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Evaluation of modeling options for in-pellet power distribution and gap gas conductance for accurate fuel temperature predictions

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ABSTRACT

Having the ability to predict fuel temperatures for efficient multi-physics steady state, depletion, and transient calculations with reasonable accuracy without the added burden of prohibitively expensive computation costs has been a major driving force in the nuclear industry. There are several parameters that have an immense impact on fuel surface and centerline temperatures. Sensitivity studies were performed to investigate the impact of gap gas conductance and internal pin power distribution on the fuel temperature predictions. As a result, areas of improvement in the CTF fuel performance model were identified by separating different effects, and analyzing the sensitivity of results to each model improvement. The performed studies demonstrated the importance of modeling internal pellet power distribution for accurate prediction of fuel centerline temperature. Furthermore, a new gap gas conductance modeling option that leverages the fuel performance code FRAPCON was implemented in the fuel rod model of CTF. Gap gas conductance data was pre-computed as a function of linear heat rate and fuel exposure, and was integrated into CTF as part of the new model. Using FRAPCON as a reference solution, the new FRAPCON-informed gap conductance model of CTF was found to calculate results within 2 degrees Kelvin of FRAPCON predictions with respect to fuel surface temperature. This study indicated the feasibility of developing an efficient framework for informing the low fidelity fuel rod models of thermal-hydraulic codes, in this case CTF, with more accurate pre-computed values by leveraging high fidelity fuel performance codes such as FRAPCON. CTF was able to utilize this tabulated data provided by the FRAPCON fuel performance code as well as to include the above mentioned improvements in each axial node of a given rod to provide a full three-dimensional representation.

1. Introduction

Subchannel methods have been actively used in industry and in several high-visibility international projects for efficient coupled (multi-physics) reactor core calculations. In any multi-physic framework the accurate and efficient fuel performance modeling plays an important role. Any miss-prediction of fuel rod temperature distribution will affect the Doppler feedback calculation. Modeling of in-pellet radial power distribution, gap gas conductance, and fuel thermal conductivity are among the most important aspects in the multi-physics codes' ability to predict accurate fuel pin temperature profiles with respect to steady state, cycle depletion, and transient simulations.

There has been a surfeit of options available to predict nuclear fuel performance, including best estimate methods to more computationally expensive but expectedly accurate ones. The prediction of fuel performance under steady state, and cycle depletion as well as transient conditions is heavily reliant on the prediction of the gap gas conductance that exists between the fuel cladding, usually composed of some sort of Zircaloy alloy, and nuclear fuel pellet in the form of UO_2. An accurate prediction of heat loss across the gap gas is of paramount importance in predicting the fuel surface temperature, which then affects the prediction of fuel centerline temperature.

The subchannel code CTF (Avramova, 2016) and the fuel performance code FRAPCON (Geelhood and Luscher, 2014) were used in the reported studies utilizing the Consortium for Advanced Simulation of Light Water Reactor (CASL) Virtual Environment for Reactor Applications (VERA) Core Physics Benchmark Progression

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Problem Specifications (Godfrey, 2014). Identical model for the benchmark problem was created in the two codes. It has to be noted that the fuel type, burnup and gadolinium dependent fuel thermal conductivity model has been implemented and tested in CTF based on the latest correlations available in FRAPCON (Yilmaz et al., 2016).

2. Problem specifications

Single pellet channel problem specifications were procured from the VERA Core Physics Benchmark Progression Problem Specifications (Godfrey, 2014). The geometry, state properties, and material properties are modeled identically among all three codes, and are listed in Table 1. Linear power used in the models is core averaged along with coolant inlet temperature set to core average temperature at Hot Full Power Conditions (HFP). Similarly, the core inlet mass flux was set to a value for an average fuel rod. The simulations were performed at three burnup steps (zero, 11.5, and 23.0 GWD/MTU) and assuming five different power levels (from 50 to 150 percent of the nominal power), which resulted in fifteen comparison points in total. It was not possible to extract accurate data for zero burnup value from FRAPCON, therefore, the burnup step of 0.1 GWD/MTU was employed for comparison. These comparison points listed in Table 2. No burnable poisons were modeled. Fig. 1 illustrates the subchannel configuration of the single pellet model used for simulation.

