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Fuel pebble optimization for the thorium-fueled Pebble Bed Fluoride salt-cooled high-temperature reactor (PB-TFHR)

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ABSTRACT

Thorium-fueled Pebble Bed Fluoride salt-cooled High-temperature Reactor (PB-TFHR) is a newly developed reactor concept featuring the technology of High Temperature gas-cooled Reactor (HTR) and the molten salt cooling for thorium-based fuels. To attain a deep burnup with enough negative temperature coefficient of reactivity (TCR), a systematic study for the graphite-to-heavy metal ratio (C/HM) from 66 to 800 and the ^{233}U-to-HM ratio (^{233}U/HM) from 5.0% to 20.0% are carried out. Neutronics characteristics, including the effective multiplication factor (k_{eff}), the TCR and the conversion ratio (CR) are analyzed in terms of neutron usage, core safety and burnup. The results show that the fuel pebble with a higher ^{233}U/HM owns a wider range of under-moderated area, which is favorable to improve TCR. Moreover, a strongly negative TCR is obtained by optimizing the C/HM and ^{233}U/HM ratios. In order to evaluate the ^{233}U saving for thorium based fuel, the burnup per fissile mass (Bu) is introduced. Bu can be improved through reducing C/HM, and it increases firstly and then achieves saturation as ^{233}U/HM increases. A burnup level of 122 GWd/tHM can be achieved for the recommended pebble design with ^{233}U/HM of about 12.5% and C/HM of about 124. With the optimized design, an improved TCR can be obtained with a value of about −2.77 pcm/K, which is much more superior to our previous work.

1. Introduction

The Advanced High Temperature Reactor (AHTR) or Fluoride salt-cooled High-temperature Reactor (FHR) is one of the recently emerging nuclear power plant concept with expected remarkable advantages in high temperature output, inherent safety and potentially efficient resource utilization. It adopts fluoride salt as the coolant while uses a fuel form (TRISO coated fuel particle) similar to High Temperature gas-cooled Reactors (HTRs). Fluoride salt (usually LiF-BeF_2, 67-33 mol%), is a good coolant due to its unique characteristics, and has been successfully applied in molten salt reactors (MSRs). It has a melting point of about 450 °C and a boiling point above 1300 °C, which allows FHR to operate at ambient pressure (Fratoni, 2008). Due to a high thermal conductivity and heat capacity of FLiBe (de Zwaan, 2005), the fission energy produced in a fuel pebble can be transferred more effectively, allowing a higher power density than a HTR (Forsberg et al., 2008). At the same time, a high fuel burnup can be achieved, which is partially due to the TRISO fuel particle. It is composed of a fuel kernel (either fuel oxide, carbide or a mixture of oxide and carbide) and four coating layers that can provide a high integrity pressure vessel to extremely retain gas fission products at elevated temperature (Zhou and Tang, 2011; Kania et al., 2013; Tang et al., 2002; Wols et al., 2012; Labar, 2002). The combination of TRISO coated particle fuel and fluoride salt is expected to smoothen the disadvantages introduced by the low thermal capacity of helium in HTRs, such as low power density and the resulting large core size (Forsberg et al., 2003).

The FHR synthesizing the features of HTR and MSR has attracted more and more attention worldwide. In 2005, a prismatic block fuel design for HTRs with smaller coolant channels was adopted by a FHR design (Kim et al., 2005). In 2006, considering the positive buoyancy issue of prismatic fuel block which may complicate refueling procedure, the University of California, Berkeley (UCB) proposed a AHTR concept using pebble fuel (i.e., PB-FHR) rather than prismatic block fuel (Griveau et al., 2007). It is an integral design with the primary loop (cooled by FLiBe) immersed in a tank containing a separate buffer salt (NaF-$NaBF_4$). The thermal power is 2400 MW with a power density of about 10.2 MW/m^3, 50% greater than that of HTR. By using the $UC_{0.5}O_{1.5}$ fuel (10% enriched ^{235}U) pebble (6 cm in diameter) filled

