COMPOSITE MATERIAL PROPERTIES SIMULATION FOR THE FUEL PERFORMANCE EVALUATION OF GADOLINIA-CORED UO_2 FUEL

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ABSTRACT: *Enhancing the efficiency, improving the burnup, and increasing the lifetime of the fuel cycle in Light Water Reactors (LWRs) are critical aspects of the development of advanced nuclear fuels. To accomplish these improvements, Burnable Absorbers (BAs) have been utilized to control the initial reactivity, which presents the excess reactivity that compensates for the fuel depletion, the fission products poisons build-up, and the loss of reactivity resulting from the temperature changes in the fuel. Lumping Gd_2O_3 into small-size particles embedded in the UO_2 pellet is a promising design to utilize the beneficial characteristics of burnable absorbers for an enhanced nuclear fuel performance. As for any newly-designed fuel, fuel performance evaluation is fundamental to assess the applicability of the new fuel design in LWRs. More specifically, examining the thermal and mechanical properties of the fuel is crucial to assess the potential of using this fuel in reactors. In this study, a selected design was analyzed through COMSOL Multiphysics to evaluate its thermal behavior in a nuclear reactor environment. The results show that the newly-designed pellet performs similarly to the typical UO_2 fuel showing negligible temperature changes when compared to the UO_2 fuel pellet performance.*

KEYWORDS: *Gadolinia-cored, nuclear fuel development, burnable absorber, simulation, FEM analysis, thermal analysis*

I. INTRODUCTION

To improve the life-time and the burnup of Light Water Reactors (LWRs), the application of Burnable Absorbers (BAs) can be utilized. These BAs control the reactivity of the fuel and more specifically, the excess reactivity available to compensate for the fuel depletion and fuel temperature change, which results in loss of reactivity, as well as fission products formation and build-up[1]. These BAs must have a high neutron absorption cross section, a burnout rate matching fuel depletion, and the absence of strongly neutron-absorbing radioisotopes to perform superiorly in the reactor[2].

The usage of burnable absorbers includes the application of materials that contain boron in separate fuel pellets such as Wet Annular Burnable Absorber (WABA) (Ref. 3) or as coatings on fuel pellets, for instance, the Integral Fuel Burnable Absorber (IFBA) (Ref. 4). Urania-Gadolinia mixed oxide fuel is also used widely as it reduces the handling exposure and decreases the water displacement as the burnable absorber exists within the fuel not in separate holes in the fuel assembly[5].

Gd_2O_3 cored UO_2 burnable absorber fuel design provides unique characteristics in addition to what the previously mentioned BA fuel designs offer. Lumping Gd_2O_3 into small-size particles embedded in the UO_2 pellet controls the Gadolinium burning as the surface area is decreased. In addition, the gradual burning of the lumped Gd_2O_3 from the surface to the core supplies the BA with a self-shielding phenomenon that enhances the controlled burning of Gadolinium. These characteristics make the lumped Gd_2O_3 embedded in the UO_2 pellet a promising design to achieve the enhanced fuel performance.

As for any newly-designed fuel, fuel performance evaluation is fundamental to assess the applicability of the new fuel design in LWRs. More specifically, examining the thermal and mechanical properties of the fuel is crucial to assess the potential of using this fuel in reactors. In this study, one of the Gd_2O_3 cored UO_2 fuel pellet designs has been evaluated to examine the fuel performance. As one of the proposed pellet design is a heterogeneous configuration of the Gd_2O_3 sphere in the UO_2 fuel pellet, composite properties are necessary to be obtained. These properties can be estimated through experimental measurements, theoretical model calculations for heterogeneous composites such as the rule of mixtures, or simulation using Finite Element Methods (FEM). The calculated fuel material properties include the thermal and mechanical properties that are presented by the thermal conductivity, thermal expansion, elastic constants, and several other properties. To obtain these properties, COMSOL Multiphysics, a FEM modeling software is used.

In this paper, the thermal analysis for one of the promising designs of the Gd_2O_3 cored UO_2 has been done. The 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.

II. PROPOSED DESIGNS AND DESIGN CHOICE

Several proposed designed showed favorable neutronics performance[6], the selected design for this study is the CSBA 1-ball fuel pellet. It contains a 1-mm in diameter Gd_2O_3 sphere at the center of the fuel pellet. Fig. 1 shows the selected design among several proposed designs based on the best neutronics behavior.

