Fusion/transmutation reactor studies based on the spherical torus concept

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Abstract. The paper presents a conceptual design for a compact fusion/transmutation experimental reactor based on the spherical torus concept, CFER-ST. A set of plasma parameters suitable for the nuclear waste transmutation blanket are given. The transmutation neutronics, integer structure, thermo-hydraulics, liquid curtain wall and magnet shield design, etc., for two types of minor actinide transmutation blankets, namely the lead–bismuth eutectic cooled blanket and the FLiBe eutectic self-cooled blanket, along with the relevant calculation results, are presented. The preliminary results show that the proposed fusion/transmutation system and the relevant parameters can meet the design goals.

1. Introduction

The realization of an economically competitive commercial fusion power plant is still a long way off, and the further development of fusion energy is an indispensable step before the building of a commercial plant [1]. In addition, China is interested in applications of fusion energy other than for electricity production, such as high level waste (HLW) disposal and hydrogen production. It is expected that these applications will benefit the ultimate development of fusion power plants.

The fusion/transmutation concept will enable improved pathways to fusion power as well as possible competitive applications earlier than the power application of fusion energy [2, 3]. In recent years, feasibility studies of HLW transmutation by fusion reactors have been performed in China [4–6]. In this paper, a conceptual design of a compact fusion experimental reactor based on the spherical torus (ST) tokamak configuration, CFER-ST, for the transmutation of minor actinide (MA) nuclear waste is presented. Two kinds of transmutation blanket, namely the FLiBe eutectic self-cooled blanket and the lead–bismuth eutectic (LBE) cooled blanket, were investigated. According to the results of the neutronics calculation, the LBE cooled blanket concept will be a suitable choice for MA waste transmutation in the CFER-ST fusion/transmutation reactor design.

2. Model and parameters

A FLiBe blanket can be operated at a constant power without interruption for refueling by adjusting the concentration of the MA and the lithium-6, extracting fission products from the blanket [7]. However, the LBE cooled blanket with integral fast-reactor-type fuel employs existing overseas technology, so it is an attractive blanket concept for transmutation reactor design. Transmutation studies of both the FLiBe and the LBE cooled metal blanket based on the ST configuration were performed. The 2-D and 3-D models for the LBE cooled blanket applied in the calculation are presented in Figs 1 and 2, respectively. The main design parameters for the CFER-ST fusion/transmutation reactor are given in Table 1.

In the CFER-ST conceptual design, 316-type stainless steel was chosen as the structural material for the blanket, the first wall and the cooling tubes. The blanket structure is characterized by a 20 cm thick transmutation zone with an appropriate MA volume rate and a tritium breeding zone of 20 cm thickness. Solid $LiAlO_2$ was chosen as the tritium breeder for the LBE cooled blanket design. In the CFER-ST design, the inboard does not contain the MA material. The average coverage ratio of the outboard is 60% in the CFER-ST design. The materials and composition used in the neutronics calculation for the LBE blanket are presented in Table 2.

3. Results and discussion

3.1. Neutronics performance

The neutronics calculations were performed by using the 1-D neutron transport and burn-up code BURD-1D, which was developed based on the 1-D diffusion-accelerated neutral-particle transport code ONEDANT [8] and the associated data libraries to optimize the blanket design. To match the neutronics transport and depletion analyses, a new data library with 46n + 21 γ energy group structures and P-3 Legendre scattering order was compiled. The neutron cross-section and decay data were derived from the evaluated cross-section library ENDF/B-6. Further, the neutronics analysis and system optimization in detail were carried out with the 2-D diffusion-accelerated neutral-particle transport code TWODANT [9], the 3-D Monte-Carlo code MCNP/4B [10] and the relevant data libraries. The calculation models applied in the transmutation neutronics calculation are shown in Figs 1 and 2. Comparison of the results of different codes for the tritium breeding ratio (TBR), the energy multiplication (M) and the effective neutron multiplication (K_{eff}) are presented in Table 3. Major results satisfying the requirements of the system design were also obtained. They are a transmutation support ratio (TSR) of 31, an energy multiplication factor (M) of 35, a TBR of 1.54 and K_{eff} of 0.83 for the LBE blanket design, using the MCNP/4B code under the operation condition of one full power year (FPY).

