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Progress in Conceptual Study of China Fusion-Based Hydrogen Production Reactor

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Abstract:
As one of the series of fusion system design concepts developed by the FDS Team of China, Fusion-Based Hydrogen Production Reactor (named FDS-III) is a competitive reactor concept with the neutron wall load of ~4MW/m^2, the surface heat flux of ~1.04MW/m^2, and fusion power of ~2600MW. FDS-III concept features high core parameters, banana segment blanket combining module to reduce impact of electromagnetic force, and big maintenance port to increase availability. A novel high temperature liquid lithium–lead blanket (HTL) module concept, which installs multilayer flow channel inserts and uses the Reduced Activation Ferritic-Martensitic steel (RAFM) steel as main structural material, is presented as one of blanket candidate concepts aimed for obtaining coolant outlet temperature of ~1000 ^{o}C for hydrogen production. The high temperature steam electrolysis (HTSE) as one option is chose for hydrogen production, which coupled FDS-III fusion reactor using a Brayton helium gas turbine closed cycle with high power conversion efficiency of 54%, and hydrogen production efficiency of 55%. This paper reports the progress in the study of FDS-III.

1. Introduction

Hydrogen is thought to be one of the best and cleanest energies which can be utilized without greenhouse gas emission compared to fossil fuel, and be stored and transported over long distance with lower loss compared to electricity. It will be demanded greatly with development of hydrogen application [1]. The advanced gas-cooled reactor (the coolant outlet temperature 800-1000^{o}C), molten-salt-cooled reactor (500-800 ^{o}C) and liquid-metal-cooled reactor (550^{o}C) technologies have been studied for more efficient thermochemical and electrochemical hydrogen production, which need high temperature in EU, JAPAN, US, etc. [2, 3]

Fusion reactor is another alternative nuclear reactor technology to achieve high temperature for hydrogen production. The U.S ARIES-AT and the EU PPCS-D had been developed as an advanced high temperature fusion reactor with liquid lithium lead blanket concepts, which feature a simple low-pressure SiC composite concentric structure using LiPb as coolant to achieve coolant outlet temperature of 1100 ^{o}C being suitable hydrogen production.[4, 5]

A series of fusion reactor concepts [6, 10] has been developed by FDS (Fusion Design Study) 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 progressively assess the feasibility and the advanced performances considering the different levels (e.g. low, middle, and high level) of technological development, a series of liquid LiPb tritium breeder blanket [11] using China Low Activation Martensitic steel (CLAM)[12] as structure material has being developed, including the He/LiPb dual-cooled high level waste transmutation (DWT) blanket for FDS-I[13], the He single-cooled LiPb tritium breeder (SLL) blanket (~450^{o}C coolant outlet temperature) and the He/LiPb dual-cooled (DLL) and blanket(~700^{o}C coolant outlet temperature) for FDS-II [14, 15]. Based on these studies, the Fusion-based hydrogen production reactor, which named FDS-III as one of FDS series, has been studying to explore the advanced fusion technology. This paper reports the preliminary progress in FDS-III reactor study, including description of FDS-III reactor, high temperature (~1000 ^{o}C) blanket scheme, and hydrogen production circle process with the Braton power conversion system.

2. Design Guideline

Objectives and requirements of developing FDS-III are defined as following:

a) The coolant temperature of approximate 1000 ^{o}C for hydrogen production based on relative mature technologies and extrapolation.
b) 2600MW fusion power with high power density, high neutron wall load of ~4MW/m^2.
c) Applying advanced operation mode of plasma core via adding fraction of bootstrap current and reducing self-consuming power of reactor.
d) High thermal conversion efficiency using high temperature gas turbine.
e) Reactor configuration allowing higher maintenance efficiency to reduce reactor planned shutdown time.
f) High safety and environmental merits.

Based on these objectives and requirements, the following design principles and approaches are defined.

a) The reactor torus is divided into 16 sectors with big equatorial port to easily access and remove in-vessel components.
b) The blanket integrates the features of both module blanket and banana segment. The module can reduce electromagnetic force impact on structure. The banana segment can significantly enhance maintenance efficiency.
c) Using dual coolant blanket concept, i.e. He gas cooling structure, LiPb serving as breeder self-cooled breeding zone.
d) Using one kind of multi-layer SiC/SiC$_f$ flow channel inserts (MFCI) to reduce temperature grade of FCI to obtain high outlet temperature of LiPb without exceeding compatibility temperature between FCI material and LiPb, as well as without exceeding maximum permitted stress of SiC.
e) Reduced Activation Ferritic-Martensitic steel (RAFM) severing as main structural material and Oxide Dispersion Strengthened (ODS) ferritic steel severing as front wall material of the First Wall (FW).
f) Tritium breeder ratio higher than 1.1 to realize the self-sufficiency.

