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Evaluation of Nuclear Fuel Centerline Temperature Using New UO_2 Thermal Conductivity Models

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Abstract: The nuclear industry needs of prediction of behavior and life-time, for a wide range of normal, off-normal and accident conditions for safe and economic operation. Among different thermo-mechanical properties that can be predictable, the knowledge on the radial temperature distribution of the UO_2 (uranium dioxide) nuclear fuel during the operation of nuclear reactors is essential for safety as different mechanical and thermal-hydraulic thresholds should be respected. One of the attributes of the Brazilian CNEN (Nuclear Energy Commission) is to assess the performance of the fuel rods used in these reactors in high-burnup regimes. The effective removal of the heat generated in the fuel rods constitutes one of the primary points to consider in the design of nuclear reactors. One of the important physical parameters in the study of heat conduction from the nuclear fuel to the coolant in a PWR (pressurized water reactor) is its thermal conductivity. It is therefore desirable that the empirical models, updated for the calculation of thermal conductivity in the fuel region be developed from new sets of experimental data from the irradiated fuel rods in controlled environments. This paper presents the obtained results of implementing of a new model for thermal conductivity of the UO_2 in the FRAPCON code.

Key words: Nuclear fuel, uranium dioxide, thermal conductivity, PWR.

1. Introduction

With the evolution of the technology, theoretical and experimental researchers have been trying to streamline the empirical equations that predict the thermal conductivity of UO_2, incorporating new models for the phonons and including the dependency of temperature in its functional form [1, 2]. Due to the low thermal conductivity of the fuel material (UO_2), a quite steep temperature gradient appears in the pellet. Considerably high temperatures are reached at the pellet center and an important safety criterion is to keep the temperature of the fuel below the melting point [3]. High-burnup is another interest of the nuclear power plants operators and researches about new models are desirable and can be found in the literature [4, 5]. In this paper the fthcon.f subroutine, contained in the MATPRO package of the FRAPCON-3.4 [6, 7] code was modified to include a new model proposed by Dias [8, 9]. The results obtained for temperature distribution in the center line of the fuel rod from the modified code were compared to those produced by the same code when using other models with an explicit dependency on temperature.

1.1 The FRAPCON 3.4 Code Description

FRAPCON-3.4 is an analytical tool developed by PNNL (Pacific Northwest National Laboratory) that calculates LWR (light water reactor) fuel rod behavior

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in "steady-state". This includes situations such as long periods at constant power and slow power ramps that are typical of normal power reactor operations. The code calculates the variation with time of all significant fuel rod variables, including fuel and cladding temperatures, cladding hoop strain, cladding oxidation, fuel irradiation swelling, fuel densification, fission gas release, and rod internal gas pressure. In addition, the code is designed to generate initial conditions for transient fuel rod analysis by FRAPTRAN, the companion transient fuel rod analysis code.

The FRAPCON-3.4 code has two major modules. FRAPCON-3.4 uses fuel, cladding, and gas material properties from MAPTRO that have been recently updated to include burnup-dependent properties and properties for advanced zirconium based cladding alloys. For the mechanical model, the user may select the FRACAS-I model (finite difference model) or the FEA (finite element analysis) model. The FRACAS-I model is recommended by PNNL and is the default selection.

2. Models for UO_2 Thermal Conductivity

2.1 Model Proposed by Ronchi et al.

Disregarding the contribution of radiation, Ronchi et al. [1] proposed the following expression for the thermal conductivity of UO_2 samples with 95% theoretical density:

$$\lambda(T) = \frac{a_1}{a_2+a_3T} + \frac{a_4}{\sqrt[2]{T^5}} e^{-\frac{a_5}{T}} \quad (1)$$

where, T is the temperature in the region of the fuel pellet, expressed in Kelvin, and $a_1 = 100.0$, $a_2 = 6.548$, $a_3 = 0.02353$, $a_4 = 2.024 \times 10^{11}$, $a_5 = 1.635 \times 10^4$ are constant.