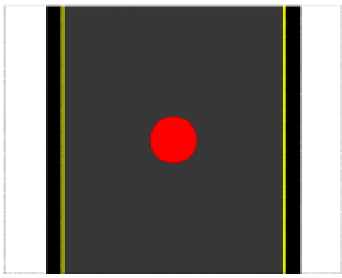

Fig. 1. The selected design of the CSBA fuel[6]

To simulate the selected fuel design, the typical dimensions of UO_2 fuel pellet are needed. Table I shows the pellet dimensions used for the simulation. These dimensions were used to simulate the Gd_2O_3 cored UO_2 fuel pellet in COMSOL Multiphysics software for the thermal behavior evaluation. Using the dimensions data in Table I, a model has been constructed. As mentioned previously, the Gd_2O_3 sphere is 1 mm in diameter.

TABLE I. UO_2 Fuel pellet dimensions and properties

Parameter		Value
Fuel Pellet[7]	Pellet Radius (cm)	0.40958
	Clad Inner Radius (cm)	0.41873
	Clad Outer Radius (cm)	0.47600
Pellet Dish[7]	Diameter (cm)	0.61
	Depth (cm)	0.002

III. PREPARATION OF DATA AND PROPERTIES

In order to simulate the thermal behavior of the Gd_2O_3 cored UO_2 fuel pellet in COMSOL, several general properties regarding the medium of the simulation and initial values are needed. In addition, material properties of the used materials are necessary to be provided for the analysis to be done. These properties are collected as functions of the temperature, mainly. In this section, the data and functions preparation is reviewed and collected.

III.A. General Parameters

General parameters for the analysis are required, these 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 values have been collected and summarized in Table II with the references of each parameter.

TABLE II. General parameters for the analysis

Parameter	Value	Reference
Ambient Temperature (ºC)	20	Initial value
Pressure (atm)	1	Initial value
Initial Value of T in the pellet (ºC)	325	Initial value
Linear Power (kW/m)	21.33	Ref. 8
Coolant Temperature (ºC)	325	Westinghouse[9]
Cladding Wall Temperature (ºC)	345	Westinghouse[9]
Heat Transfer Coefficient (W/m^3.K)	~40,000	Calculated from the temperatures and the heat flux & found in Ref. 10

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, assuming a constant radial power distribution, 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, as the difference in the radial power distribution will be taken into account in the future work. 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.

After obtaining the general parameters and properties needed for the analysis, properties of the materials of interest as functions of temperature are gathered and obtained. For the thermal analysis, the thermal conductivity, heat capacity, density, and the linear thermal expansion strain are gathered for all the materials of the fuel pellet.

III.B. UO_2 Properties

As the next step for this study is to apply the new composite material properties in the fuel performance codes FRAPCON and FRAPTRAN, the focus while collecting the data was related to what models these codes use for the material properties of the fuel. Based on that, the material properties of UO_2 were reviewed from MATPRO[11], FRAPCON/FRAPTRAN manuals[12] and some material properties documents[13]. These properties were compared and collected for the analysis. 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.

III.C. Zircaloy-4 Cladding and the Helium Gap Properties

Similar to UO_2, Zircaloy-4 cladding properties as functions of temperature were obtained through the comparison of what MATPRO[11] provides and what is used in FRAPCON and FRAPTRAN codes[12]. According to these references, the density does not suffer any changes due to the thermal expansion as the temperature of the cladding is relatively low when compared with the temperature of UO_2 or Gd_2O_3. The properties of the Helium gas in the gap between the fuel and the cladding was used directly from COMSOL materials library as it provides all the necessary properties as functions of temperature. The initial fill helium gas pressure is 1.0 MPa (Ref. 14).

III.D. Gd_2O_3 Properties

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. The remainder of this section discusses and reviews the material properties of Gd_2O_3.

The thermal conductivity and the heat capacity of Gd_2O_3 were obtained experimentally. Gd_2O_3 sphere samples were prepared and sent to KARA, the material characterization facility at KAIST, to measure the thermal conductivity and the heat capacity as a function of temperature. The properties were obtained in the temperature range 298 – 1073 K (Ref.15.

Gd_2O_3 density change was calculated through the thermal expansion coefficient or the linear thermal expansion strain. The thermal expansion coefficient data is a function of temperature covering the temperature range of 300 – 1568 K (Ref. 16).

IV. RESULTS AND DISCUSSION

After applying all the properties as functions of temperature in COMSOL, the thermal analysis has been carried out. Three scenarios have been evaluated; the first scenario evaluates the standard UO_2 fuel pellet with no Gd_2O_3 sphere inside. The second case shows the fuel pellet performance with a 1 mm in diameter Gd_2O_3 sphere in the center of the UO_2 fuel pellet. The third scenario is similar to the second one but it takes into account the axial heat transfer through the top of the fuel pellet as the helium gas between the pellets contributes in the heat transfer through the fuel pellet. Fig. 2 represents the thermal analysis of the Gd_2O_3 cored UO_2 fuel pellet taking into account the radial and axial heat transfer. Table III shows the temperature at different positions in the center of the fuel pellet for the three cases as referred to in Fig. 2.