3. Plasma Core and configuration of FDS－III

3.1 Plasma Core Parameters

According to the design guidelines, a set of plasma physics and engineering parameter is selected by using SYSCODE [16] code developed by FDS Team and two-dimension (2D) fusion physical model and the MHD equilibrium calculation is performed by EFIT equilibrium code [17]. The basic plasma parameters are optimized in the MHD equilibrium calculation and the reasonable profile of current density and plasma pressure are obtained, as shown in Fig.1. The main parameters of FDS-III are listed in Table 1. Considering that the divertor geometry should match the MHD equilibrium obtained, the preliminary divertor scheme, shown in Fig.1, consists of inner target plate, outer target plate, dome, baffles and wing.

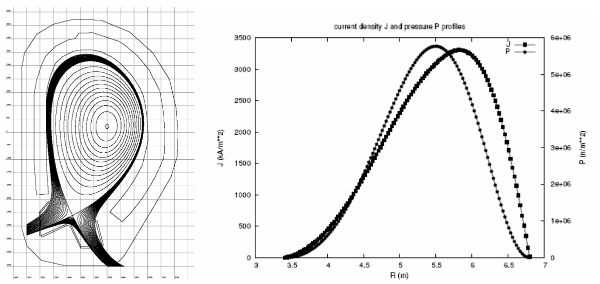


Fig. 1: The magnetic configuration and the profiles of current density and plasma pressure in FDS-III

Table 1: Basic parameters of FDS-III

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
Bootstrap current fraction	f_b	0.65
Fusion power	P_{fu}[MW]	2600

3.2 Configuration and Maintenance

Based on the investigation of the international fusion reactors aimed for faster maintenance, such as ARIES and CREST [18, 19], the FDS-III is designed for easy replacement of blankets and divertor. Full sector removal from horizontal ports is adopted in order to easily replace in-vessel components, to reduce time for planned shutdown time, and to improve efficiency of maintenance. Fig.2 shows the configuration of FDS-III with 16 large toroidal coils and 16 large horizontal maintenance ports. The increased cost, which is aroused by the increased size of both the TF and PF coil to have large space for maintenance port between the outer legs of the TF coil, can be compensated by the benefit of improved availability.

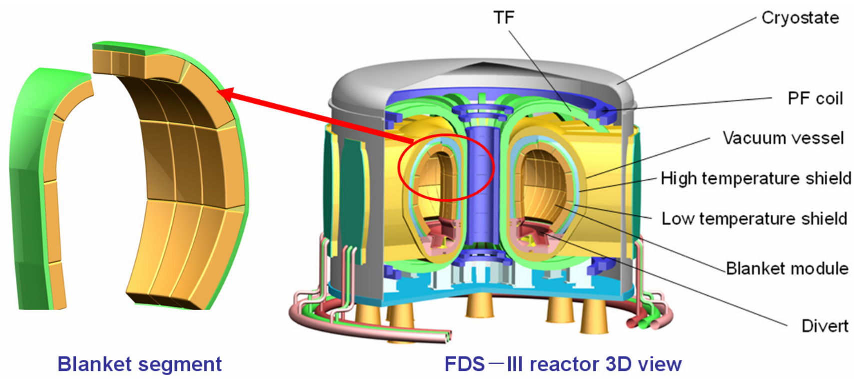


Fig. 2 The configuration of FDS-III

Considering reducing waste and cost, in-vessel components are divided according to components' lifetime. The blanket is short-life components to be planned for maintenance and replacement. The low temperature shielding is life-of-plant components. The high temperature shielding is intermediate lifetime.

The FDS-III blanket integrates the features of both module blanket and banana segment. The module can reduce thermal stress and impact of electromagnetic force caused by plasma disruption. The high temperature shielding as the banana segment can provide support with enough strength for modules and significantly enhance maintenance efficiency. Each outboard banana segment of 22.5 ^{o} is integrated by 12 modules (3 poloidal * 4 toroidal) and one outboard high temperature shielding. Each inboard banana segment of 22.5 ^{o} is integrated by 8 modules (2 poloidal * 4 toroidal). The coolant manifold feeding blanket modules is inserted in high temperature shielding.