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with a kernel diameter of 425 μm and packing factor of 12.5%, the discharge burnup can achieve 129 GWd/tHM. Afterwards, a modular design (900 MWth) with a higher power density (20–30 MW/m^3) and smaller pebbles (3 cm in diameter), was proposed by Bardet et al. (Bardet et al., 2008). This small-pebble design doubles the pebble surface area per unit volume and halves the thermal diffusion length, enabling a substantial increase in power density while maintaining relatively low peak fuel particle temperature. In 2012, a commercial prototype FHR pre-conceptual design (Mark-1) with the thermal power downgraded to 236 MW for limiting the risk associated with a first-of-a-kind (FOAK) advanced nuclear reactor concept was developed by UCB under the Nuclear Energy University Programs (NEUP) integrated research project (Cisneros et al., 2014). The Mark-1 adopts an annular core geometry consisting of two radial layers: the inner core fueled by low enriched uranium (LEU) and the thin outer layer of graphite reflector pebbles providing shielding to the fixed outer radial graphite reflector. Then, a comprehensive parametric study is conducted over various performance characteristics, including burnup, temperature coefficient of reactivity (TCR). It was found that an average burnup of 178 GWd/tHM can be achieved with the uranium enrichment of 19.8%, and C/HM should be less than 400 to maintain a negative coolant TCR (Cisneros, 2013).

The graphite-moderated FHR can potentially provide a technically credible option for thorium utilization. Several thorium fueled experimental HTRs like Dragon reactor in UK, AVR in Germany and Peach Bottom reactor in USA, and prototype HTRs like Fort St. Vrain in USA, THTR in Germany had been operated successfully decades ago and demonstrated a satisfactory performance of the HTR systems (IAEA, 1997; IAEA, 2005), which provided the technological basis for the future utilization of the thorium in high temperature reactors. In recent years, some studies have also been performed to evaluate the performance of the thorium utilization in HTR. F.J. Wols et al. introduced a conceptual design of a passively safe thorium breeder Pebble Bed Reactor (PBR) and analyzed its conversion capacity and safety features with ^{233}U and enriched uranium, respectively. It was found that the PBR can achieve a net production of ^{233}U with either of the two starter fuels and fulfill the passive safety requirements (Wols et al., 2015a; Wols et al., 2015b). Moreover, in the work of M. Ding and J.L. Kloosterman, two types of fuel blocks, the Th/U MOX fuel block using mixed uranium and thorium in each fuel kernel, and the seed-and-blanket (S&B) fuel block consisting of seed region with uranium in the center and a blanket region with thorium, were investigated for an application of the U-Battery (a small, long-life and transportable HTR), respectively. The results show that C/HM (carbon to heavy metal atoms) ratio can greatly affect the neutronic performance and the S&B fuel block design is better than the Th/U MOX fuel block with respect to the lifetime and reactivity swing (Ding and Kloosterman, 2014a, 2014b). Furthermore, thorium based fuel has been widely studied in India whose thorium reserves are abundant (Hanly and Vance, 2014), and these studies are associated with the HTRs (Sinha and Dulera, 2010; Dulera et al., 2017) and fast reactors (Chetal et al., 2011) that are supported under the three stages nuclear power program (Vijayan et al., 2013). To achieve effective thorium utilization, UCB proposed an annular PB-FHR concept with a thorium blanket surrounding the outer core for decreasing neutron leakage and extending the life of graphite reflector (Cisneros et al., 2010). In addition, G.F. Zhu et al. (Zhu et al., 2015) conducted a study on an annular pebble fueled FHR and made an comprehensive parametric optimization on the core geometry and the composition of uranium and thorium to improve fuel utilization.

