The Fusion-Fission Hybrid Reactor for Energy Production: A Practical Path to Fusion Application

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Abstract. The fusion-fission hybrid system has the potential attractiveness of good safety performances and plenty of fuel compared to the fission reactor system and also easing the requirement of fusion plasma technology. It is a practical path to the early fusion application for energy production. In this paper, a fusion-driven subcritical reactor for energy multiplier, named FDS-EM, is proposed. It can generate about an electricity power of ~1.2 GW with self-sustaining tritium cycle. The tokamak can be designed based on relatively easy-achieved plasma parameters extrapolated from the operation of the EAST tokamak, and the subcritical blanket can be designed based on the well-developed technology of pressurized water reactor. The conceptual design of FDS-EM, which consists of fusion plasma core parameters design and optimization, fission blanket and fuel cycle, and reference blanket module design, has been presented. And the preliminary performance analyses covering neutronics, thermal-hydraulics and thermo-mechanics have been carried out.

Key words: Fusion; Blanket; Hybrid reactor; Energy production

1 Introduction

Although the recent experiments and associated theoretical studies of fusion energy development have demonstrated the feasibility of fusion power, there will still be a long way to realize fusion energy application. Some countries, e.g. China, are speeding up the development of their fission industry, however, the shortage of fissile fuel and the trouble of safety and radioactive wastes will be faced.

The fusion-fission hybrid systems/reactors have the potential attractiveness of good safety performances and plenty of fuel and easing the requirement of fusion plasma technology (with a low fusion gain Q) and plasma-facing material technology (with a low neutron wall loading). As an intermediate step between fission energy application and fusion energy application, the fusion-fission hybrid reactors can be further utilized as a neutron source for R&D of fusion reactor itself.

Since 1986, many studies on the fusion-fission hybrid reactors have been performed to evaluate the feasibility and attractiveness of the hybrid systems for transmutation of nuclear wastes and breeding of fissile fuel [1~11]. Along with the achieved and ongoing efforts to establish fusion an energy source, there is a renewed interest in fusion-fission hybrid reactor for energy production, especially based on the progress in the construction and operation of the EAST in China [12] and the ITER [13].

This contribution proposes a practical path to the early fusion application for energy production in a sub-critical reactor, which is based on available fusion technologies (the level extrapolated from the operation of the EAST tokamak) and mature fission reactor technologies such as PWR (Pressurized Water Reactor) technology.

2 Fusion plasma core

The fusion-driven subcritical system for energy production named FDS-EM (Energy Multiplier), as one of the series FDS fusion reactor concepts [14-17], can generate about an electricity power of ~1.2GW with self-sustaining tritium cycle, which is driven by a tokamak core of the fusion power of ~50MW. The tokamak can be designed based on relatively easy-achieved plasma parameters extrapolated from the operation of the EAST tokamak considering the progress in recent experiments and associated theoretical studies of magnetic confinement fusion plasma.

A set of reference plasma parameters of FDS-EM is selected by using SYSCODE code [18], which is developed by FDS Team, and optimized in the MHD equilibrium calculation using EFIT equilibrium code [19]. FIG.1 shows the magnetic configuration, the profiles of current density and plasma pressure of FDS-EM. The main plasma parameters of FDS-EM are listed in TABLE Ⅰ, as well as the parameters of the EAST and ITER for purpose of comparison.

TABLE Ⅰ: THE CORE PARAMETERS OF FDS-EM, EAST AND ITER.

Parameters	Design		
	FDS-EM	EAST	ITER
Major radius(m)	4	1.7	6.2
Minor radius(m)	1	0.4	2.0
Aspect ratio	4	4.25	3.1
Plasma elongation	1.7	1.7	1.85
Triangularity	0.45	0.6	0.33
Toroidal magnetic field on axis (T)	5.1	3.5	5.3
Fusion power(MW)	49.26	/	500
Plasma current(MA)	6.1	1	15
Neutron wall loading(MW/m^2)	0.17	/	0.57
Fusion gain	0.95	/	⩾5

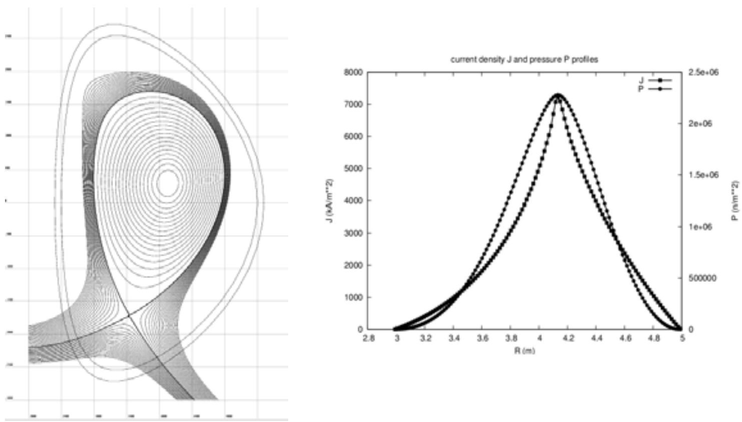

FIG. 1 Magnetic configuration and profiles of current density and plasma pressure