2.2 Model Proposed by Fink et al.

From a set of experimental information fuller than that used by Ronchi et al. [1], Fink recommended the use of the following expression for the thermal conductivity of UO_2 samples with a 95% theoretical density [2]:

$$\lambda(T) = \frac{a_1}{a_2+a_3T+a_4T^2} + \frac{a_5}{\sqrt[2]{T^5}} e^{-\frac{a_6}{T}} \quad (2)$$

where, T is the temperature in the region of the fuel pellet, expressed in Kelvin, and $a_1 = 100.0$, $a_2 = 7.541$, $a_3 = 0.01769$, $a_4 = 3.6142 \times 10^{-6}$, $a_5 = 2.24 \times 10^{11}$ and $a_6 = 1.635 \times 10^4$ are constant.

Eq. (2) adjusts the data of Ronchi et al., as well as that from different authors who used other experimental data sources for temperatures under 2,600 K [1].

2.3 Original Model for the fthcon.f Subroutine

The original *fthcon.f* subroutine form the FRAPCON-3.4 code calculates the UO_2 thermal conductivity using the following expression:

$$\lambda(T) = \frac{1}{a_1+a_2T+f(Bu)+g(Bu)h(T)} + \frac{a_3}{T^2} e^{-\frac{a_4}{T}} \quad (3)$$

where, constants $a_1 = 4.52 \times 10^{-2}$, $a_2 = 2.42 \times 10^{-4}$, $a_3 = 3.5 \times 10^9$, $a_4 = 1.66 \times 10^4$ are defined for the start of life of the reactor (BOL), T is the temperature of the pellet in Kelvin, Bu is the fuel burn in MWD/kg UO_2 and functions $f(Bu)$, $g(Bu)$ and $h(T)$ are written as:

$$f(Bu) = 1.87 \times 10^{-3} Bu \quad (4)$$

$$g(Bu) = 3.8 \times 10^{-2} Bu^{0.28} \quad (5)$$

$$h(T) = \frac{1}{1+396.0e^{-\frac{6380.0}{T}}} \quad (6)$$

From a more detailed analysis of Eq. (3), it is possible to conclude that, for low temperatures, the thermal conductivity quickly decreases in low burns, whilst in high temperatures this decline is approximately linear.

2.4 Model Proposed by Dias

The model proposed by Dias for the UO_2 thermal conductivity is based mainly on the form of derivatives for the variation models and exponential for grid defects. Based on 1195 experimental measurements on the thermal conductivity of UO_2 found in the literature, Dias [8]. adjusted the following expression:

$$\lambda(T) = \sum_{i=1}^{4} \frac{3f_{pi}a_i}{g_{pi}T_i} \left(\frac{\frac{T}{g_{pi}T_i}}{1+\left(\frac{T}{g_{pi}T_i}\right)^3} \right)^2 + a_5 g_{p5} E \cdot \frac{e^{-(g_{p5}E)/(T+3113)}}{(T+3113)^2} \quad (7)$$

where,

$$f_{pi} = \frac{1}{1+a_{pi}p} \quad (8)$$

$$g_{pi} = 1 + b_{pi}p_1 \quad (9)$$

Porosity effect correlations valid for $0 \leq p \leq 0.27$. The adjustment coefficients in Eq. (7) are found in Table 1.

The five different terms in Eq. (7) have a clear functional dependency on temperature and are written as follows:

$$Term\ 1 = \frac{1.110\times10^{-3}T^2}{(1+6.889\times10^{-4}T^3)^2} \quad (10)$$

$$Term\ 2 = \frac{6.434\times10^{-6}T^2}{(1+1.079\times10^{-7}T^3)^2} \quad (11)$$

$$Term\ 3 = \frac{3.298\times10^{-7}T^2}{(1+4.496\times10^{-9}T^3)^2} \quad (12)$$

$$Term\ 4 = \frac{5.007\times10^{-8}T^2}{(1+4.923\times10^{-10}T^3)^2} \quad (13)$$

$$Term\ 5 = \frac{3.206\times10^{8}e^{-\frac{34202.0}{T+3113.0}}}{(T+3113.0)^2} \quad (14)$$

3. Specifications of the Nuclear Fuel Rod Simulated

The basic parameters used in the performance evaluation of a typical fuel rod in PWRs, as in operation in Brazil, are provided in Table 2.