The annular pebble fueled FHR with a separate driver zone and a blanket zone, however, may complicate the core structure. Therefore, a single-zone core with regularly stacked pebble bed is employed in this work. Compared to the core with randomly stacked pebble bed, it can facilitate the insertion of control rods in accident condition. Meanwhile, it offers several significant advantages over the prismatic core due to on-line refueling, such as the lower initial fissile loading and the excess reactivity, and continuous operation without required shutdowns (Kasten and Bartine, 1981). Accordingly, it can be proposed as an option for the first step to develop the PB-AHTR considering its complicacy and innovation. In our previous work (Li et al., 2015), the neutronics study on a whole-core model of FHR was carried out. The thorium-based fuels composed of thorium and fissile materials were assumed to be homogenous mixed in each fuel kernel in a form of ($^{233}U/^{235}U/^{239}Pu$, ^{232}Th) O_2. The uranium-based fuels ($^{233}U/^{235}U/^{239}Pu$, ^{238}U) O_2 were also analyzed for comparison. As a result, the (^{233}U, ^{232}Th) O_2 fuel achieves the deepest burnup over other fuel types, and the radio-toxicity of spent nuclear fuel discharged within about 1000 years is almost two orders of magnitude lower than those fuels involving ^{239}Pu due to the much lower transuranium (TRU) production in the thorium based fuel. However, the TCR was found to be too small for the thorium based fuel, and furthermore the coolant TCR and the moderator TCR tend to be positive when ^{233}U is the dominant fissile component. It is therefore necessary to optimize the fuel composition and the pebble geometry to improve the performances of a thorium based FHR (TFHR).

The aim of this work is to obtain an enough negative TCR for (^{233}U, ^{232}Th) O_2 fuel and a deep burnup by optimizing the graphite-to-heavy metal ratio (C/HM) and the ^{233}U-to-HM atom ratio ($^{233}U/HM$) of the fuel pebble. It should be noted that the attainable burnup for a fuel pebble is not only determined by its geometrical structure and fuel composition but also by the performance of TRISO fuel particles undergoing neutron irradiation for a long time. The related researches on the TRISO form fuel to improve its capability for deep burnup have been performed extensively since the 1960s (Griveau et al., 2017; Bardet et al., 2008; Prados and Scott, 1964; Kaae, 1969; Walther, 1969; Bongart et al., 1980). The TRISO fuel particles can withstand burnup far beyond that in either light water reactor (LWR) or fast reactor systems, as demonstrated in former tests (Jonnet et al., 2010; Alberstein, 1994). The main objective of this study is to perform a neutronic optimization of fuel pebble to obtain its attainable burnup without considering the actual fuel damage limit by neutron irradiation. The neutronic analyses, including effective multiplication factor (k_{eff}), temperature coefficient of reactivity (TCR) and conversion ratio, are performed in a view of neutron usage. The methodology for pebble and core modeling is introduced in Section 2. The calculation tool is introduced in Section 3. The calculated results and discussions are presented in Section 4. The conclusions are given in Section 5.

2. General description of PB-TFHR

2.1. Fuel pebble modeling

The schematic diagram of the fuel pebble is shown in Fig. 1. The fuel pebble consists of an inner fuel zone with thousands of tri-structural isotropic (TRISO) coated particles embedded in a spherical graphite matrix and an outer spherical graphite shell. The TRISO coated particle

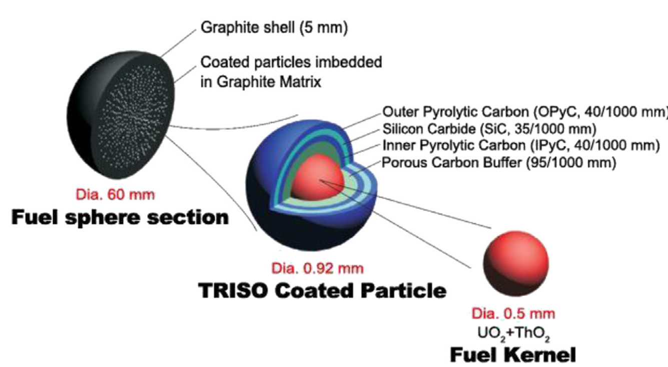

Fig. 1. Schematic sketch of a fuel pebble and TRISO.