the multi-layer flow channel inserts in the liquid metal LiPb channels and the reduced activation ferritic/martensitic steel as the structural material is proposed to achieve LiPb outlet temperature of about 1000 °C for high efficient production of hydrogen. The preliminary performance analyzes have demonstrated the feasibility of the design. Based on the design and analyzes, a selection of the materials for the FDS-III reactor and related auxiliary systems has been performed with indication of further R&D needs.

1. Introduction

Hydrogen is one of the cleanest energies which can be utilized without greenhouse gas emission compared to fossil fuel, and can be stored and transported over long distance with lower loss than others. It will be demanded greatly with development of hydrogen application [1]. However, operation temperature for high efficient hydrogen production is required to be above 900 °C with iodine–sulfur (I–S) process. Fusion reactor is an attractive way to achieve around 1000 °C of coolant outlet temperature suitable for hydrogen production [2–8].

Based on the current status or promising extrapolation of material technology and a series of fusion reactor conceptual designs [9–12], which have been developed by the FDS Team in China, including the fusion-driven sub-critical reactor (FDS-I), the fusion power reactor (FDS-II), the spherical tokamak-based compact reactor (FDS-ST), in order to obtain the high temperature for the efficient production of hydrogen, a fusion-based hydrogen production reactor, named FDS-III, is proposed and designed.

In this paper, the conceptual design and related analyzes for the FDS-III reactor are presented, including the selection of the materials and related auxiliary systems have been performed with indication of the further R&D needs in the future.

2. Fusion core engineering

2.1. Plasma core

A set of main plasma parameters of FDS-III, listed in Table 1, including the fusion power of 2500–3000 MW with the neutron wall load of ~4 MW/m^2 and surface heat load ~1 MW/m^2, is designed on the basis of advanced operation mode of plasma core with the SYSCODE code [13], which is developed by FDS team, and optimized by the MHD equilibrium calculation with the EFIT equilibrium code [14]. Fig. 1 shows the magnetic configuration, the profiles of current density and plasma pressure in FDS-III.

2.2. Reactor configuration

Fig. 2 shows the configuration of FDS-III with 16 large toroidal coils and 16 large horizontal ports for convenient and fast maintenance [15]. The in-vessel blanket design adopts combined module blanket, which is to reduce the thermal stress and electric–magnetic force caused by plasma disruption, and banana segment, which is to quicken the replacement to improve efficiency of maintenance. Each outboard banana segment of 22.5° is integrated with 12 modules (4 poloidal × 3 toroidal) and one outboard high temperature shielding with the installation of the coolant manifold feeding blanket modules. Each inboard banana segment of 22.5° is integrated with 8 modules (4 poloidal × 2 toroidal).

2.3. HTL blanket module

On the basis of relatively mature material technologies and even conservative extrapolation, a coolant outlet temperature of

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Table 1
Basic parameters of FDS-III reactor.

Major radius	R[m]	5.10
Minor radius	a[m]	1.70
Aspect ratio	A	3.00
Plasma current	I_P[MA]	16.00
Toroidal field	B_0[T]	8.00
Elongation	κ	1.90
Triangularity	δ	0.53
Safe factor	q	8.03
Edge safe factor	q_{95}	3.30
Toroidal β	β_T[%]	5.65
Poloidal β	β_P	1.88
Normalized β	β_N	4.80
Average density	$<n_e>[10^{20}\ m^{-3}]$	1.00
Average temperature	<Te>[KeV]	10.00
Bootstrap current fraction	f_b	0.65
Fusion power	P_{fu}[MW]	2600
Drive power	P_d[MW]	20

1000 °C in the HTL blanket is required. In the blanket module, the mature reduced activation ferritic/martensitic (RAFM) steel is adopted as the structural material and helium gas and LiPb acts as the coolants for structure and the self-cooled breeder, respectively. There is a remarkable feature that the multi-layer flow channel inserts (MFCI) as function component are put into the breeding zone to reduce the temperature gradient of FCI and achieve the LiPb outlet temperature of around 1000 °C.

