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Composite Material Properties Simulation for the Fuel Performance Evaluation of Gd_2O_3-Cored UO_2 Fuel

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1. Introduction

Several unique characteristics to enhance the efficiency, improve burnup, and increase the lifetime of the fuel cycle in Light Water Reactors (LWRs) are desired to be obtained in new nuclear fuel designs. These characteristics can be achieved through the utilization of burnable absorbers within the fuel to control the initial reactivity, the fission products poisons buildup, and the loss of reactivity resulting from the temperature changes in the fuel [1]. Therefore, Gadolinia-cored UO_2 burnable absorber fuel design is proposed.

The use of burnable absorbers in previous fuel designs includes the application of boron-containing materials as coatings on fuel pellets as used in Integral Fuel Burnable Absorber (IFBA) [2] or in separate fuel pellets like Wet Annular Burnable Absorber (WABA) [3]. Urania-Gadolinia mixed oxide fuel is also used widely as it provides additional characteristics. Since the burnable absorber exists within the fuel not in separate holes in the fuel assembly, therefore it reduces the handling exposure and decreases the water displacement [4].

Several exclusive characteristics of lumping Gd_2O_3 into small-size particles embedded in the UO_2 pellet make this fuel design a desired option among the advanced nuclear fuel designs. This design enables the control of Gadolinium burning as the surface area is decreased when compared Gadolinia mixed oxide fuel. In addition, the gradual burning of the lumped Gd_2O_3 from the surface to the core supplies a self-shielding phenomenon that enhances the controlled burning of Gadolinium.

The fuel performance evaluation stage for any newly-designed fuel is fundamental to assess the applicability of the new fuel design in the reactors. In this study, the thermal behaviour of Gd_2O_3-cored UO_2 fuel has been evaluated. The preliminary proposed pellet design is a heterogeneous configuration of Gd_2O_3 sphere in the UO_2 fuel pellet. Therefore, composite material properties are necessary to be obtained through experimental measurements, theoretical model calculations for heterogeneous composites such as the rule of mixtures, or simulation using Finite Element Methods (FEM). For this reason, COMSOL Multiphysics, a FEM modeling software, is used to obtain these properties.

In this paper, the thermal analysis for one of the promising designs of the Gd_2O_3 cored UO_2 has been shown. The mechanical analysis results are anticipated to be the next step. The thermal analysis shows the effect of Gd_2O_3 sphere addition to the UO_2 fuel pellet thermally by comparing the temperature profile through the pellet of Gd_2O_3 cored UO_2 and the traditional UO_2 fuel pellets.

2. Design Choice and Dimensions

The design choice is initially influenced by the resulting favorable neutronics performance [5], the chosen design for this study is called the CSBA 1-ball fuel pellet. It consists of a 1-mm in diameter Gd_2O_3 sphere in the center of the UO_2 fuel pellet. Fig. 1 shows the selected design based on the best neutronics behavior.

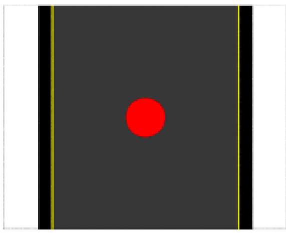

Fig. 1. The selected design of the CSBA fuel [5].

After the design selection, the dimensions of the typical UO_2 fuel pellet are needed. These dimensions were used to simulate the Gd_2O_3 cored UO_2 fuel pellet in COMSOL Multiphysics. Table 1 shows the pellet dimensions used for the simulation [6].

Table 1: UO_2 fuel pellet dimensions and properties [6].

Parameter		Value (cm)
Fuel Pellet	Pellet Radius	0.40958
	Clad Inner Radius	0.41873
	Clad Outer Radius	0.47600
Pellet Dish	Diameter	0.61
	Depth	0.002

3. Data Preparation

Certain general properties regarding the medium of the simulation and initial values as well as material properties of the used materials are necessary to be provided to simulate the Gd_2O_3 cored UO_2 fuel pellet in COMSOL. These properties are collected as functions of mainly the temperature.

It is worth mentioning that the properties of UO_2 fuel, Zircaloy-4 cladding, and the Helium gap are well documented, however, several properties of Gd_2O_3 are not available in the literature. Therefore, the required properties of the analyses, such as the thermal conductivity, were measured at KAIST facilities. The measured properties of Gd_2O_3, alongside UO_2 properties documented in the literature, were used for the analysis.

3.1 General common properties

The common parameters include the initial values of the model, the linear power of the fuel, which is applied as a heat source in the pellet, and some convective heat transfer parameters, such as the heat transfer coefficient and the cladding wall temperature. These parameters are required regardless of the design choice or the materials used. Table 2 summarizes the parameters, their values, and the reference of each parameter's value.

