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Development and application of optimal burnup estimation methodology for pebble bed reactor

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ABSTRACT

The optimal burnup, which is essential for core design, represents the discharged fuel properties of the core at equilibrium state. The optimal burnup estimation is complex in a pebble bed reactor because the fuel elements are small, numerous and continuously recirculated through the core. In this work, a facilitative method for estimating the optimal burnup of pebble bed reactor is developed. The method employs a single pebble depletion analysis and the neutron non-leakage probability of the core to estimate the attainable burnup of the pebble fuel in the core. With the developed method, the properties of homogeneous mixture fuel of thorium and uranium were analyzed, and the relation of heavy metal utilization with C/HM (graphite-to-heavy metal atom ratio) was also studied. The result shows that, for thorium utilization with homogeneous mixture of seed uranium and thorium fuel, higher enrichment of uranium is preferred. And for a typical pebble design with 20% enriched seed uranium, the heavy metal utilization is about 0.64%, which is equivalent to traditional pressurized water reactor.

1. Introduction

The fluoride salt cooled High temperature Reactor (FHR) (Allen et al., 2013a,b,c; Ingersoll et al., 2004; Forsberg, 2008) has received particular attention because of its excellence in safety, high temperature outlet, deep burn fuel cycle and potential thorium fuel utilization (Wols et al., 2014, 2015; Gintner, 2010; Cisneros et al., 2012). The robust pebble fuel provides an essential foundation for the above attracting performances of FHR.

Thorium has been considering as potential nuclear fuel that could be an alternative fuel to natural uranium from early days in the development of nuclear energy. During the mid 1950s to the mid 1970s, several experimental and prototype power reactors were successfully operated using thorium fuels (IAEA-TECDOC-1450, 2005).

Thorium utilization in FHR relies on the high burnup in equilibrium fuel cycle. However, the equilibrium depletion analysis of FHR is difficult because of pebble fuel element movement and fuel composition changes.

For physics codes of FHR depletion analysis, the attainable burnup and the related fuel composition should be represented accurately. Several models have been developed for FHR depletion analysis by employing deterministic or Monte Carlo method with complicated full core simulations and simplified fuel assembly calculations (Fratoni, 2008; Fratoni and Greenspan, 2010; Holcomb et al., 2011; Xhonneux et al., 2014; Setiadipura and Obara, 2014; Rtten et al., 2011; Zhu et al., 2015; Fratoni et al., 2007, 2008). Among these models, in order to determine the pebble residence time in core and the equilibrium fuel composition, the full core simulation method (Fratoni, 2008; Fratoni and Greenspan, 2010; Holcomb et al., 2011; Xhonneux et al., 2014; Setiadipura and Obara, 2014; Rtten et al., 2011) couples the pebble trajectory in core with its burnup history; however, the simplified fuel assembly model implements the calculation from the neutron balance point of view without considering the pebble movement (Zhu et al., 2015; Fratoni et al., 2007, 2008). The infinite uniform bed method and single pebble in equilibrium bed method (Fratoni, 2008; Fratoni et al., 2007, 2008) are two instances of the simplified fuel assembly model. The infinite uniform bed model assigns all pebbles with same equilibrium composition, and this composition is determined with iteration method of depletion analysis under constant flux. The single pebble in equilibrium bed model assigns equilibrium composition to all of the pebbles in the simulated subset, except that in the center of the subset one fresh pebble is placed. And the fresh pebble is depleted while the other pebbles maintain their set composition. For the two methods, the most

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important procedure is searching the equilibrium state of the system. Before the equilibrium state be confirmed, a tremendous calculations, including k_{eff}, flux, material composition and power has to be performed for each iteration cycle, which requires massive computer time.

This study presents a simple method for estimating the attainable burnup of pebble bed reactor at equilibrium by combining a single pebble fuel depletion analysis with the core neutron non-leakage probability. This method do not searching the equilibrium state, i.e., do not considering how the equilibrium core composition is reached. The validation of this method is performed by calculating the attainable burnup of several FHR designs from references. The depletion analysis is performed by employing MCNP (https://laws.lanl.gov/vhosts/mcnp.lanl.gov/references.shtml#mcnp6refs) with ENDF/B-VII.0 library. This method facilitates the calculating of optimal burnup of pebble bed reactor with reliable precision. Based on the developed method, the thorium utilization of FHR, loaded homogenous mixture fuel of thorium with enriched seed uranium, is calculated.

The rest of this paper is organized as follows. Section 2 gives the detailed explanation of the method. The results of validation of the method are given in Section 3. The application of the method and the results discussion are given in Section 4. And conclusion is presented in Section 5.

2. Methodology

The intent of the developed method is to estimate the optimal discharge burnup level of the pebble fuel in FHR. Normally, the optimal burnup is connected to the equilibrium state of the core, accordingly the deduction of the developed method is based on equilibrium state.

The reactivity of a pebble bed core is a composite of every pebble, considering the contribution to the core total reactivity according to its burnup level. From this point of view, the infinite neutron multiplication factor (IMF) $k_{\infty,\text{core}}$ of the core is expressed with the $k_{\infty,\text{pebble}}$ of pebble lattices in the core.