Fig. 3 shows the structure and LiPb flow scheme of the HTL outboard blanket module (2.12 m Pol. × 0.91 m Tor. × 0.64 m Rad.) in the equatorial port region. It is enclosed by first wall of U-shape, covers, and back plates. The radial-poloidal stiffening plate (rpSP) provides strong strength inside box, and divides box into two breeder zones in toroidal direction. The breeder zone is configured three concentric LiPb channels by MFCIs. The ribs between layers of FCI are employed to provide restrictions and support for the MFCIs to form concentric LiPb channels. The three layer concentric

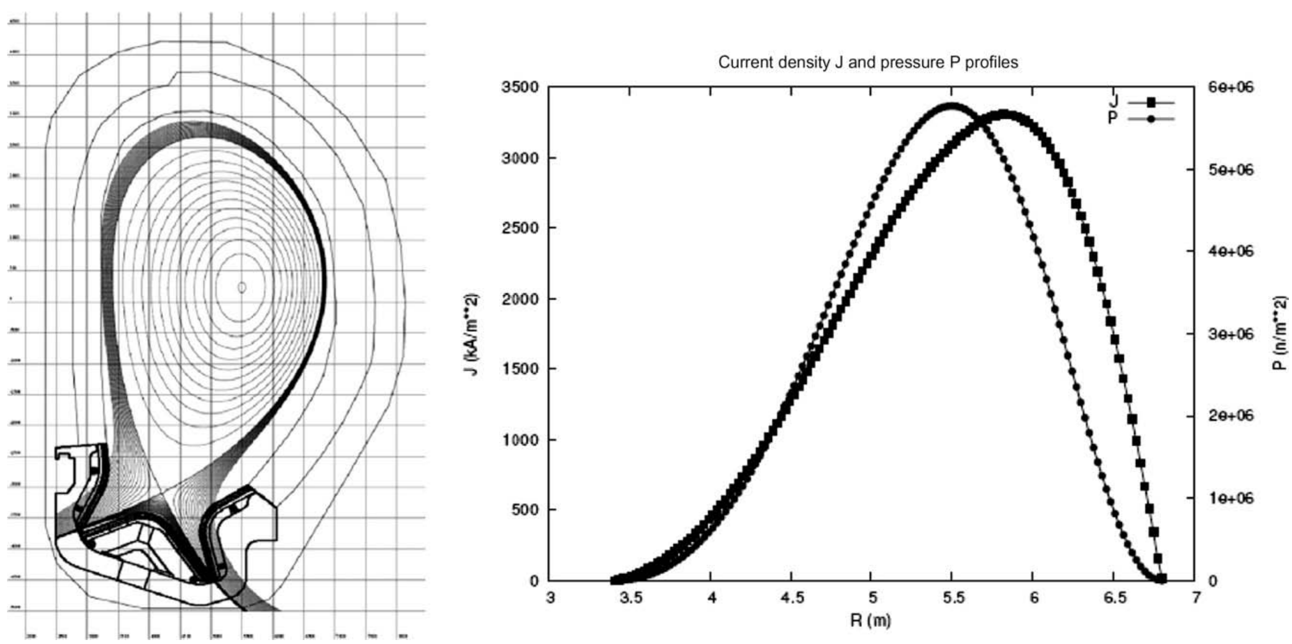

Fig. 1. Magnetic configuration and profiles of current density and plasma pressure.

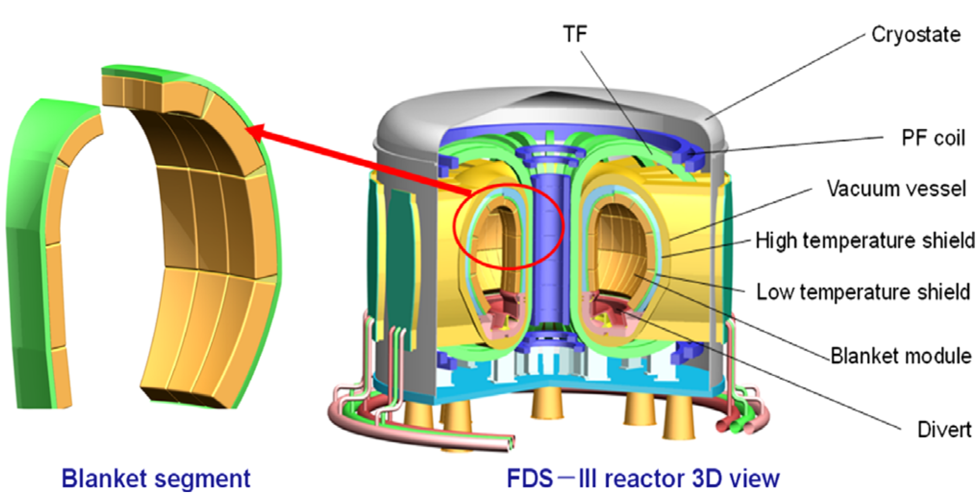

Fig. 2. Configuration of FDS-III reactor.