3 Blanket concept and reference module design

3.1 Fission blanket and fuel cycle

The general design of the FDS-EM is to have the subcritical blanket which interacts with a copious source of fusion neutrons provided by the fusion core to achieve tritium breeding and energy multiplication on the basis of the fission and fusion fuel cycle. The blanket system has been designed based on the well-developed technologies of pressurized water reactor. Besides the shielding modules, two types of functional blanket modules i.e. tritium breeding module (TBM) and fission energy production module (EPM) are designed, respectively, for the inner board, which is only designated to breed tritium, and the outer board, which is designated to produce energy with fission materials.

The low activation ferritic-martensitic steel (RAFM) is considered as a candidate structural material because of its good performance in the highly corrosive and radiative environment. The fission materials in the blanket of EPM compose of depleted uranium as the fissile fuel breeding material and plutonium isotopes as neutron multiplier with long-lived Minor Actinides (MA), i.e. ^{237}Np.^{241}Am, ^{243}Am, ^{244}Cm, together as a fuel package complying with the composition of the spent fuel directly unloaded from the commercial fission power plants (e.g. PWR) so as to escape the hard separation process of those isotopes. The fuel form of dioxide is adopted to palliate the reprocessing technology of the spent fuel. And the light water is served as the coolant as well as the neutron moderator for the outer board. LiPb in breeding-zones severs not only as tritium breeder but also as coolant by itself. Pb is also a kind of neutron multiplier. The reference module, basic material compositions and radial configuration is shown in FIG. 2 and TABLE Ⅱ.

The main design objectives of the blanket are to achieve the balance of possible fuel support and to keep the blanket system operating for a long time such as 5 years, without fuel loading and unloading. In this design, homogeneous fissile core is considered as the reference core design concept. The blanket electric power is set to about 1.2 GW in order to obtain about a net power of 1.0 GW considering the consumption of pumping power, heating power and the power for other auxiliary systems. The total heat power is assigned to about 3.5~4.5 GW with the thermal efficiency ~33% using water as the coolant. The energy multiplication factor (EM) in the subcritical blanket is expected to be 70~90.

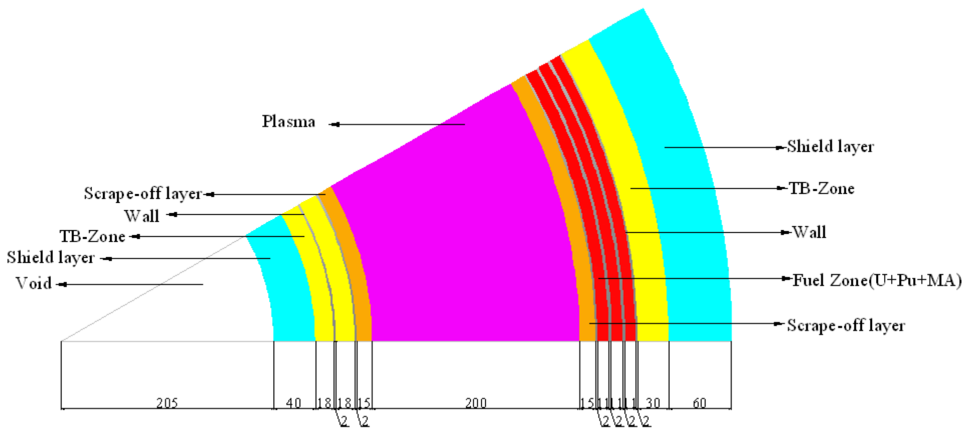

FIG. 2 Radial configuration of FDS-EM

TABLEⅡ: ATERIAL COMPOSITIONS AND RADIAL SIZES OF FDS-EM

Zones	Material component (%)	Thickness (cm)
Inboard blanket		
FW	RAFM steel (50) +H_2O (50)	2
Tritium breeding zone	LiPb (^{6}Li:90%) (100)	18×2
Structural walls	RAFM steel (50) +H_2O (50)	2
Shield layer	RAFM steel (50) +H_2O (50)	40
Outboard blanket		
FW	RAFM steel (50) +H_2O (50)	2
Fuel zone1/2/3	UO_2 (43.31)+PuO_2 (14.9)+MAO_2 (1.79)+Zr (10)+H_2O (30)	11×3
Structural walls	RAFM steel (50) +H_2O (50)	2×3
Tritium breeding zone	LiPb (^{6}Li:90%) (100)	30
Shield layer	RAFM steel (50) +H_2O (50)	60

3.2 Blanket reference module design

FDS-EM blanket is a fusion driven hybrid blanket for energy production by fission fuel and breeding tritium by breeder material. It is designed considering the availability of the current PWR technology [20-21] and feasibility of tritium breeding blanket technology for early application [11].