3. Gap conductance and in-pellet power distribution sensitivity study

The sensitivity study was performed to investigate the impact of different gap conductance modeling options, and internal pin power distribution (RPD) on the fuel temperature predictions. Furthermore, it illustrated areas of improvement in CTF fuel performance model by separating the different effects, and analyzing the sensitivity of the results to each model improvement.

3.1. *In-pellet radial distribution sensitivity*

Fig. 2 and Table 3 show results depicting the impact of in-pellet RPD on fuel rod centerline temperature at different burnup levels. As expected, there was practically no variation in the outcome with respect to inner and outer clad temperatures. Looking at the fuel centerline temperatures, it is evident from the results that the in-pellet RPD had the largest impact when the fuel thermal conductivity was burnup-dependent. Since most of the power is generated at the outermost region of the pellet, a model which takes into account the internal pin distribution should display lower fuel centerline temperature. This observation was corroborated by the results in Fig. 2, where the results with modeling option for in-pellet radial pin power distribution active (with RPD) are shown along with the results with the model inactive (w/o RPD).

Table 1
Problem geometry and boundary conditions.

Parameter	Value
Fuel pellet radius	0.4096 cm
Inner clad radius	0.418 cm
Outer clad radius	0.475 cm
Fuel pellet length	1.3462 cm
Fuel rod pitch	1.26 cm
Fill gas material	Helium
Plenum spring material	Stainless Steel
Initial cladding thickness	0.057 cm
Initial gap thickness	0.0084 cm
Nominal Linear Power	18.3031 kW/m
Coolant flow rate	0.3063 kg/s
Percent fuel theoretical density	95.5%
CTF theoretical density	10.9704 g/cm^3
FRAPCON theoretical density	10.96 g/cm^3
CTF theoretical density input	95.5%
FRAPCON theoretical density input	95.5906%
Percent Uranium in UO$_2$	88.15%
Coolant inlet temperature	585 K
System pressure	15.513 MPa
Coolant mass flux	3485.31 kg/m^2-s

Table 2
Case Matrix for Comparison (15 comparison points).

Power Level [%]	Burnup Level [MWD/kgU]		
50	0.1	11.5	23
75	0.1	11.5	23
100	0.1	11.5	23
120	0.1	11.5	23
150	0.1	11.5	23

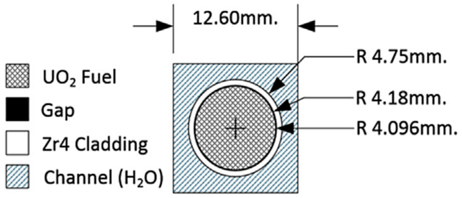

Fig. 1. Single pellet channel initial geometry.

3.2. *Gap conductance sensitivity*

Additional sensitivity study was performed to purely investigate the effect of different gap gas conductance modeling options on the fuel temperature predictions. For this analysis, the CTF "best estimate model", which uses a fixed gap conductance of 9000 W/(m^2-K) was compared to the CTF model procuring the gap gas conductance from FRAPCON. The fuel thermal conductivity burnup-dependency option was turned off for this comparison. Aside from the difference in the gap gas conductance values, the two models were identical. Table 4 through 7 present the results of this comparison. Outer clad and inner clad temperatures were nearly identical, as expected, since gap gas exists between inner clad and fuel surface and the calculation moves from outer clad to inner clad, from inner clad to fuel surface, and finally from fuel surface to fuel centerline. A fairly large discrepancy was observed for fuel surface temperature followed by an equally larger discrepancy with respect to fuel centerline temperature.

3.3. *CTF and analytical solution comparison*

To confirm the accuracy of the CTF heat conduction solver, CTF results were compared to the analytical solution for cladding inner temperature, fuel surface temperature, and fuel centerline temperature. Cladding outer temperature was taken from CTF as-is to initiate the calculation. No attempt was made to analytically solve the clad outer temperature since that was beyond the scope of this study. The difference between the two solutions (delta) was computed by subtracting CTF temperature solution from the analytical temperature solution.

The comparison was performed first with the fuel thermal conductivity burnup dependency option disabled in the input, and