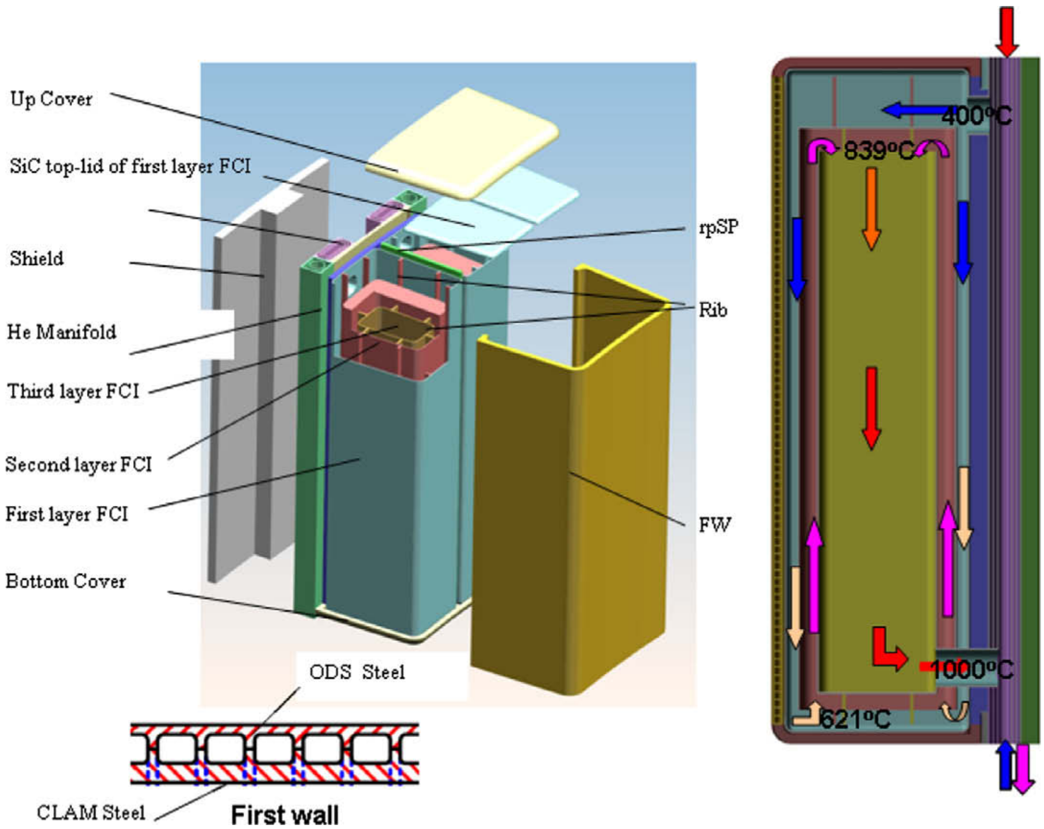

Fig. 3. HTL blanket module structure and LiPb flow scheme.

Table 2
Design parameters of HTL blanket.

Neutron wall load (MWm^{-2})		~4
FW surface heat load (MWm^{-2})		~1.04
FW channel	mm^2	18 × 20
	T_{in}/T_{out} (°C)	350/366.5
	V_{He} (m/s)	100
Cover channel	mm^2	12 × 18
	T_{in}/T_{out} (°C)	350/368
	V_{He} (m/s)	88
Radial-poloidal stiffening plate channel	mm^2	7 × 14
	T_{in}/T_{out} (°C)	350/363.5
	V_{He} (m/s)	81
Helium pressure (MPa)		8
	$T_{LiPb\ in}/T_{LiPb\ out}$ (°C)	400/1000
	LL1 $V_{LiPb\ 1}$ (m/s)	0.041
	LL2 $V_{LiPb\ 2}$ (m/s)	0.028
	LL3 $V_{LiPb\ 3}$ (m/s)	0.030

manifold couples three concentric LiPb channels inside module. Outer layer of pipe adopts RAFM steel, the other layers are SiC material. The design parameters of blanket module are listed in Table 2.

The 400 °C LiPb feeds into module from outside pipe of manifold, then flows in series in outside, middle, and inside FCI channel, and finally, about 1000 °C LiPb flows out of module into the inner pipe of manifold. The flowing LiPb in the intermediate pipe of the manifold is only circulated to reduce temperature gradient between outer and inner layers pipes.

2.4. Divertor

Since the divertor geometry should match the MHD equilibrium shown in Fig. 1, the preliminary divertor design for FDS-III is carried out and the basic structure, shown in Fig. 4, similar to that of ITER using "vertical targets" [16] mainly consists of inner target plate, outer target, dome, baffles, and cassettes. The oxide dispersion strengthened (ODS) RAFM steel is used as structure and LiPb as coolant. The target using 3 mm W tiles as armor should be capable of handling peak heat flux of 10 MW/m^2.

