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Neutronic study of an innovative natural uranium–thorium based fusion–fission hybrid energy system

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ABSTRACT

An innovative design for a water cooled fusion–fission hybrid reactor (FFHR), aiming at efficiently utilizing natural uranium and thorium resources, is presented. The major objective is to study the feasibility of this concept balanced with multi-purposes, including energy gain, tritium breeding and ^{233}U breeding. In order to improve overall neutron economy of the system, the fission blanket is designed with two types of modules, i.e. the natural uranium modules (U-modules) and thorium modules (Th-modules), which are alternately arranged in the toroidal and poloidal directions of the blanket. This innovative design is based on a simple intuition of neutron distribution: with the alternate geometrical arrangement, energy multiplication by uranium fission, tritium breeding and ^{233}U breeding are performed separately in different sub-zones in the blanket. The uranium modules which has excellent neutron economy under the combined neutron spectrum, plays the dominant role in the energy production, neutron multiplication and tritium breeding. Excess neutrons produced by the uranium modules are then used to drive the thorium modules (which have poor neutron economy) to breed ^{233}U fuel. Therefore, it creates a new free dimension to realize the blanket's balanced design. The COUPLE code developed by INET of Tsinghua University is used to simulate the neutronic behavior in the blanket. The simulated results show that with the volumetric ratio of thorium modules about 0.4, the balanced design for multi purposes is achievable, with energy multiplication $M \geqslant 9$, tritium breeding ratio TBR $\geqslant 1.05$, and at the end of the five years refueling cycle, the ^{233}U enrichment in thorium modules exceeding 1.0%. The neutronic analysis results also show that the preliminary design of this innovative FFHR is of great potential to utilize the bred ^{233}U effectively after the initial fuel load of the first ten-year operation.

1. Introduction

Thorium is 3–4 times more abundant than uranium and is widely distributed in nature as an easily exploitable resource in many countries. During the pioneering years of nuclear energy, from the mid 1950s to mid 1970s, there was considerable interest worldwide to develop thorium fuels and fuel cycles in nuclear research and power reactors for conversion thorium to 'fissile fuel' ^{233}U in order to supplement uranium reserves (IAEA, 2005). FFHR was proposed to breed fissile fuel (Lidsky, 1975; Bethe, 1979; Lee and Moir, 1981; Kotschenreuther et al., 2012). A FFHR uses the fusion reaction T (D, n) 4He in the plasma confined in its tokamak to generate high-energy neutrons with 14.1 MeV. These fusion neutrons are employed to drive fission and tritium conversion reactions in the subcritical blanket surrounding the plasma. The blanket is filled with natural uranium, spent nuclear fuel or natural thorium for generating fission energy and multiplying neutrons, and lithium based breeders for producing tritium used to fuel fusion in tokamak.

However, for the FFHR fueled with only natural thorium, the energy gain M is relatively small (less than 2.0) in the initial operating stage, which would be challenging on the fusion capability requirement for energy generation (Piera et al., 2010; Lafuente and Piera, 2011). ITER is an experimental fusion reactor which has been investigated extensively for years. It has yet to achieve the performance required for power reactor operation. Early application of fusion energy may be realized under much lower plasma condition than in a fusion-only power reactor. The blanket should have higher energy multiplication factor M to accomplish this goal. The early design of a water cooled natural uranium–thorium fueled blanket concept (Xiao et al., 2012, 2013) could not reach the balanced operation with multi-purposes, i.e., high energy gain, tritium self-sufficiency and good ^{233}U breeding rate due to thermal neutron barrier effect of ^{232}Th fuel arranged in the fission blanket.

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A new type of hybrid blanket aiming at efficiently utilizing thorium resource while maintaining higher M and tritium self-sufficiency, proposed by this paper, adopts the seed–blanket design concept of Wang (2003) for a PWR with thorium–uranium fuel cycle. This innovative design uses U-modules as the seed zones, Th-modules and tritium breeding modules as the fuel breeding blanket zones. U-modules and Th-modules are separated geometrically to reach an excellent neutron economy. The natural uranium fuel (U-modules) functions as energy generation and neutron multiplication source (Seed). Excess neutrons released by the U-modules are then used to convert natural thorium to ^{233}U fuel in Th-modules and to breed tritium from lithium-based material in tritium-modules. The blanket employs water as coolant and operates under the combined thermal and fast neutron spectrum. Different fuel to water volumetric ratio and thorium fuel fraction are investigated to find optimized blanket design parameters.

The preliminary results indicate that it is rather promising to design a high-performance water cooled fission blanket of FFHR for electric power generation and ^{233}U breeding by directly loading natural uranium and thorium if fusion neutron source from an ITER-scale tokamak is achievable.

2. Simulation model and method

Focusing only on the neutronic performance of the blanket with some details omitted, a simplified one dimensional 'D-Shape' model of FFHR has been chosen for simulating the plasma-blanket zone of a typical tokomak. The water cooled natural uranium/thorium fueled FFHR blanket is depicted also in Fig. 1.