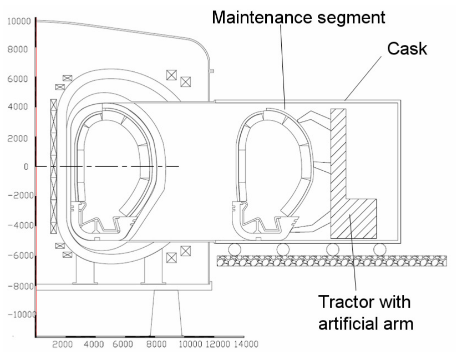


Fig. 3. Process of one maintenance unit removed by tractor in cask

The blanket segment and divertor may be integrated one maintenance unit of 22.5^{o}, Fig.3 presents the process of one unit removed after big transfer cask with tractor docks into the port: 1) opening the double seal door; 2) cutting and clearing all kind of pipes; 3) removing the out-door of vacuum to temporary parking area outside reactor; 4) removing the out low temperature shield to temporary parking area outside reactor; 5) drawing the maintenance unit out in-vessel and transfer to Hot Cell. The order of the installation process is reversed.

4．Blanket Module

4.1 Structure Feature

In FDS-III, the outboard blanket module in equatorial port zone is 7.5^{o} sector steel box which is enclosed by U-shape first wall (FW), covers, and back plate. The radial-poloidal stiffening plate (rpSP) provides strong strength inside box, and divides box into two breeder zones in toroidal direction. Its dimension is approximately 2.12m (Pol.) X 0.91mm (Tor.) X 0.64m (Rad.). Fig. 4 shows its exploded 3D view. The design parameters of blanket module are listed in Table 2

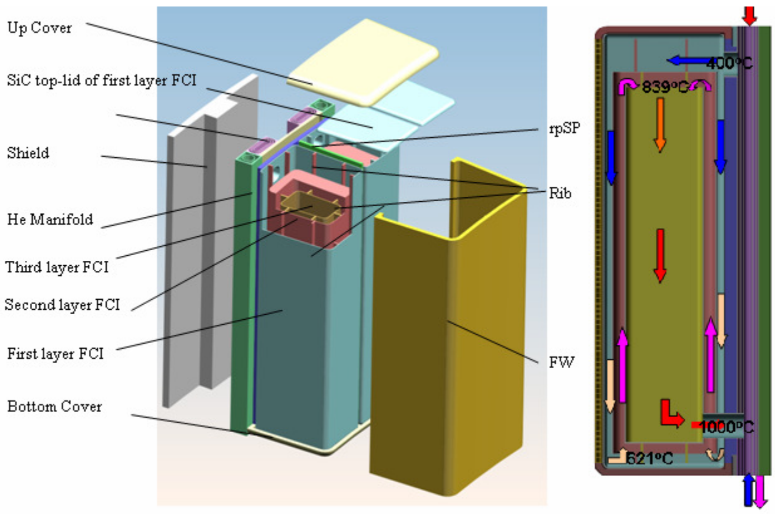


Fig. 4 FDS—III HTL blanket module structure (left) and LiPb flow scheme inside module (right)

The RAFM steel serves as material of main structure, including cover, back plate, rpSP, shields, and rear part of FW. The front wall of the FW adopt ODS steel to improve the capacity resisting high heat flux from plasma side.

One of the main features of FDS-III blanket is to use a kind of multi-layer SiC_f / SiC flow channel inserts (MFCI) as function component to reduce temperature gradient of FCI and obtain LiPb outlet temperature of around 1000 ^{o}C without exceeding compatibility temperature between FCI material and LiPb as well as maximum permitted stress of SiC. The breeder zone is configured three concentric LiPb channels by mutil-layer FCI. The ribs provide restrictions in toroidal and radial between layers of FCI forming LiPb channel. FCI may slide limited displacement in poloidal. The extended rib between first and second layer FCI can provide limited poloidal support. Another is to use the three layer concentric manifold to couple MFCI inside module. Outside layer (first layer) pipe adopt RAFM steel, the other layers pipes are SiC material.