The results show that for the CFER-ST with the LBE blanket, the transmutation capabilities for ^{237}Np and ^{241}Am are 380 and 264 kg, respectively, with a fusion power of 67 MW and a neutron wall loading of 0.8 MW/m^2 for one FPY. However, the transmutation reactor with a FLiBe blanket under the same conditions can only consume 57 kg of ^{237}Np and 60 kg of ^{241}Am for one FPY. The reason might be that the neutron spectrum in the LBE cooled solid breeder blanket is harder than in the FLiBe blanket, owing to there being no Be neutron moderator in the blanket. In order to effectively transmute the MA nuclides, a harder neutron spectrum is necessary. With the objective of optimization, four kinds of fuel composition were investigated. It was found that the optimal fuel composition will be 30% Pu + 70% MA in the proposed LBE blanket design.

It is found that the peak power density of the transmutation zone is 253 W/cm^3 near the first wall. The average power density in the blanket zone is 221 W/cm^3. It was shown that the small gradient of the power density distribution in the blanket zone will be useful for the improvement of the thermo-hydraulics design and the stress distribution. The smooth distribution of the power density is an attractive advantage for the LBE transmutation blanket design.

The neutron spectrum distributions in the LBE cooled solid blanket in different transmutation zones are shown in Fig. 3. In order to effectively transmute the MA, a fast neutron spectrum in the transmutation blanket is required in the neutronics design.

3.2. Thermo-hydraulics calculation

The structural design and the thermo-mechanical analysis of the cooling tubes in the LBE and FLiBe transmutation blankets were performed in the CFER-ST conceptual design. Based on the neutronics calculation, the thermodynamics calculations for the two kinds of blanket in the CFER-ST were also performed. The 2-D calculation model is shown in Fig. 4. The main results of the thermo-hydraulics calculation are shown in Fig. 5. It was found that the proposed design can meet the thermodynamic requirements of the blankets through adjustment of the design parameters. Utilizing the ANSYS [8] code, the thermal stress and temperature distributions of the two designs were obtained. The results show that the design objective was achieved. The calculation results for the temperature and stress distributions for the FLiBe self-cooled blanket are given in Fig. 6, which shows that for HT-9 structural material the peak temperature and maximum equivalent stress are 524ºC and 223 MPa, respectively. The peak temperature and stress values are located near the first wall surface. The values found can meet the cooling requirement of the whole blanket design in the range permissible for the structural and breeding materials. In order to provide adequate magnet protection, an optimization design of the magnet shield has been carried out.

3.3. Liquid wall concept

In the CFER-ST conceptual design, a liquid curtain wall concept has been explored. The calculation codes used for analyzing the properties of the liquid curtain were developed based on ANSYS, whose control diagram is shown in Fig. 7. Then the MHD effects of free-surface liquid lithium flow in the metal duct were analyzed. Figures 8(a) and (b) show the velocity distribution of the liquid curtain in the wall with no magnetic field and with a 2 T external field, respectively. The results show that: the induced electromagnetic force can alleviate the acceleration effects of gravity to form a stable liquid curtain in front of the blanket; the electric field effect should be taken into account in analyses of the blanket liquid curtain; the blanket liquid curtain is a two-stream liquid wall — a fast moving free surface layer and a slowly moving layer behind it. The design and analysis show that the liquid curtain with suitable design parameters can meet the requirements of the CFER-ST design.

4. Summary

The main conclusions of this study are that the tokamak transmutation reactor design based on CFER-ST, a small-scaled and compact ST configuration with a low fusion power, has attractive advantages if used for the transmutation MA wastes. The proposed fusion/transmutation reactor system with the LBE cooled blanket and FLiBe eutectic self-cooled blanket can be designed based on existing ST tokamak physics and fusion technology databases. The transmutation capabilities of the LBE blanket design for the MA nuclides ^{237}Np and ^{241}Am will be 380 and 264 kg, respectively, for one FPY. In addition, the neutronics performance and thermo-hydraulics parameters of the designed system can meet the design requirements. The engineering feasibility of the fusion/transmutation reactor system will be further investigated.