Table 2: The general common parameters.

Parameter	**Value**	**Reference**
Ambient Temperature (°C)	20	Initial value
Pressure (atm)	1	Initial value
Initial Value of T in the pellet (°C)	325	Initial value
Linear Power (kW/m)	21.33	[7]
Coolant Temperature (°C)	325	Westinghouse [8]
Cladding Wall Temperature (°C)	345	Westinghouse [8]
Heat Transfer Coefficient ($W/m^{3}\cdot K$)	~40,000	Calculated from the temperature and heat flux & found in [9]

It is important to mention that the same heat generation rate (linear power) was used for the standard UO_2 fuel and the Gd_2O_3 cored UO_2 fuel even though the fissile material content has been reduced due to the addition of the Gd_2O_3 sphere and the removal of UO_2. In this study, it is assumed that the fuel part of the pellet has higher enrichment that the standard UO_2 fuel to compensate for the less content of the fissile material due to the addition of the Gd_2O_3 sphere in the center of the pellet.

3.2 The UO_2, Zircaloy-4, Helium Gap, and Gd_2O_3 properties

As the materials involved in the analysis are UO_2 fuel, Zircaloy-4 cladding, the Helium gap between the fuel and cladding, and the Gd_2O_3 BA sphere, their properties have been collected from the literature or, when necessary, measured as functions of mainly the temperature.

The material properties of UO_2 were reviewed from MATPRO [10], FRAPCON/FRAPTRAN manuals [11] and a well-known IAEA material properties document [12]. For this study, the thermal conductivity model of unirradiated fuel with a fuel relative density 95% is used. This means that the thermal conductivity was calculated as a function of temperature at zero burnup. In future analysis, the thermal conductivity of irradiated fuel will be used in the thermal evaluation at different burnup steps with the power history of the fuel.

Similar to UO_2, Zircaloy-4 cladding properties as functions of temperature were obtained through the comparison of what MATPRO [10] provides and what is used in FRAPCON and FRAPTRAN codes [11].

The properties of the Helium gas in the gap between the fuel and the cladding was used directly from COMSOL materials library as functions of temperature.

On the other hand, the properties of Gd_2O_3 are scarce and rarely found in the literature. In this regard, all the available material properties of Gd_2O_3 were used and some of the properties were measured at KAIST material characterization facilities, such as the thermal conductivity and the heat capacity. These properties were measured in the temperature range 298 – 1073 K.

After applying all the properties as functions of temperature in COMSOL, the thermal analysis has been carried out. The following sections presents the results and the discussion of the thermal analysis.

4. Results and Discussion

In the thermal analysis, a comparison between the thermal behavior of the standard UO_2 fuel pellet with no Gd_2O_3 sphere and the fuel pellet with a 1 mm in diameter Gd_2O_3 sphere in the center of the UO_2 fuel pellet is presented. Fig. 2 shows the temperature profile as a result of the thermal analysis of the two cases.

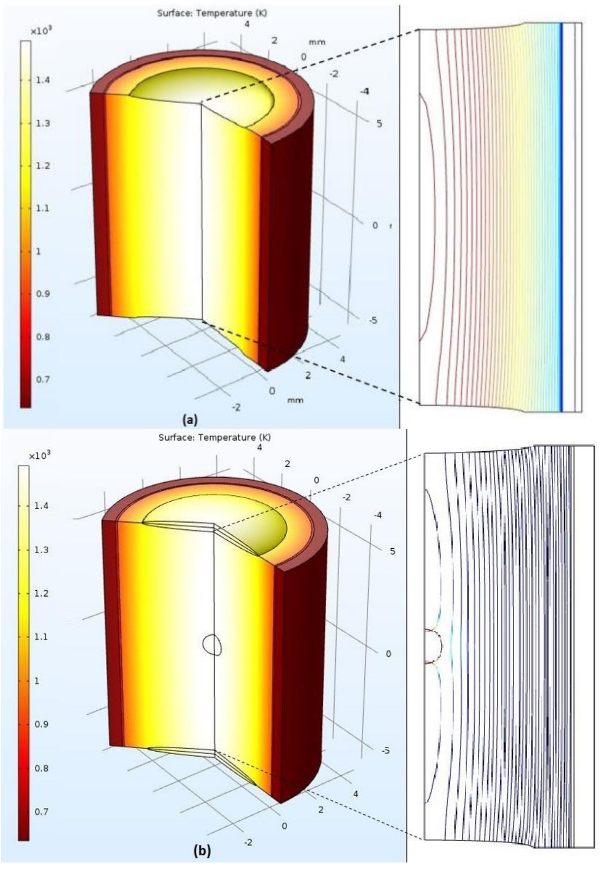

Fig. 2. The temperature profiles of (a) the standard and (b) the Gd_2O_3 cored UO_2 fuel pellets.