The major radius of the plasma R is 510 cm, and the minor radius a is 154.5 cm and b equals 286 cm. The elongation b/a is 1.85 and the aspect ratio R/a is 3.30 (Zhou et al., 2011). In the front fuel region, the thickness of each natural uranium or thorium fuel plate is 2 cm, and the H_2O coolant/moderator thickness is 1 cm for the U-modules and 0.5 cm for Th-modules. While in the tritium breeding region, the Li_4SiO_4 plate with 90% ^{6}Li enrichment is 4 cm each and the H_2O coolant/moderator thickness is 4 cm. The thickness of shielding reflector is set to be 45 cm. Five uranium fuel plates are inserted into the U-modules. And Th-modules are equipped with four thorium fuel plates. The arrangement of U- and Th-modules in toroidal directions is shown in Fig. 2. In the preliminary design, only the alternate arrangement of U- and Th-modules in toroidal direction is considered.

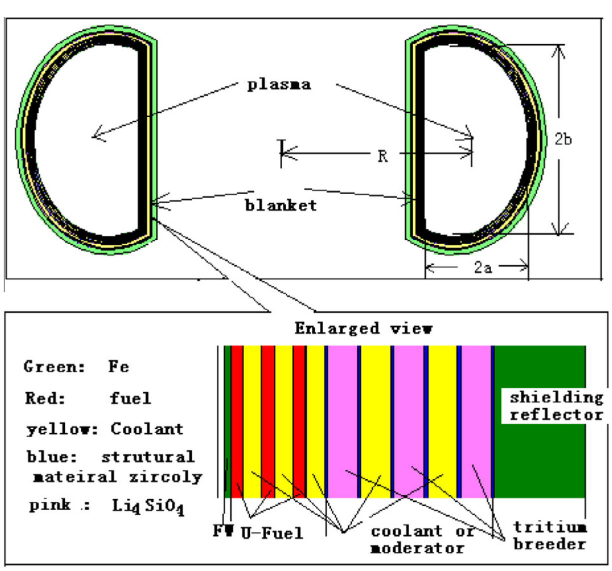

Fig. 1. Computational 'D-Shape' model of water cooled natural uranium/thorium fueled FFHR.

A uniform volumetric circular cylindrical fusion neutron source in toroidal direction is placed at the center of plasma region, the radius range of which is from 415 cm to 635 cm, and the height is 560 cm. The fusion neutron source is based on physics similar to or less demanding than that used for the ITER design, so the existing R&D program supporting ITER will cover the requirements in tokamak physics design of this innovative FFHR. In all calculations, the total fission power of the blanket is set to 3000 MW, which could be realized by adjusting the fusion power during the fission fuel depletion process. The refueling cycle is 3650 days. The code system Couple2.0 (Zhou et al., 2011) developed by INET, Tsinghua University, which couples the codes MCNPX and Origin 2.0, is used to simulate neutron transport in fission blanket and calculate the fissile material depletion and conversion.

3. Results and discussion

3.1. The essence of blanket neutronic design

The essential goal of optimal neutronic design of subcritical FFHR blanket is to achieve balance of its multi-operating purposes, i.e., high energy multiplication M, tritium self-sufficiency and good ^{233}U breeding rate, under the constraint of utilizing only natural uranium and thorium as initial fuel. Neutron economy is the direction towards optimal design. The blanket's neutron multiplication effect should be strong enough to ensure that available excess neutrons could be used to induce fission reaction and breed tritium and ^{233}U. Furthermore, these neutrons should be distributed optimally among these neutron competing reactions.

3.2. The rationale of seed–blanket concept in the blanket design

It is well known that ^{232}Th has poor neutronic behavior for fission. For the thorium fueled blanket, the general method to obtain good system neutron balance is the adoption of the seed–blanket concept, in which natural uranium modules (Seed) act as the energy generation and neutron multiplication components, while natural thorium modules and tritium breeding modules (Blanket) as the blankets to breed fissile and fusion fuels. The basic logic of this concept is to use the excess neutrons generated in the natural uranium fuel region to breed fissile fuel ^{233}U in the thorium fuel region, while maintaining high energy multiplication factor (M) and tritium self-sufficiency. The subtle idea of the seed–blanket

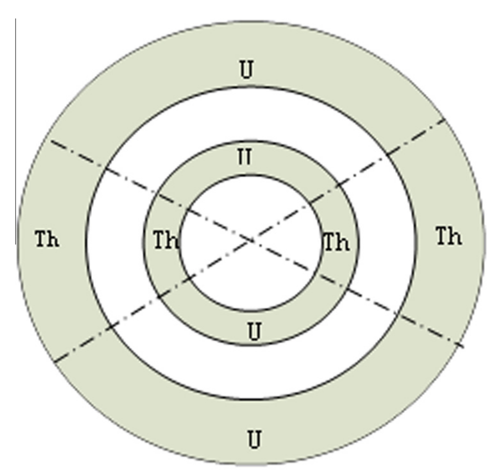

Fig. 2. Alternately arrangements of natural uranium and thorium modules in the toroidal directions of the blanket (equatorial plane).