The simulation presented here took into account a constant linear power history of 21.33 kW/m during 1,000 days, for a total burnup of 44.25 MWD/kg of UO_2.

In order to evaluate the burnup evolution of the centerline temperature, the fuel rod was axially sub-divided into 7 equally-spaced intervals where only the central interval was considered, that is, of the fourth interval, contained between the quotas (1.829 m, 2.351 m). Table 3 shows the axial distribution of the heat flow in the fuel rod, considered as co-sinoidal for the peak to average power ratio, equal to 1.5080.

In the next section, the results obtained using the modified FRAPCON-3.4 code including the Dias model for the thermal conductivity of the UO_2 will be presented. The results will be compared with the results obtained using the models proposed by Ronchi et al. [1] and Fink et al. [2] that had been presented in Section 2.

Table 1 Adjustment constants for thermal conductivity as proposed by Dias [8], Eq. (7).

a_1	1.12	a_3	31.3	a_5	9,373.0
a_{p1}	21.7	a_{p3}	5.6	a_{p5}	3.16
T_1	9.22	T_3	561.0	E	284,000.0
b_{p1}	4.56	b_{p3}	1.6		
a_2	24.5	a_4	33.9		
a_{p2}	4.67	a_{p4}	0.0		
T_2	210.0	T_4	1236.0		
b_{p2}	0.0	b_{p4}	0.493		

Table 2 Fuel rod specifications (Zircaloy 4).

Pellet diameter	8.192 mm
Inner diameter of lining	8.357 mm
Length of pellet column	3.6576 mm
Internal pressure of the He gas	3.103 MPa
Pressure of coolant	15.494 MPa
Coolant inlet temperature	287.5 ºC

4. Results

The importance of each one of the terms in Eq. (7), written by Eqs. (10)-(14), can be seen in the Fig. 1.

From Fig. 1, it is possible to observe that Terms 2-4 are the most important for lower temperatures (T < 500 K) while the Term 5, rules the behavior of the thermal conductivity in higher temperatures (T > 2,000 K). In median temperatures (500 K < T <2,000 K) all terms except the Term 2 contribute significantly with the behavior of the thermal conductivity. It is interesting that the model proposed by Dias [8] includes low temperatures that are actually of little practical interest in nuclear reactor engineering.

The Fig. 2 shows the models proposed by Ronchi [1], Fink [2], and Dias [8], respectively Eqs. (1), (2) and (7).

Table 3 Axial distribution of the heat flow in the fuel rod.

Axial region	Height (m)	Unnormalized heat flux
1	0.261	0.2768
2	0.783	0.6484
3	1.306	0.9023
4	1.829	0.9923
5	2.351	0.9023
6	2.874	0.6484
7	3.396	0.2768

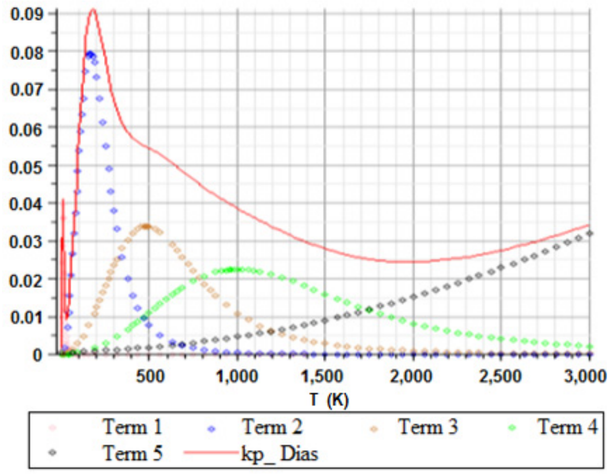

Fig. 1 Evaluation of the importance of each term used in the model proposed by Dias [8].