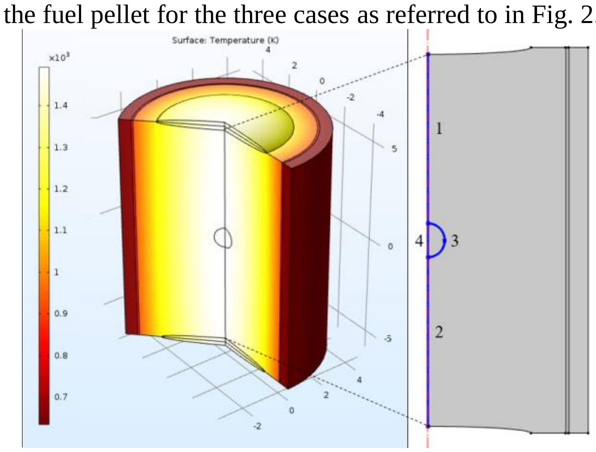

Fig. 2. Thermal analysis results of the Gd_2O_3 cored UO_2 fuel pellet (radial and axial heat transfer)

TABLE III. The temperature at different positions in the center of the fuel pellet for the three cases

Case	Temperature at Positions (K)			
	1	**2**	**3**	**4**
Standard UO_2 Pellet – Radial Heat Transfer	1497.9	1497.9	-	1497.9
Gd_2O_3-cored UO_2 Pellet – Radial Heat Transfer	1493.7	1493.7	1493.7	1487.1
Gd_2O_3-cored UO_2 Pellet – Radial and Axial Heat Transfer	1493.1	1493.1	1493.1	1486.6

When comparing the results of the three scenarios in Table III, it is shown that a slight temperature difference of 4.2 ^{o}C 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). Since there is no fission in the Gd_2O_3 sphere, it is expected that the temperature at the centre of the sphere is lower than of the surrounding UO_2. The temperature at the centre of the Gd_2O_3 sphere is 6.6 ^{o}C less than the temperature of the surrounding UO_2 fuel. In addition, taking into account the heat transfer in the axial direction through the helium gas between the pellets reduces the overall temperature of the fuel pellet by 0.6 ^{o}C (as shown in Table III).

The difference between the first two cases and the third case is that in the first case, thermal isolation was assumed at the top and bottom of the fuel pellet forcing all the heat to go to the center axially. In this case, as the heat has one direction to transfer to, which is the center of the fuel pellet towards the Gd_2O_3 sphere, the temperature of the Gd_2O_3 sphere is expected to be higher than the second case. This phenomenon is reflected in the values as the second case shows a 6.6 ^{o}C difference between position 1 and position 4 and the third case shows a 6.5 ^{o}C difference between the same two positions.

As a result, the thermal performance in terms of the temperature distribution shows negligible changes (maximum of 4.2 ^{o}C). It is expected that the temperature distribution when the Gd_2O_3 sphere is applied at 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 and these three cases validates that phenomenon.

V. CONCLUSIONS

In this paper, the thermal performance of a selected design of Gd_2O_3 cored UO_2 fuel pellet was performed. Three cases were evaluated for the sake of comparison; the standard UO_2 fuel pellet was analyzed first, then its thermal behavior was compared with the Gd_2O_3 cored UO_2 fuel pellet, considering the heat transfer in the radial direction. Lastly, the third scenario represents the Gd_2O_3 cored UO_2 fuel pellet taking into account the axial heat transfer through the top and the bottom of the fuel pellet.

The results of the three cases show a negligible temperature difference in the temperature profile of the pellet without sphere and with the sphere. In addition, the heat transfer in the axial direction through the helium gas between the pellets shows a slight temperature change when taken into account. As expected, these results indicate that the fission happening in the fuel and the heat source that results from fission is large enough to heat the Gd_2O_3 sphere to the same temperature of the fuel.

The next step of the performance evaluation is the thermal expansion/stress analysis of the Gd_2O_3 cored UO_2 pellet, taking into account the elastic and plastic behavior between the Gd_2O_3 and UO_2 fuel with the radial power distribution differences. This analysis will provide reliable information about how safe Gd_2O_3 performs in the UO_2 fuel. In addition, composite material properties, presented by the thermal conductivity, thermal expansion, elastic constants, and other properties, can be calculated.

After acquiring the composite material properties, the fuel performance codes for normal operation and transient scenarios FRAPCON and FRAPTRAN, respectively, will be employed to estimate the performance of the fuel. The calculated property models are reflected into the codes by changing the source code of each of the fuel performance codes. The results of the evaluation provide the effects of lumped Gd_2O_3 inclusion on the fuel performance, including the thermal behavior in terms of the temperature distribution and the mechanical behavior presented as the stress and strain distribution.

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