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Improving the Thermal Conductivity of UO_2 Fuel with the Addition of Graphene

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1. Introduction

Improvement of fuel performances by increasing the fuel thermal conductivity using the BeO [1, 2] or W [3] were reported elsewhere. In this paper, some major fuel performances of improved thermal conductivity oxide (ICO) nuclear fuel with the addition of 10 v/o graphene have been compared to those of standard UO_2 fuel. The fuel thermal conductivity affects many performance parameters and thus is an important parameter to determine the fuel performance. Furthermore, it also affects the performance of the fuel during reactor accidents. The improved thermal conductivity of the fuel would reduce the fuel temperature at the same power condition and would improve the fission gas release, rod internal pressure and fuel stored energy.

Graphene is well known for its excellent electrical conductivity, strength and thermal conductivity. The addition of graphene to the UO_2 fuel could increase the thermal conductivity of the ICO fuel. Although the graphene material is extensively studied recently, the characteristics of the graphene material, especially the thermal properties, are not well-known yet.

In this study, we used the Light Water Reactor fuel performance analysis code FRAPCON-3.2 [1] to analyze the performance of standard UO_2 and ICO fuel.

2. Thermal conductivity modeling of the ICO fuel.

Several theoretical models are available to calculate the expected thermal conductivity of ICO fuel. Classical and widely used model is the Maxwell [2] model which deals with the random mixture of spherical particles in the matrix.

$$k_{nf} = k_f \left[1 + \frac{3(\alpha - 1)\varphi}{(\alpha + 2) - (\alpha - 1)\varphi} \right] \tag{1}$$

Where k_{nf} is the effective thermal conductivity of the mixture, k_f is the thermal conductivity of the matrix, α is k_p/k_f (k_p is the thermal conductivity of solid particles), and φ is the particle volume fraction.

The Hamilton-Crosser model [3] could be applied to the mixture of different shape particles by introducing the empirical shape factor of the dispersed particles:

$$k_{nf} = k_f \left[\frac{\alpha + (n-1) - (n-1)(1-\alpha)\varphi}{\alpha + (n-1) + (1-\alpha)\varphi} \right] \tag{2}$$

Where n is an empirical constant which reflects shape effects of the particle and must be determined experimentally for mixtures containing particles of arbitrary shapes. The equation (2) is reduced to the Maxwell equation (1) when the dispersed particle shape is spherical.
Hamilton-Crosser described in their paper [3] that the data on the mixtures of graphite flakes are correctly predicted by equation 2 with n value to be 6. With no other data on graphene geometry effect are available and considering the shape of the graphene to be thin plate, we took the value of n to be 6 for conservative estimate of the effect of graphene addition. The thermal conductivity of ICO fuel was calculated using the Hamilton-Crosser model with the thermal conductivities of the graphene and of the standard UO_2 fuel.

3. FRAPCON Thermal Conductivity Function.

The subroutine FTHCON in FRAPCON code [1] is the part where the thermal conductivity of the fuel is calculated. Lucuta model [4] is used as thermal conductivity model for UO_2 fuel and as the basic model to derive the thermal conductivity of the ICO fuel with the effect of graphene addition as described in above.

The Lucuta model is as follows:

$$K = K_o \bullet FD \bullet FP \bullet FM \bullet FR \tag{3-1}$$

Where K_o is thermal conductivity of unirradiated, FD is a factor for dissolved fission products, FP is a factor for precipitated fission products, FM is a factor to correct for the Maxwell porosity effect and FR is factor for the radiation effect.

Thermal conductivity of un-irradiated, fully dense urania and factors included in the Lucuta model are described by the Equations (3-2) through (3-6).

$$K_o = \frac{1}{0.0375 + 2.165\times10^{-4}T} + \left[\frac{4.715\times10^9}{T^2}\right]\exp\left[-\frac{16361}{T}\right] \tag{3-2}$$

$$FD = \left[\frac{1.09}{B^{3.265}} + \frac{0.0643}{\sqrt{B}}\sqrt{T}\right]\arctan\left[\frac{1}{\frac{1.09}{B^{3.265}} + \frac{0.0643}{\sqrt{B}}\sqrt{T}}\right] \tag{3-3}$$

$$FP = 1 + \left[\frac{0.019B}{3-0.019B}\right]\left[\frac{1}{1+\exp\left(-\frac{T-1200}{100}\right)}\right] \quad (3\text{-}4)$$

$$FM = \frac{1-p}{1+(s-1)p} \quad (3\text{-}5)$$

$$FR = 1 - \frac{0.2}{1+\exp\left(\frac{T-900}{80}\right)} \quad (3\text{-}6)$$

Where K_o is conductivity of un-irradiated (W/m-K), T is temperature (K), B is burnup in atom% (1 atom% = 9.383 GWD/MTU at 200 MeV/fission), p is porosity fraction (as-fabricated plus swelling) and s is shape factor (= 1.5 for spherical pores).