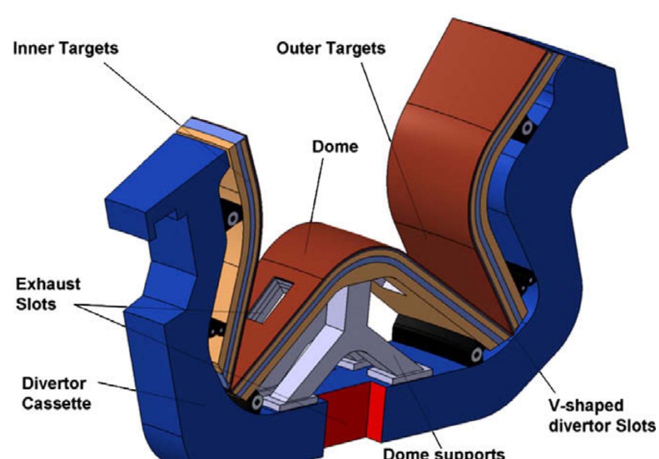

Fig. 4. Structure of divertor module.

3. Performance assessment

The feasibility of the FDS-III design has been preliminarily validated with a series of performance analyzes which cover neutron-

Table 3
Main performance parameters for HTL blanket compared to DFLL-TBM.

		FDS-III/ HTL	DFLL-TBM (DLL)
Fusion power (MW)		2600	500
Neutron wall Load (MW/m^2)		~4	0.78
FW surface heat flux (MW/m^2)		~1.04(Ave.)	0.3(Ave.)/ 0.5(Max.)
LiPb	Pressure (MPa)	1	1
	T_{in}/T_{out} (°C)	400/1000	480/700
	Max. velocity inside blanket (m/s)	0.041	0.014
He	Pressure (MPa)	8	8
	T_{in}/T_{out} (°C)	350/365	340/402
	Max. velocity inside blanket (m/s)	100	64
Max. structural temperature (°C)		635	534
Max. structural von mises stress (MPa)		379	234
Max. FCI temperature (°C)		948	583
Max. FCI von mises stress (MPa)		67	103

ics analysis, thermal-hydraulics analysis including MHD effects of liquid metal flow, thermo-mechanics analysis and tritium permeation analysis on the basis of 2D/3D real models and theoretic calculation. In the preliminary results, it is shown that the design can satisfy the requirements of the materials, environment safety and tritium self-sufficiency. With the comparison of Chinese ITER DFLL-TBM [17], the main performance parameters for the HTL blanket are listed in the Table 3 and the details can be found in Ref. [11].

4. Material selection

4.1. Structure material

RAFM steel is attractive and has been thought to be a primary candidate structural material for first generation fusion power plant (FPP) due to good swelling resistance to neutron irradiation, higher thermal conductivity and good compatibility with breeding material (e.g. eutectic LiPb) [18]. However, its operating temperature is low so as to limit the coolant outlet temperature and the capability resisting high heat flux from plasma. To combine the attractiveness of breeding blanket with RAFM steels as structure material, for example, the CLAM steel [19] is considered to be used as the main structure material for FDS-III, the ODS RAFM steel was proposed as advanced fusion structural material to be applied to the front wall of the FW to improve the capacity resisting high heat flux from plasma side. So the further R&D issues should be focused on the performance properties of ODS RAFM, and also the fabrication of RAFM and ODS RAFM.

4.2. FCI material

Flow channel insert (FCI) has been adopted in the LiPb blanket [12,20–22] to act as the electrical and thermal insulating layer to reduce MHD effect and to elevate the outlet temperature of LiPb. SiC_f/SiC composite is considered as the first candidate material of FCI due to the good performance at the high temperature, the good compatibility with LiPb and so on. The properties for SiC_f/SiC FCI materials are required to have low transverse thermal and electrical conductivities, such as less than 2–20 W/mK and 5–500 $(\Omega m)^{-1}$ respectively. However, with the development of SiC_f/SiC composite material, the more difficult challenges, which involves thermal conductivity degradation under irradiation, bending strength reduction and enhanced swelling at the higher operational temperature, insufficient hermetic sealing capability, and fabrication/joining technique etc. [23], have to be faced. At present, the R&D activities on SiC_f/SiC composite are mainly focused on the characterization of these composites before and after irradiation in the range of the operating temperature (600–1000 °C), chemical compatibility with LiPb, and their fabrication and joining ability.