Table 2. The design parameters of blanket module

Neutron wall load / MWm^{-2}	~4
FW surface heat load / MWm^{-2}	~1.04
FW channel: mm	18 X 20
T in / T out °C	350 / 366.5
V_{He} m/s	100
Cover channel: mm	12 X 18
T in / T out °C	350 / 368
V_{He} m/s	88
Radial-poloidal stiffening plate:	
mm	7 X 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
First layer FCI $V_{LiPb\ 1}$ m/s	0.041
Second layer FCI $V_{LiPb\ 2}$ m/s	0.028
Third layer FCI $V_{LiPb\ 3}$ m/s	0.030
LiPb pressure drop MPa	0.01

The scheme of LiPb flow is shown in Fig 4. LiPb of 400 °C from outside pipe of manifold feeds into the blanket module, and flows down from top to bottom in the first layer FCI; then turns up and flows from bottom to top in the second layer FCI; then again, turns down and flows in the third FCI from top to bottom, finally, LiPb of 1000 °C flow out the module into the inside pipe of manifold. The flowing LiPb in the intermediate pipe of the manifold is only circulated and provides intermediate zone to reduce temperature grade between outside and inside pipes. It is finally fed into divertor instead of feeding module.

He gas from cold leg of one concentric manifold in rear of module is fed in parallel into FW, cover, and back plate, and then flow back hot leg of another concentric manifold.

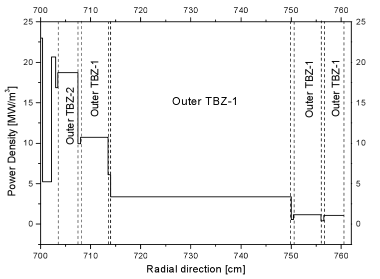
4.2 Neutronics analysis

Based on the 2D 22.5 degree torus sector model of FDS-III, neutronics calculations for nuclear heating, tritium breeding rate were preliminarily performed by using the Monte Carlo code MCNP [20] and nuclear data library FENDL2.1[21]. The tritium breeding ratio (TBR) by 90 % Li-6 enrichment in LiPb is approximately 1.38. The nuclear heating density distribution is presented in Fig.5.

4.3 Structure stress calculation

The calculations and analyses of thermal-stress for first wall of blanket module have been carried out based on 2D finite element model by using commercial finite element code

ANSYS. The thermal and stress distribution are shown in Fig 6. The maximum temperature of first wall is 635 ^{o}C and the maximum thermal stress is 379 MPa, satisfying performance requirement of first wall material.



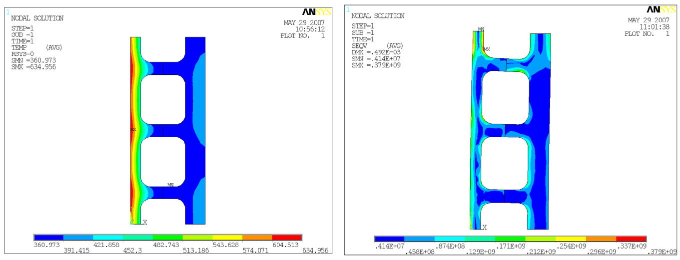


Fig.5 The nuclear heating density *Fig.6 Thermal and stress distribution at the First Wall*

5. FDS III-based Hydrogen Production Cycle

In the reference [2][22, 23], it is shown that the hydrogen production efficiencies of Iodin-sulfur cycle and HTSE are both above 50%, which is remarkably higher than the overall conversion efficiency from heat to electricity and to hydrogen. However, HTSE process shows its particularly advantages because there is no other chemicals involved in circulation except gases H_2O, O_2, and H_2, and it can benefit very high overall thermal-to-hydrogen efficiency when the power cycles of nuclear reactor has high efficiency. The HTSE hydrogen production process coupled to FDS-III is selected as alternative process whose schematic diagram is shown in Fig 7. This preliminary diagram consists of an indirect Brayton helium gas turbine cycle for power conversion and heat transfer loop to electrolysis stack. This intermediate helium loop can also serve as isolate loop preventing the tritium and hydrogen from permeating between reactor system and hydrogen production system.

In power conversion system, the operating pressure at inlet of helium turbine is chosen as 15 MPa. The reference [24] thought helium Braton system components may reach higher efficiencies; system pressure loss is lower under high helium pressure. Some key assumed parameters of power conversion system are listed in Table 3. The power conversion efficiency of approximately 54% can be obtained by formulation (1) [25].

In the reference [26], it is shown that when the electrolysis stack operates at 1 voltage and 973 ^{o}C, the total energy required for steam electrolysis , ΔH, is 248 kJ/mol, and the sum of the electrical energy demanded (Gibbs free energy change) for producing a unit amount of hydrogen within the electrolysis process, ΔG, is 194 kJ/mol. The energy loss is assumed to be accounted for 2% initially supplying heat. According to power conversion efficiency of FDS-III, the thermal-hydrogen production efficiency of approximately 55% can be obtained using formulation (2) .

