Annals of Nuclear Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Performance of radial fuel shuffling sodium cooled Breed and Burn reactor core

M.Y. Zheng, W.X. Tian, D.L. Zhang, S.Z. Qiu, G.H. Su *

State Key Laboratory of Multiphase Flow in Power Engineering, School of Nuclear Science and Technology, Xi'an Jiaotong University, Xi'an 710049, China

ARTICLE INFO

Article history:
Received 17 July 2015
Received in revised form 26 May 2016
Accepted 18 June 2016
Available online xxxx

Keywords:
Breed and Burn reactor
Assembly optimization
Fuel shuffling strategy
Core performance

ABSTRACT

In this paper, performance of radial fuel shuffling of sodium cooled Breed and Burn reactor core is investigated. Neutronics and depletion calculations are carried out by MCORE based on the ENDF/B-VII data library. Thermal-hydraulic analysis is performed based on a self-developed parallel channels model steady-state code SAST. First of all, the assembly parameters are optimized from neutronics and thermal-hydraulics. The results show that assembly with 127 fuel rods and P/D of 1.12 is the best design. Secondly, the core critical features and radial power peaking factors of the inward and outward fuel shuffling strategy under different fuel shuffling periods are carried out. The results show that k_{eff} of the beginning of equilibrium cycle (BOEC) and end of equilibrium cycle (EOEC) of both the inward and outward fuel shuffling strategy parabolically vary with the fuel shuffling period. Power peaking factor of the inward fuel shuffling strategy decreases with the increase of fuel shuffling period exponentially, while that of the outward fuel shuffling strategy increases with the fuel shuffling period exponentially. The outward fuel shuffling strategy with shuffling period of 500 days performs better in core critical features and radial power peaking factors. Reactivity coefficients of the optimized core are calculated. Finally, preliminary thermal-hydraulic analysis of the optimized core is performed. The results show that maximum cladding interface temperature and maximum fuel temperature are all within the acceptable limits.

1. Introduction

Light Water Reactors (LWRs) utilize about only 0.6% of the overall uranium. For the once-through Fast Breeder Reactors (FBRs), the uranium utilization is not significantly different from the LWRs due to the high uranium enrichment required to fuel the FBRs (Greenspan and Heidet, 2011). Closed fuel cycle can make high uranium utilization, but fuel reprocessing is difficult and expensive. Fortunately, Breed and Burn reactors can obtain a very high level of burn-up using non-enriched uranium, realize significantly high uranium utilization and do not need fuel reprocessing.

Feinberg (1958) firstly proposed the concept of Breed and Burn reactor, in which burning wave propagates continuously through the fertile fuel region. During the past five decades of investigation, two concepts of Breed and Burn reactors have been proposed: Traveling Wave Reactor (TWR) and Standing Wave Reactor (SWR). In TWR, the breeding/burning wave moves through the fuel, while fuel is shuffled in or out of the burning region in SWR. The TWR concept was firstly investigated by Feoktistov (1988), finding that traveling nuclear burning wave can self-sustained in the Breed and Burn reactors. After that, a series of studies for TWR were performed by Teller et al. (1996), Seifritz (2000), Sekimoto et al. (2001), Van Dam (2003), Fomin et al. (2008), Chen et al. (2008, 2012), and so on. The first SWR core design was conducted at Brookhaven National Laboratory (BNL) in collaboration with the Massachusetts Institute of Technology (MIT) in 1970s. After that, the studies of SWR were performed by Marshall et al. (2005), Greenspan and Heidet (2009), Chen et al. (2011), Heidet and Greenspan (2012, 2013), Qvist and Greenspan (2012), Zhang et al. (2013), Zheng et al. (2014a, 2014b, 2015), and so on. In 2008, the Terra Power LLC was founded to develop commercial TWR (actually SWR), which brings a huge boost to the investigation of Breed and Burn reactors.

In the previous studies of SWR type of Breed and Burn reactor, the fuel shuffling strategy and thermal-hydraulic analysis have been investigated by some researchers. Chen et al. (2011) compared the inward and outward fuel drifting theoretically and found that the inward fuel drifting has a better breeding utilization than the outward one, in which the achieved asymptotic k_{eff} is lower. Zhang et al. (2013) studied the power peaking factor, asymptotic k_{eff} and burn-up of different shuffling period based on the European Sodium cooled Fast Reactor (ESFR). Zheng et al.

* Corresponding author.
E-mail address: ghsu@mail.xjtu.edu.cn (G.H. Su).

http://dx.doi.org/10.1016/j.anucene.2016.06.019
0306-4549/© 2016 Published by Elsevier Ltd.

(2014a, 2014b, 2015) proposed the concept of checkerboard type Breed and Burn reactor, in which a number of breeding assemblies are arranged in the center core to increase the breeding ability. Qvist and Greenspan (2014) developed an automated fast reactor core design code ADOPT, which has been applied to Breed and Burn reactor. Heidet and Greenspan (2013) performed a preliminary neutronics design of a Breed and Burn reactor core, in which an improved shuffling scheme was proposed and preliminary thermal-hydraulic analysis was performed. However, the core was modeled as concentric cylindrical regions, which limits the engineering practicability of the research results.