4.3. Coating material

The coating, one key material in blanket design, can serve as tritium barriers to reduce tritium permeation, as electrical insulator to mitigate MHD effect and as corrosion barriers to reduce corrosion of structural steel especially under high temperature and neutron irradiation conditions. The Al_2O_3 coating would be considered in all the coolant channels inside blanket and all the pipes in the auxiliary system to be the permeation barriers to decrease the tritium and hydrogen inter-contamination between FDS-III fusion reactor and H-production system. The TPRF (tritium permeation reduction factor) would reach 1000 for a 50 μm layer referencing in the auxiliary system and usually from 1 to 70 inside the blanket [24]. However, sufficient lifetime under irradiation for these barriers has not been demonstrated. In addition, the coating chemical compatibility with the flowing LiPb and the substrate wall steel and also the thermodynamical stability will be concerned in the condition of high temperature and high neutron irradiation.

4.4. Divertor material

The material of divertor must meet the requirement of high resistance against high heat flux and sputtering, high thermal conductivity, low activation and high strength. Due to the advantage of high resistance against sputtering, good thermo-physical properties, high melting point, and high heat conductivity, etc. [25], the tungsten is preferred the armor material for the LiPb cooling divertor of FDS-III. The ODS RAFM steel, with low activation, high swelling resistance to neutron irradiation, good compatibility with LiPb and good operating temperature, can be used as the structure and support material. Therefore, the compatibility between tungsten and LiPb needs to be considered as one issue of R&Ds.

4.5. Heat exchanger material

Since the high temperature heat exchanger (HTHE) for the coolant circulation system in FDS-III will operate in the temperature of ~1000 °C, the refractory metals (e.g. W, Nb, Ta, etc.), high temperature alloy (e.g. ODS-FeCrAl), ceramic (e.g. SiC) and ceramic matrix composite (CMC) materials (e.g. SiC_f/SiC composites), might be the most potential candidate of the structural materials for this heat exchanger with the high temperature, harsh and aggressive corrosive environments encountered. However, the refractory metals have no sufficient oxidation properties at very high temperature [26] due to the high temperature alloy has critical issues of melting point, high temperature oxidation and high temperature creep, etc. An obvious disadvantage of ceramic materials with better high temperature properties is the inherent brittleness to make the fabrication difficult. With the attractive high temperature strength and thermal characteristics, CMC, which has been used for gas–gas high temperature heat exchanger conceptual design in 500–1000 °C [27], can be regarded as the potential structural material in the future, but its fabrication technology with high cost is not mature at present [28]. Moreover, a ceramic plate-fin heat exchanger based on the offset strip fin (OSF) design was presented in Ref. [29]. It can be used for the high temperature heat exchanger in the externally fired combined cycle (EFCC) or other applications that need operational material temperatures up to 1250 °C. Based on investigation for HTHE, the SiC ceramic and SiC_f/SiC composites were preferred as the structural material for the heat exchange of FDS-III.

4.6. Component material for hydrogen production

I–S thermo-chemical cycle is recommended for the hydrogen production process for FDS-III so as to induce the aggressive corrosive chemical environment of H_2SO_4, HI, and I_2 at high temperature of 950–1000 °C. Hence, the material for this process should be carefully chosen to resist corrosion. In Japan, the corrosion tests for material have been carried out and it is found out that the refractory alloy, such as Hastelloy, represented the corrosion resistance in gas phase environments and the special material, e.g., ceramic (SiC, etc.), and rare metals (Zr, Ta, etc.) represented the resistance to corrosion [30,31]. Therefore, the SiC ceramics can be used for the components in contact with the process fluid at high temperature in hydrogen process of FDS-III, and, in order to reduce the cost, the carbon steel may be applied in other parts as much as possible.

5. Summary

The FDS-III reactor, aiming at obtaining high temperature (~1000 °C) for efficient production of hydrogen, has been designed based on the advanced level of plasma physics and the adoption of novel high temperature blanket design with MFCIs in lithium–lead channels. The detailed design of plasma core, reactor configuration, blanket and divertor structures have been presented. The analyzes of the plasma physics, neutronics, thermal-hydraulics, thermo-mechanics and tritium permeation have been performed to assess the feasibility of the design which is based on hopefully achievable material technology. Several materials systems, which have the potential to meet the demanding operating conditions of FDS-III, have been identified, including structural material, FCI material, coating material, divertor material, high temperature heat exchanger material and component material for hydrogen production, etc. The critical issues of necessary R&D have been specified.

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