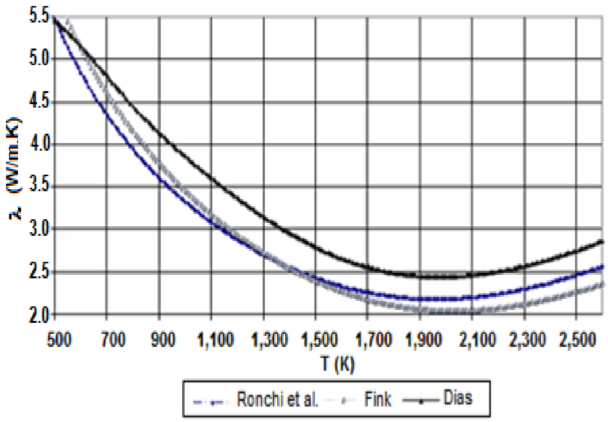

Fig. 2 Dependent temperature models, simulated in the present work using the FRAPCON 3.2 code.

From Fig. 2, it is possible to conclude that the model recommended by Dias [8] overestimates the other models, keeping the same behaviour in the temperature interval (500 K, 2,500 K).

This section presents the results obtained with the FRAPCON-3.4 code for the core temperature of the fuel rod specified in Table 2. The original FRAPCON-3.4 code was used and then modified with the correlations for thermal conductivity for the UO_2 pellet, with 95% theoretical density as shown in Section 2.

From Fig. 3, it is possible to conclude that the original FRAPCON code model predicts the highest temperatures for the core line of the fuel rod, being the most conservative model amongst all of those simulated. The other models, recommended by Fink

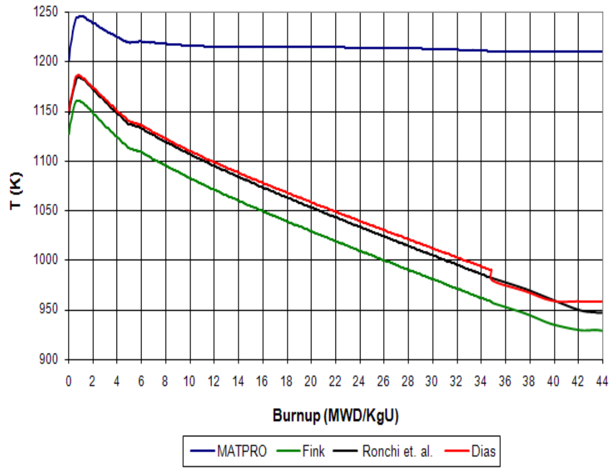

Fig. 3 Centerline temperature according to the models proposed by Fink et al. [1], Ronchi et al. [2], and Dias. [8]

[1], Ronchi et al. [2] and Dias [8], do not have an explicit dependency on the burnup and, because of that, produce similar results amongst them, albeit smaller than those produced by the original model in existence in the set of MATPRO subroutines. The model proposed by Dias [8] is the one that gets the closest to the original one along the entire operating range although it presents considerable deviations when in high burn regimes.

5. Conclusions

A new model for the thermal conductivity of the UO_2 was inserted in the FRAPCON 3.4 code replacing the original model that considers the burnup in an explicit way. The same was made with the models proposed by Ronchi et al. [1] and Fink. [2]. Based on the results obtained, it is possible to conclude that, from a regulatory standpoint, it is advisable to use models for thermal conductivity that take the fuel burnup into account, as the original model of the FRAPCON 3.4 code. The original model in the FRAPCON 3.4 code considers the reduction in the capacity to conduct heat of the fuel pellet as time goes by during normal operation and should be used, avoiding the models that consider only the temperature in the explicit way.

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