The objective of the present paper is to optimize the assembly parameters from neutronics and thermal-hydraulics, compare the core critical features and power peaking factors of the inward and outward fuel shuffling strategy under different fuel shuffling periods, and perform preliminary thermal-hydraulic analysis of the optimized core. The assembly parameters optimization is performed in Section 2. A detailed description of the Breed and Burn reactor core, inward and outward fuel shuffling strategy, and the core modeling are provided in Section 3. Section 4 compares the assembly performance from neutronics and thermal-hydraulic, the core critical features and power peaking factor under different fuel shuffling period and performs preliminary thermal-hydraulic analysis of the optimized core. The general conclusions of the present paper are provided in Section 5.

2. Assembly design

2.1. Assembly description

Assembly parameters will influence the loading of uranium, the neutron spectrum, and then influence the breeding ability of assembly. At the same time, assembly parameters will influence the thermal-hydraulic parameters, such as coolant flow area and hydrodynamic diameter, and then influence the thermal-hydraulic characteristics. So, the assembly parameters should be optimized to satisfy neutronics and thermal-hydraulic limits. The main purpose of assembly optimization is to increase the assembly breeding ability and decrease the maximum cladding interface temperature, maximum fuel temperature and pressure drop by adjusting the P/D (Pitch/Diameter) parameters and the number of fuel rods per assembly through keeping the main assembly parameters unchanged, such as inside flat-to-flat distance, assembly pitch and active core height.The main parameters of assembly are listed in Table 1. As shown in Fig. 1 that 91, 127, 169, 217 and 271 fuel rods assembly, commonly used in FBRs, are taken into account. P/D of 1.04, 1.06, 1.08, 1.10, 1.12, 1.14, 1.16, 1.18 and 1.20 are taken into account. Detailed assembly parameters for different fuel rods with different P/D are listed in Tables. 2–6. Metallic fuel U + 10%Zr is used as fuel material; the fuel nominal density is 16.0 g/cm^3 and the smear factor is 75%. Sodium is used as coolant with a density of 0.85 g/cm^3. Ferritic/Martensitic alloy HT-9 is used as the cladding material with a density of 7.9 g/cm^3.

Table 1
Main parameters of assembly.

Parameters	Value
Inside flat-to-flat distance (cm)	15.86
Outer flat-to-flat distance (cm)	16.46
Assembly pitch (cm)	16.86
Lower end plug (cm)	58.00
Active core (cm)	250.00
Upper plenum (cm)	200.00
Upper end plug (cm)	2.50

2.2. Assembly simulation

MCORE, which couples MCNP and ORIGEN, is used to perform neutronics and depletion calculations in the present paper (Zheng et al., 2014c). MCORE has been verified by VVER-1000 LEU assembly benchmark and OECD/NEA fast reactor benchmark. The NJOY code was previously used to generate the cross-section data, used by MCNP, based on the original ENDF/B-VII libraries. The displacements per atom (DPA) of structural material can not be calculated by MCORE, so DPA of cladding material is not considered in the present paper.

For the thermal-hydraulic analysis, a steady-state code SAST has been developed based on parallel channels model. The calculation procedure of SAST is shown in Fig. 2. SAST has been verified by KALIMER-600 equilibrium design value, the results obtained by SAST show a good agreement with the design value. Deviations from design value is found to be −2.58% and −0.52% for assembly flow rate and coolant outlet temperature.

3. Core design and fuel shuffling strategy

3.1. Core description

Previous research at Xi'an Jiaotong University proposed the concept of sodium cooled checkerboard type Breed and Burn reactor (Zheng et al., 2014a,b) and performed MA transmutation analysis based on this concept (Zheng et al., 2015). The so-called checkerboard type means that a number of breeding assemblies are arranged in the inner core in a scattered way to increase the breeding ability of the core. As mentioned by Greenspan and Heidet (2011) that fuel discharged from a Breed and Burn reactor can be additionally used in Breed and Burn reactor as ignition material, spent fuel assemblies are discharged from the core other than moved to the outer core. The present design is named as BSWR (checkerboard type Standing Wave Reactor), set as core design A in the present paper. For the BSWR, if outward fuel shuffling strategy is adopted, fully bred assemblies will be moved to the center of the inner core, which will increase the power density of this area and bring a big radial power peaking factor. Based on previous research experience, breeding assemblies in the inner core are not included in the present paper, while the outer core and the arrangement of control rod assemblies, absorbing assemblies, reflector assemblies and shield assemblies are the same, set as core design B in the present paper.

As mentioned above that U + 10%Zr, HT-9, sodium and B_4C are used as fuel material, structural material, coolant and absorbing material, respectively. The active core is divided into two regions in radial direction, the inner core and the outer core. 204 depleted uranium assemblies are loading in the outer core and 48 absorbing assemblies are arranged in the outer core to absorb neutrons and reduce power density in this area. About three layers 252 reflector assemblies are arranged in the outside of the outer core and about two layers 198 shield assemblies are arranged in the outer most of the core. For core design A, 14.0% and 11.0% enrichment ignition assemblies are arranged in the inner core with the number of 96 and 60, respectively. 36 depleted uranium assemblies are loaded in the inner core in a checkerboard type way. The core layout in radial view is shown in Fig. 3. For core design B, 5.0%, 9.0%, 11.0%, 14.0%, 12.0% and 10.0% enrichment ignition assemblies are arranged in the inner core with the number of 12, 18, 36, 30, 36 and 60, respectively. The core layout in radial view is shown in Fig. 4. The loading of ^{235}U is the same for the two cores. Core and surrounding layout in section view and detailed core parameters for the two cores are shown in Fig. 5 and Table 7, respectively.