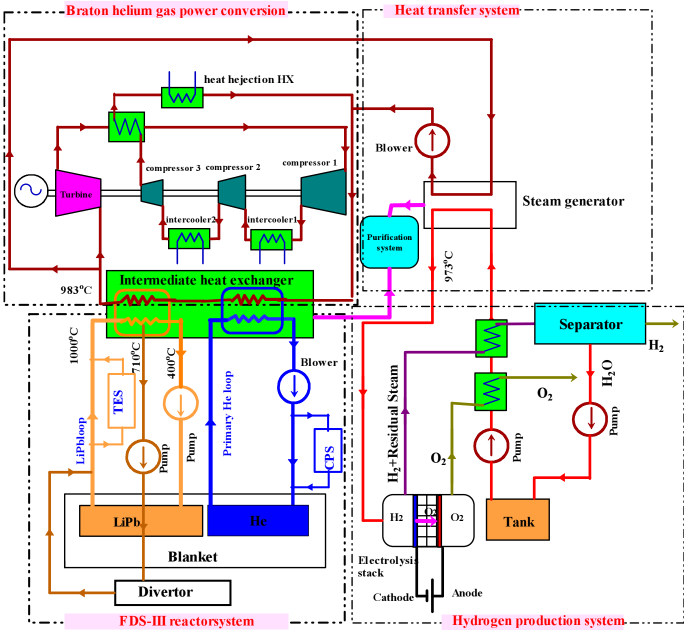


Fig.9 Diagram of FDS III-based hydrogen production

Table 3. the efficiency of the components and key parameters of system

Turbine efficiency	90%
Compressor efficiency	89%
Recuperator efficiency	95%
Generator efficiency	98%
Pressure drop ratio	5.0%
Compressor pressure ratio (total of all stages) r	2
Turbine inlet temperature T_O	1000 °C
Lowest helium temperature Ts	35 °C
Overall pressure loss ratio β	1.02
Ratio of helium specific heat γ=Cp/Cv	1.66

$$\eta = \frac{\eta_t \frac{T_{in}}{T_{\min}}\left(1-\beta\left(\frac{1}{r}\right)^{\frac{\gamma-1}{\gamma}}\right)-\left(\frac{3}{\eta_c}\right)\left(r^{\frac{\gamma-1}{3\gamma}}-1\right)}{(1-\eta_x)\left(\frac{T_{in}}{T_{\min}}-1-\frac{1}{\eta_c}\left(r^{\frac{\gamma-1}{3\gamma}}-1\right)\right)+\eta_x\eta_t\frac{T_{in}}{T_{\min}}\left(1-\beta\left(\frac{1}{r}\right)^{\frac{\gamma-1}{\gamma}}\right)} \quad (1)$$

$$\eta = \frac{\Delta H}{Q_{N,El}+Q_{N,ES}+Q_{loss}} = \frac{\Delta H}{\Delta H+\frac{1-\eta_{El}}{\eta_{El}}\bullet\Delta G+Q_{loss}} \quad (2)$$

5. Summary

The progress in conceptual study of China Fusion-Based Hydrogen Production Reactor, FDS-III, is reported. FDS-III features high core parameters, banana segment blanket combining big module, and big maintenance port to increase availability. The novel high temperature liquid lithium–lead blanket (HTL) concept, which install multilayer flow channel inserts and use RAFM steel as main structure material (RAFM), is presented as one of blanket candidate concepts aimed for obtaining coolant outlet temperature of 1000 ^{o}C for hydrogen production. Preliminary performance analyses indicate this conceptual blanket design may satisfy requirement of design. The high temperature steam electrolysis as one option is chose for hydrogen production, which coupled FDS-III fusion reactor using a Brayton helium gas turbine closed cycle.

The study of FDS-III is preliminary. The detailed design and performance analysis are being carried out, e.g. MFCI channel optimization, neutronics analysis using real 3D model, thermal-mechanical analysis based on 3D model, and MHD simulation, etc. The relative R&D is underway. However, a lot of critical issues remain to be focused on, e.g. material evaluation, tritium and hydrogen permeation issues in high temperature, and advanced material issues for high temperature heat exchanger etc.

Acknowledgment

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