Acknowledgment

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Table 1. Main parameters of the CFER-ST design

Major radius, R (m)	0.91	Fusion power, P_f (MW)	67
Minor radius, r (m)	0.70	Plasma elongation ratio, k	2.3
Aspect ratio (A)	1.3	Driven current, I_{CD} (MA)	1.11
Neutron wall loading, W_L (MW/m^2)	0.80	Magnetic field, B_T (T)	1.87
Plasma current, I_p (MA)	6.52	Plasma current, I_C (MA)	8.51

Table 2. Materials and composition of the LBE cooled transmutation blanket design

Zones	Radius (cm)	Thickness (cm)	Materials and composition
Centre post	0.00–20.00	20.0	70% Cu, 20% H_2O
First wall	20.00–20.50	0.5	100% 316 SS
Void	20.50–26.50	6.0	Void
Plasma	26.50–136.50	130.0	Plasma
Void	136.50–142.50	6.0	Void
First wall	142.50–143.50	1.0	100% 316 SS
Transmutation zone	143.50–163.50	20.0	40% LBE, 55% Zr–Pu (MA)[a)], 5% 316 SS
Tritium breeding zone	163.50–183.50	20.0	20% LBE, 75% $LiAlO_2$[b)], 5% 316 SS
Shield zone	218.50–258.50	40.0	30% 316 SS, 30% B_4C, 40% H_2O

a) Composition depends on different scenario.

b) Natural lithium.

Tabel 3. Comparison of calculation results from different codes

Codes	TBR	M	K_{eff}	Models	
ONEDANT	1.96	44.6	0.85	1-D Cylinder model	With same material arrangement and space size for all calculation models
TWODANT	1.61	39.4	0,84	2-D Cylinder model	
MCNP-4C	1.54	35	0.85		
MCNP-4C	2.31	52	0.88	3-D Real model	

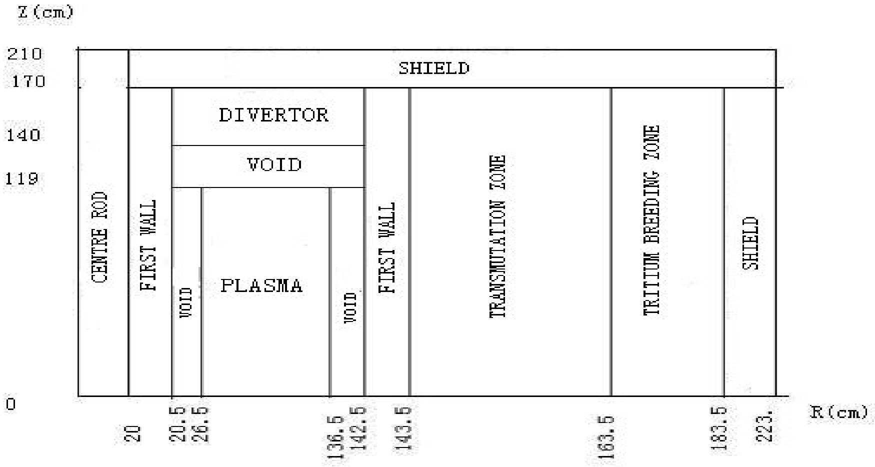


FIG. 1. 2-D calculation model of the TWODANT code.

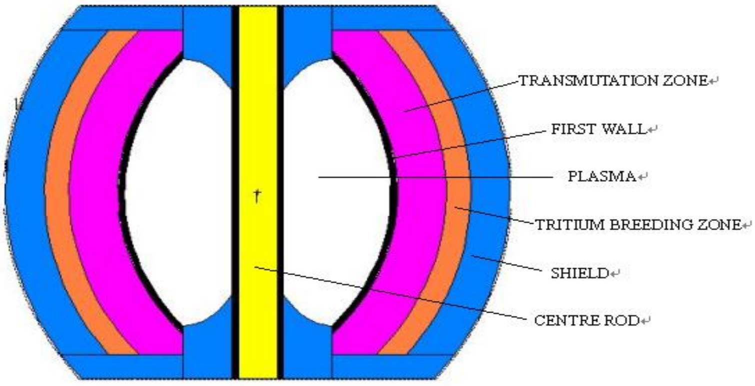


FIG. 2. Radial–poloidal cut of the MCNP model.