The $k_{\infty,\text{pebble}}$ is calculated from number of fission neutrons and the absorbed ones of the pebble fuel. For pebble i, the $k_{\infty,i}$ can be written as:

$$k_{\infty,i} = \frac{F_i}{A_i}. \tag{1}$$

F_i is the fission neutron number of pebble i, and A_i is the number of neutron absorption that related to the pebble lattice, including the coolant. The multiplication factor $k_{\infty,\text{core}}$ of a core can be calculated from the sum of reactivity of all pebbles in the core:

$$k_{\infty,\text{core}} = \frac{\sum_{i=1}^{N} F_i}{\sum_{i=1}^{N} A_i} = \frac{\sum_{i=1}^{N} \frac{F_i}{A_i} A_i}{\sum_{i=1}^{N} A_i} = \sum_{i=1}^{N} k_{\infty,i} \frac{A_i}{\sum_{i=1}^{N} A_i}, \tag{2}$$

where N is the total number of pebbles in the core. Defining f_i as the absorbtion fraction of pebble i to all pebbles, that is:

$$f_i = \frac{A_i}{\sum_{i=1}^{N} A_i}, \tag{3}$$

$$\sum_{i=1}^{N} f_i = 1. \tag{4}$$

Then Eq. (2) can be written as:

$$k_{\infty,\text{core}} = \sum_{i=1}^{N} k_{\infty,i} f_i. \tag{5}$$

For pebble i, the $k_{\infty,i}$ and f_i is associated with its burnup level BU_i. Eq. (5) can be expressed as:

$$k_{\infty,\text{core}} = \sum_{i=1}^{N} k_{\infty,\text{pebble}}(BU_i) f(BU_i), \tag{6}$$

in this way the burnup level of all pebble in core were divided into N levels, and BU_i is the burnup level of pebble i. Hence, $f(BU)$ represents the probability or the importance (Sekimoto, 2007) of the pebble fuel with burnup level BU in the core. And, the $k_{\infty,\text{core}}$ is expressed by the weighted mean of the IMFs of all the pebbles in the core. As $k(BU)$ and $f(BU)$ is continuous function, while $N \to \infty$ Eq. (6) is written in integral form:

$$k_{\infty,\text{core}} = \frac{\int_0^{BU_M} k_{\infty,\text{pebble}}(BU) f(BU) d_{BU}}{\int_0^{BU_M} f(BU) d_{BU}}. \tag{7}$$

The upper limit of the integral BU_M is the maximum burnup level of the fuel in core. Pebbles with this burnup level will be discharged from the core.

The function $f(BU)$ represents the fuel burnup level distribution in the core. Since pebbles are circulated through the core many times and reinserted in a random radial location every time, it was reasonable to assume that, at equilibrium, the pebbles are well-mixed so that there is an equal probability to find in any region of the core a pebble at any burnup level at any given time (Allen et al., 2013b). Hence, integrating of all pebbles' neutron contribution to the core (see Eq. (7)) accounts for that the core at equilibrium is equivalent to that a core loaded with an average fuel component. This average fuel component is related to $f(BU)$, i.e., the fuel burnup level distribution in the core. For $f(BU)$ is an continuous function, thus the $f(BU)$ in Eq. (7) could be replaced with a certain average constant value.

While the well mixed pebbles represent the average fuel composition of the core (Allen et al., 2013b) in equilibrium state, and hence dominates the neutron spectrum. And the neutron flux is a constant at equilibrium state. From this perspective, Eq. (7) becomes:

$$k_{\infty,\text{core}} = \frac{1}{BU_M} \int_0^{BU_M} k_{\infty,\text{pebble}}(BU) d_{BU}. \tag{8}$$

Define P_{NL}as the neutron non-leakage probability of the core, then:

$$k_{\infty,\text{core}} = \frac{k_{\text{eff,core}}}{P_{NL}} = \frac{1}{BU_M} \int_0^{BU_M} k_{\infty,\text{pebble}}(BU) d_{BU}, \tag{9}$$

where $k_{\text{eff,core}}$ is the effective neutron multiplication factor of the core. As in equilibrium state, $k_{\text{eff,core}} = 1$ and P_{NL} is considered as a constant. Eq. (9) is written as:

$$\frac{1}{P_{NL}} BU_M = \int_0^{BU_M} k_{\infty,\text{pebble}}(BU) d_{BU}. \tag{10}$$

As Eq. (10) is deduced from the equilibrium state of a pebble bed core, the average fuel composition of the core and the optimal discharge burnup of the pebble fuel could be obtained by solving Eq. (10). The solution of Eq. (10) relies on the evolution of $k_{\infty,\text{pebble}}(BU)$, i.e., the pebble fuel depletion.

In this work, a graphic method is employed to solve Eq. (10). As shown in Fig. 1, Eq. (10) predicates that at a certain BU_M, the inclosed area of $k_{\infty,\text{pebble}}(BU)|_0^{BU_M}$ with the X axis is equal to BU_M/P_{NL}, namely, the area of S1 equals that of S2.

By solving Eq. (10) with graphic method, the BU_M is obtained and hence the components of the discharged fuel. This method saves significant computation time in estimating the optimal burnup of a pebble bed core, since it does not need to search the equilibrium state of the core and only a single pebble depletion evolution simulation is required, which is the same to a traditional burnup simulation.