4. Simulation results

Performances of the UO_2 and the ICO fuel were evaluated by FRAPCON code. The effect of the graphene addition into the ICO fuel was incorporated into the K_o of the Lucuta model using the model derived in Section 2. The ANO 2 power history which is included in FRAPCON manual was used in this calculation as a reference power history. Comparisons of some of the important fuel performances are shown in graphical form.

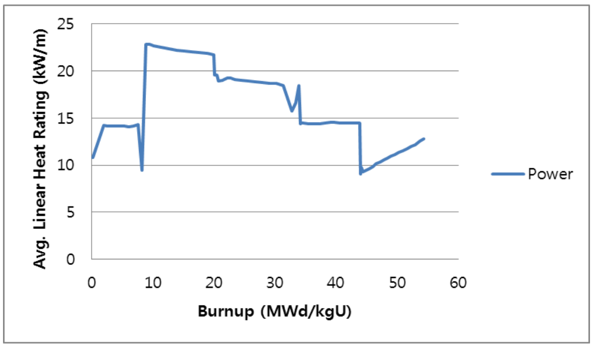

Fig. 1. The reference power history used in this calculation.

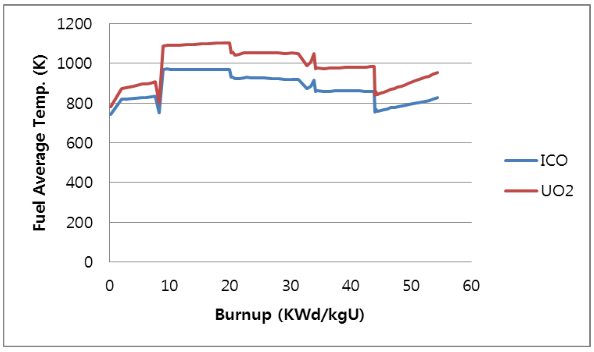

Fig. 2. Fuel average temperature as a function of fuel rod average burnup for UO_2 and ICO fuels.

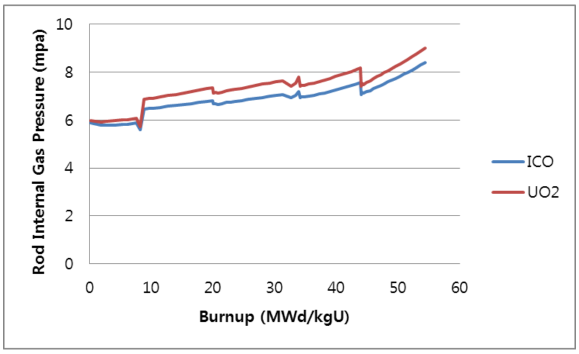

Fig. 3. Fuel rod internal pressure as a function of fuel rod average burnup for UO_2 and ICO fuels.

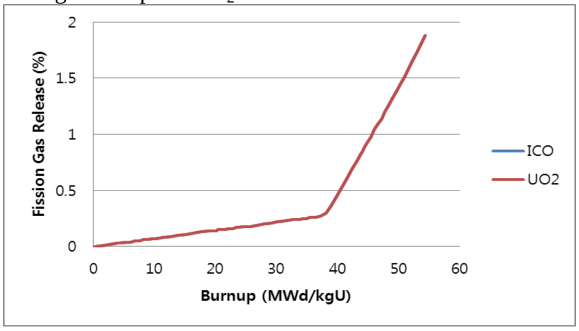

Fig. 4. Fission gas release as a function of fuel rod average burnup for UO_2 and ICO fuels.

5. Conclusions

In this study, the effect of 10 v/o graphene addition to UO_2 fuel was evaluated by comparing the performances of the UO_2 fuel and ICO fuel using FRAPCON code. The thermal conductivity of the ICO fuel was modeled by the Hamilton-Crosser model to incorporate the shape effect of the graphene. As was expected, the ICO fuel showed marked improvements in major performance parameters such as fuel average temperature, rod internal pressure and fission gas release.

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