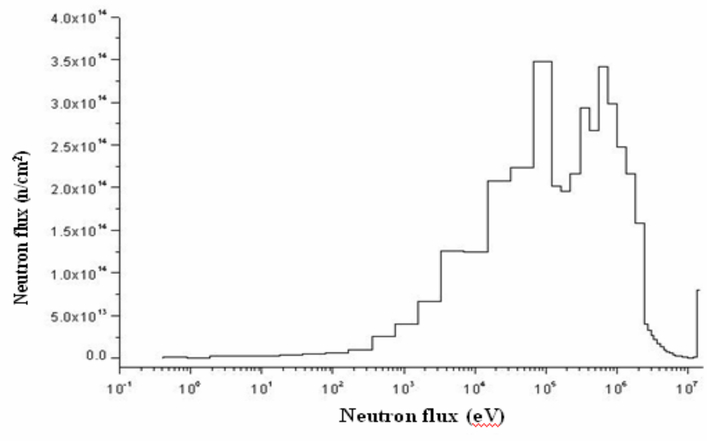


FIG. 3. Neutron spectrum distribution in the LBE cooled solid blanket.

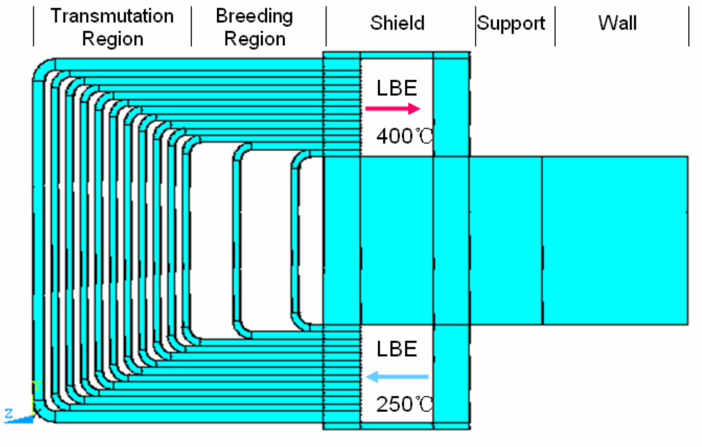
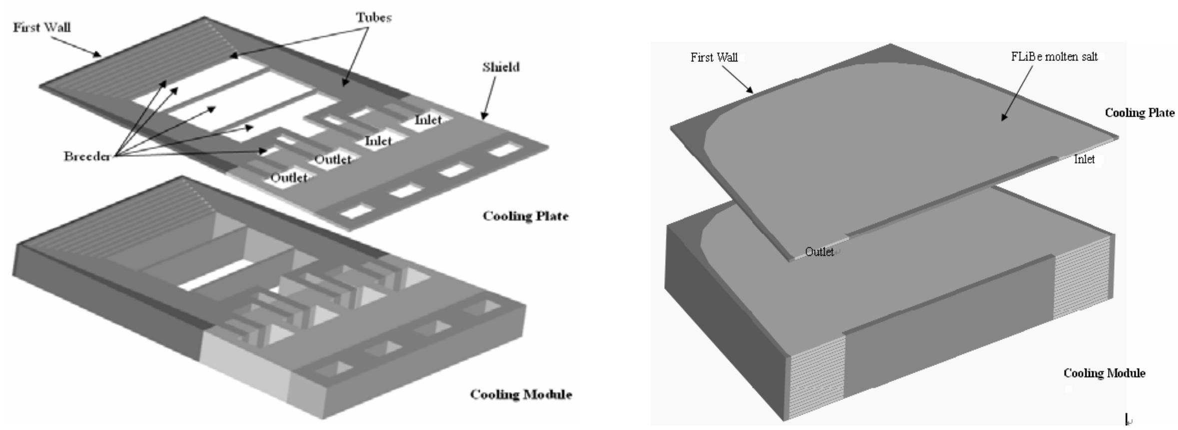
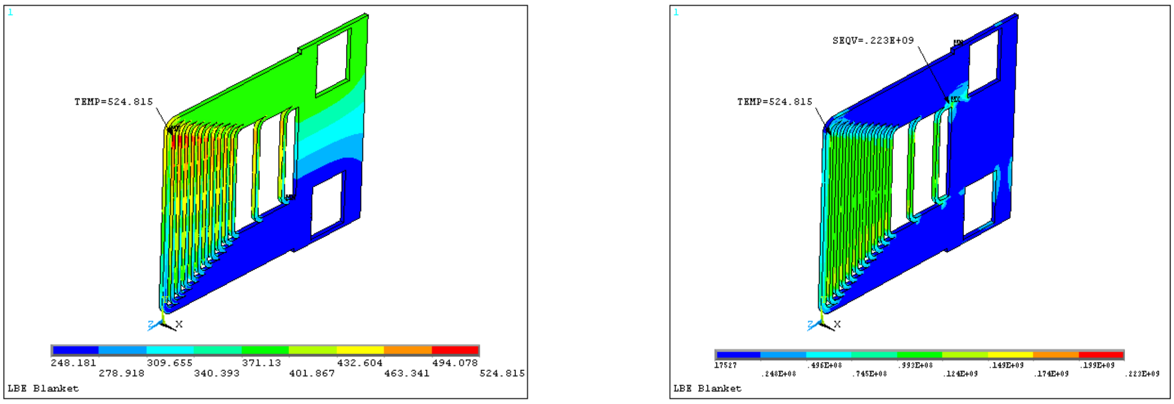