FDS-EM blanket as shown in FIG.3 features a banana type module of 7.5 degree section angle, closed by steel wall and internally supported by stiffening plate, using promising RAFM steel e.g. the CLAM (China Low Activation Martensitic) steel [22] as structure material. It is divided into the thick first wall (FW) containing coolant tube bundles, fission fuel zone, thick stiffening plate (SP) containing coolant tube bundles and tritium breeding zone in radial direction. The circle tubes lead coolant water flowing down. The coolant water collects at bottom, and then feeds into fission fuel zone cooling fuel assemblies. The entire structure design with FW, side wall (SW), and stiffening plate may sustain 15.5 MPa water coolant pressure.

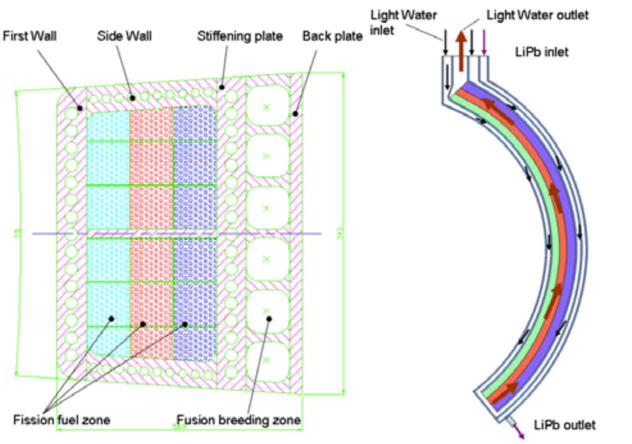

FIG.3 Schematic view of EM outboard blanket

The LiPb serves as tritium breeder and coolant which self-cools the breeding zone in six channels parallelly at the rear of blanket. The LiPb is fed into blanket from the top of the blanket and flow out at the bottom. This scheme can easily empty LiPb in an accident by gravity. The coating in the LiPb chaneel is employed to mitigate MHD pressure drop and reduce tritium permeation.

4. Preliminary performance analyses

4.1 Neutronics analysis

The main purpose of neutronics design and analysis is to optimize the composition and spatial arrange in the functional zones and the fuel cycle to achieve tritium self-sufficiency, sufficient energy gain and enough safety margin in the normal operation and all transient events. The main neutronics constraints and objectives of FDS-EM blanket are listed in TABLE Ⅲ, where the units of UPWRx is defined as the equivalent amount of identified x-isotopes from the spent fuel at the burnup of 33,000MWD/MTU from a standard 3000MW PWR in a full power year.

TABLE Ⅲ: MAIN CONSTRAINTS AND OBJECTIVES OF NEUTRONICS DESIGN PARAMETERS

Items	constraints and objectives
Keff	≤ 0.95 (safety margin limit)
Pd_{max}(MW/m^3)	≤ 100 (cooling capability limit)
TBR	≥ 1.05 (tritium sustainability limit)
Energy multiplication	70~90
Fuel initial loading balance	To keep equivalence of loaded Pu, MA in the unit UPWR
Fuel cycle	To operate for 5 years without fuel loading and uploading

To evaluate and optimize the performances of the blanket system, the neutronics calculations have been performed with the code VisualBUS [23] and the multigroup Hybrid Evaluated Nuclear Data Library (HENDL) [24]. The time-dependant fuel loading and cycling are preliminarily optimized based on the 1D geometrical model.

A set of preliminarily optimized paramemeters presented in TABLE Ⅳ show a set of reference parameters of the blanket system which can operate for 5 years without fuel loading and unloading. This system can achieve fuel burnup of 51,933 MWD/T(HM), the same magnitude as that of commercial PWR[25]. The highest effective multiplication factor of 0.932 can meet the design limit of less than 0.95. The mean energy multiplication can be 79, which means the system can obtain the electricity power of 1.2 GW. The calculation results show that the preliminary blanket concept design can meet the requirements of tritium self-sufficiency and the sufficient energy multiplication.