The results show that a slight temperature difference between the pellet without sphere and the pellet with a sphere in the temperature profile (1497.9 K for the standard UO_2 pellet and 1493.7 K for the Gd_2O_3-cored UO_2 pellet). It is expected that the temperature at the center of the sphere is lower than of the surrounding UO_2 since there is no fission in the Gd_2O_3 sphere.

Fig. 3 shows the temperature contour lines for the standard UO_2 fuel pellet with no Gd_2O_3 sphere and the Gd_2O_3 cored UO_2 fuel pellet.

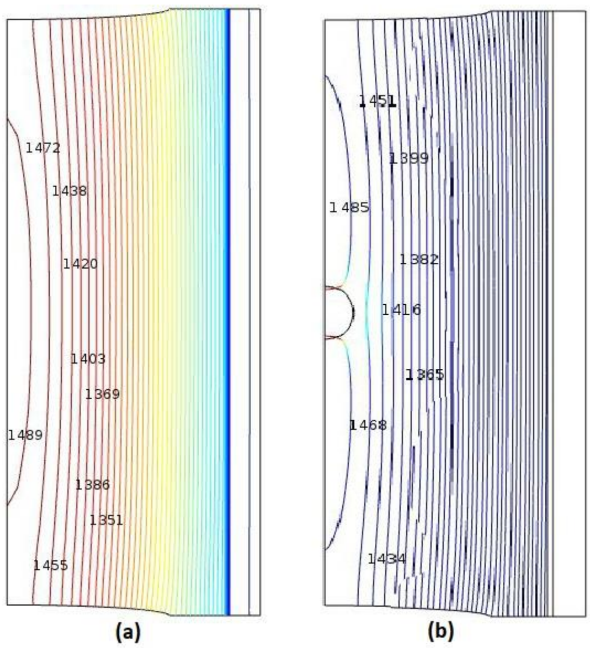

Fig. 3. Temperature contour lines of (a) the standard and (b) the Gd_2O_3 cored UO_2 fuel pellets (temperatures in K).

The results presented in Fig. 3 show that, quantitatively, the maximum temperature, which is around the center of the Gd_2O_3-cored fuel pellet, is around 1485 K. This temperature is lower than the maximum temperature around the center of the standard UO_2 fuel pellet without the sphere, which is approximately around 1489. The difference between the two cases is around 4 K. It is also noticeable that the temperature difference between the two cases within the whole pellet follows the same trend from the center to the surface, radially.

Therefore, it is important to mention that the heat transfer in the presented cases is the radial heat transfer from the center of the pellet to the outer surface, as the radial heat transfer in the top and bottom of the pellet through the helium gap is not considered. In addition, the heat source used in the simulation is a homogeneous fission heat source in the fissile material region. These conditions explain the lower temperature in the Gd_2O_3-cored UO_2 fuel pellet case, due to the absence of the fissile material in the center, which means that the only source of heat in that region is heat generated in the surrounding fissile material.

As a result, the temperature distribution shows negligible changes between the two cases. It is expected that the temperature distribution when the fuel pellet has Gd_2O_3 sphere in the center is similar to that of the standard UO_2 fuel pellet. As the Gd_2O_3 sphere is small compared to the pellet dimensions and its position is in the center, the fission heat in the fuel part is high enough to heat the Gd_2O_3 sphere to a matching temperature to the fuel part of the pellet.

5. Conclusions

In this study, the thermal performance of a selected design of Gd_2O_3 cored UO_2 fuel pellet was performed though the radial heat transfer analysis. A comparison between the thermal behavior of a standard UO_2 and the newly-designed Gd_2O_3 cored UO_2 pellets was presented. The results of the thermal analysis show a negligible difference in the temperature profiles between the Gd_2O_3 lumped pellet and the standard UO_2 pellet.

In addition, as the anticipated next step is the stress analysis, it is expected that the elastic stress analysis results would address minimal stress distributions between the Gd_2O_3 sphere and UO_2 fuel since the thermal expansion mismatch between the two materials is insignificantly small. The preliminary elastic stress analysis showed matching results to the anticipated behavior, but more analysis is needed for the results to be presented.

The next step of the performance evaluation includes some improvements in the thermal analysis, such as taking into account the axial heat transfer, followed by the stress analysis. The stress analysis should take into account the plastic behavior between the Gd_2O_3 sphere and the UO_2 fuel. Followed by the fuel performance evaluation using the codes for normal operation and transient scenarios FRAPCON and FRAPTRAN, respectively. The calculated property models, reflected into the codes by changing the source code, will provide the effects of lumped Gd_2O_3 inclusion on the fuel performance.

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