FIG. 4. Calculation model of the cooling plate for the LBE blanket.



(a) LBE cooled blanket (solid breeder) *(b) FLiBe self-cooled blanket*

FIG. 5. Structure of cooling tubes in the two kinds of blankets.



a). Temperature distribution *b). Equivalent stress distribution*

Fig.6 The calculation result of LBE cooled blanket

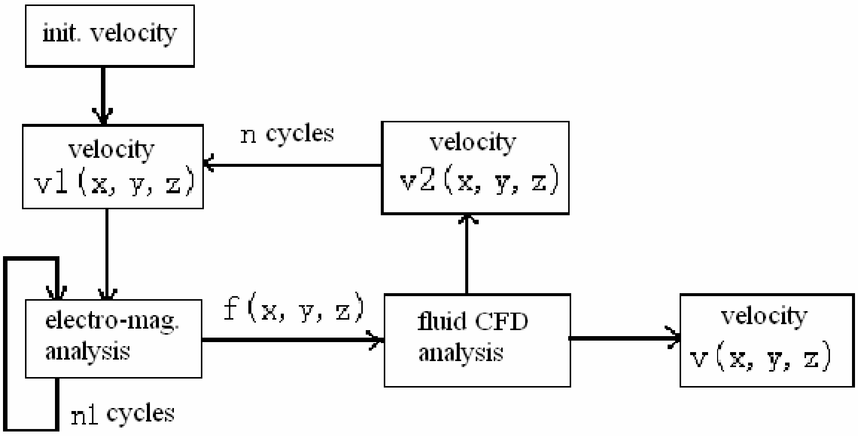
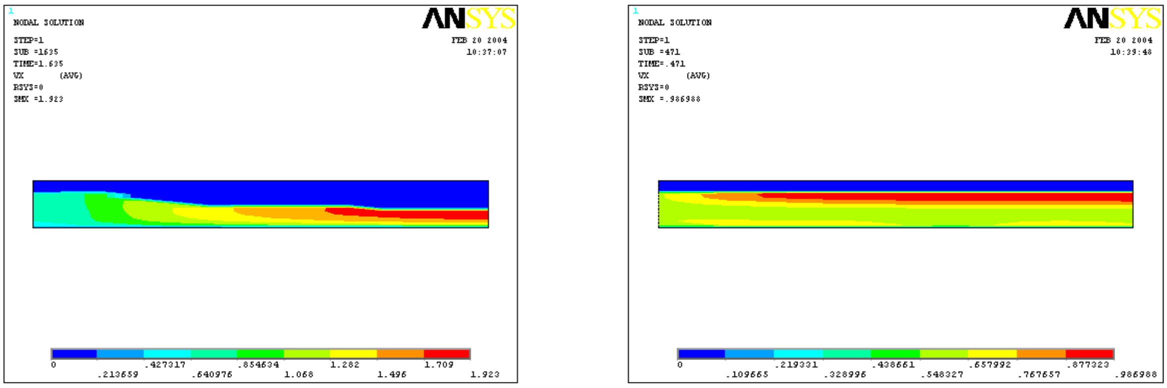


FIG .7. Calculation of flow for the liquid curtain.



(a) With no magnetic field

(b) With 2 T external field

FIG. 8. Velocity distributions. for the liquid curtain