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Thermo-mechanical Finite Element Analysis of Fuel Pellets Containing Lump Burnable Absorbers

Hyeong Jin Kim [a], Ho Jin Ryu [a] *
[a]Department of Nuclear and Quantum Engineering, KAIST, Daehak-ro 291, Yuseong-gu, Daejeon, 34141, Korea
Corresponding author: hojinryu@kaist.ac.kr

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1. Introduction

A burnable absorber, also known as a burnable poison is a material with a high neutron absorption cross-section, used to control the reactivity of nuclear reactors. More specifically, burnable absorbers are used to reduce the non-flat reactivity: the reactivity swing. Boron and gadolinium are the most common elements in burnable absorbers.

In pressurized water reactors, boric acid (soluble boron) is commonly adopted to reduce the reactivity swing. However, high boron concentrations can cause a positive moderator temperature coefficient (MTC), which can threaten passive reactor safety. To prevent the positive MTC issue, it is necessary to decrease the initial boron concentration, and solid-state burnable absorber can be used for this purpose.

The conventional fuel-burnable absorber designs for commercial reactors are described in Fig. 1. Burnable absorbers can be either (1) mixed with nuclear fuel in powder form, (2) coated on the fuel pellet surface, or (3) both. However, these approaches can lead to increased fuel centerline temperatures, due to the lower thermal conductivity of burnable absorber. At the same time, burnable absorbers in powder form burns out quickly, making it difficult to apply to high burnup cores.

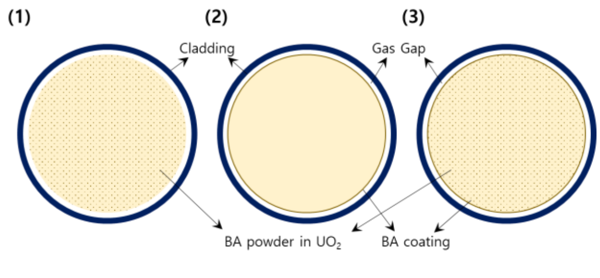

Fig. 1. Common fuel-burnable absorber design for commercial reactors

KAIST research team proposed a method of embedding the lump gadolinia (Gd_2O_3) inside the fuel pellet, known as the centrally-shielded burnable absorber concept [1] to delay the burning of the burnable absorber during the reactor operation. The concept enables its application in long-cycle, high burnup reactors. In this research, material design and database construction for CSBA were performed. And the thermo-mechanical properties of the CSBA composite fuel were calculated using the finite element method.

2. Methods and Results

During the reactor operation, CSBA composite fuel undergoes a decrease in density due to thermal expansion and the phase transformation caused by neutron irradiation, while densification due to sintering. To predict these complex in-reactor behaviors of the CSBA composite fuel, a thermo-mechanical properties database for the burnable absorber material was constructed. Then the high-temperature behavior at the first increase in power (beginning of life, BOL) was analyzed using the finite element analysis tool, ANSYS.

2.1 Burnable absorber material design

The phase transformation of gadolinia from a cubic to monoclinic structure around 1200°C has been reported. The theoretical density of gadolinia is 7.51 and 8.31 g/cm^3 for cubic and monoclinic structures, respectively [2, 3]. In this study, gadolinia discs were manufactured at sintering temperatures ranging from 1050°C to 1400°C. The dimensions and weights were measured to construct a shrinkage rate and sintering density database.

The apparent density of gadolinia discs gradually increased with increasing sintering temperature, and an irreversible phase transformation from a cubic to a monoclinic structure occurred at sintering temperatures above 1250°C.

2.2 Burnable absorber thermal property model

The temperature and porosity-dependent properties of uranium dioxide and gadolinia were collected and formulated for the following thermo-mechanical calculations. Thermal expansion, thermal conductivity, and modulus of 95% TD uranium dioxide were obtained as a function of temperature (using FRAPCON material property correlations for reactor performance analysis codes). Similarly, the temperature-dependent thermal expansion, thermal conductivity, and modulus of gadolinia were obtained for different porosities.

The constructed property models were formulated and input into finite element analysis software for computational simulations of stress generation due to temperature increases.

2.3 Thermo-mechanical analysis of fuel pellet

Computational simulations based on the finite element method were performed to predict the in-reactor high-temperature behavior of CSBA composite fuel. To predict the stress induced by the initial temperature increase (BOL), thermo-mechanical calculations on a CSBA composite fuel composed of uranium dioxide and gadolinia burnable absorber, were conducted: 1) simulations with and without the burnable absorber discs, and 2) simulations with different densities of the burnable absorber. The simulations targeted identifying the stress distribution in the fuel and discs, and assessing the potential for the fuel cracking.

The computational results showed that the maximum stress increased slightly, by approximately 1.7% with the insertion of the gadolinia discs. During the temperature rise, the discs experienced compression in the axial direction, leading to lateral deformation. The change in stress distribution shows that the maximum stress region inside the pellet was on the side of the disc. The identified maximum fuel stress was higher than the UO_2 fracture stress, suggesting the possibility of the fuel cracking at the beginning of operation.

3. Conclusions

In this study, we conducted material design and high-temperature behavior analysis of CSBA concept fuel pellets, to develop a high-burnup, long-cycle fuel technology. We established a density database according to the sintering temperature and optimized the manufacturing conditions. A thermal property database for the fuel and burnable absorber was collected, and then the stress calculation was performed at the BOL.

The finite element analysis predicted the in-reactor high-temperature behavior of CSBA composite fuel, revealing an increase in maximum stress with the insertion of gadolinia discs. In the following research, calculations and experiments on fuel cracking should be conducted to enhance the safety of the CSBA fuel.

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