TABLE Ⅳ: MAIN NEUTRONICS PARAMETERS FOR FDS-EM

Burnup (year)	**Inventories**			K_{eff}	P_{th} (GW)	**Energy multiplication**	**Max power density** (W/cm^3)	**TBR**
	U (kg)	**Pu** (UPWR)	**MA** (UPWR)					
0	504144	592	592	0.932	4.52	90	53.8	1.34
1	/	/	/	0.927	4.23	85	50.9	1.25
2	/	/	/	0.924	4.01	80	48.8	1.19
3	/	/	/	0.920	3.84	76	47.1	1.14
4	/	/	/	0.917	3.69	74	45.7	1.10
5	/	/	/	0.914	3.56	72	44.4	1.06
Mean	/	/	/	/	3.96	79	/	1.18

4.2 Thermal-hydraulics analysis

Thermal-hydraulics analysis of FDS-EM blanket is performed based on the design requirement limits of structural material and coolant. The vaporizing temperature for the water coolant is 345°C at 15.5MPa. The lower operation temperature of RAFM steel is 200~300°C, owing to the low temperature irradiation-induced hardening and embrittlement effects. And the highest operation temperature of RAFM steel is 550 °C.

In this analysis, the operation pressure is selected as 15.5MPa, corresponding to the system coolant pressure of commercial PWRs, e.g., Chinese Dayawan PWR [26]. The coolant velocity in fission zone is designed to be 4.9m/s in the fuel assembly. The outlet temperature of water coolant in fission zone is assumed to be 328 °C lower than vaporizing temperature. The inlet and outlet temperature of LiPb in breeding zone are designed 300 °C and 500 °C, respectively.

The thermal-hydraulics parameters are summarized in TABLE Ⅴ.

TABLE Ⅴ: THE THERMAL-HYDRAULICS PARAMETERS FOR EM BLANKET

	Parameters
Fission zone	
Coolant	Water
Operation pressure	15.5MPa
Velocity	4.9m/s
Flow rate	280kg/s
Inlet temperature	291°C
Outlet temperature	328°C
Hydraulics loss	0.7MPa
Max. temp. on cladding shell of rod	338.5°C
Fusion Zone	
Coolant	LiPb
LiPb velocity	0.14m/s
MHD pressure drop	0.002MPa
Inlet temperature	300°C
Outlet temperature	500°C

4.3 Thermo-mechanics analysis

The calculations and analyses of thermal-stress of the FDS-EM blanket module have been carried out based on 2D finite element model by using commercial finite element code ANSYS. The thermal and stress distributions are shown in FIG. 6. The maximum temperature of first wall is 429°C, lower than the highest operation temperature limit of RAFM steel. The maximum thermal stress is 382MPa, satisfying 3Sm criteria of structure material.

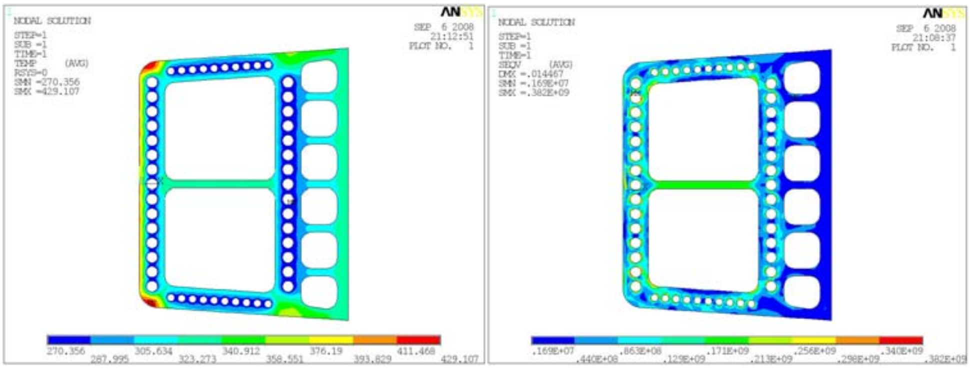

FIG. 6 Distributions of temperature (Left) and stress（Right）of FDS-EM blanket

5. Summary

A fusion-fission hybrid reactor concept for energy production is proposed based on relatively easy-achieved plasma parameters conservatively extrapolated from the plasma conditions of EAST and the realizable technology of PWR. The conceptual design of FDS-EM, which consists of fusion plasma core parameters design and optimization, fission blanket and fuel cycle, and reference blanket module design, has been performed. The preliminary performance analyses covering neutronics, thermal-hydraulics and thermo-mechanics have been carried out showing that the conceptual design can meet the requirements of tritium self-sufficiency, sufficient energy gain, and structrual material requirement. The further economics analysis, compared with the pure fusion system and the pure fission PWR, and enviroment and safe assessment will be carried out in the next step.

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