Nuclear Engineering and Design 322 (2017) 464–473

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Comparative analysis of different fidelity fuel performance models for fuel temperature predictions

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ARTICLE INFO

Keywords:
CTF
BISON
FRAPCON
Nuclear
Fuel performance

ABSTRACT

Thermal-hydraulics subchannel models have proven to give an acceptable compromise between modeling fidelity and computational efficiency in coupled multi-physics steady state, depletion, and transient calculations. The accuracy in modeling both gas-gap conductance and fuel thermal conductivity is of significant importance for fuel temperature prediction, which, in turn, is crucial for calculation of Doppler feedback on power. A comparative analysis of fuel performance models of different fidelity was performed using the sub-channel code CTF, and the higher fidelity fuel performance codes FRAPCON and BISON. The purpose of this study was to ascertain the predictive accuracy of the informed fuel rod model in CTF, thus the potential to inform this model using data from higher fidelity fuel performance models. Excellent agreement was found between CTF and FRAPCON, and between CTF and BISON with respect to inside clad temperature as well as to fuel surface and fuel centerline temperatures when the CTF gap conductance was set to the BISON and FRAPCON calculated gap conductance values. With respect to the CTF and FRAPCON comparison, the maximum temperature difference between the two codes for a given power level and burnup value was below 2 degree Kelvin for clad inner surface and fuel surface temperature. For fuel centerline temperature, the maximum temperature difference was found to be below 7 degree Kelvin at the highest power level and burnup value. Similarly, the CTF and BISON comparison resulted in maximum temperature differences less than 5 degree Kelvin for the fuel centerline temperature. These results demonstrate that, if the gap conductance, dimensions, and radial power distribution is correctly set in CTF, the CTF-predicted rod temperature distribution will match closely with higher fidelity tools and licensed industry level fuel performance codes for normal operating conditions.

1. Introduction

Sub-channel methods are ideal candidates for efficient coupled (multi-physics) calculations, and in this coupled approach the fuel performance modeling plays an integral part. Any miss-prediction of fuel rod temperature distribution will affect the Doppler feedback calculation. Both gap conductance modeling and fuel thermal conductivity modeling play an important role in the codes' ability to predict accurate fuel pin temperature profile with respect to multi-physics cycle depletion and transient simulations.

In order to test the fuel performance capability of the sub-channel code CTF (Avramova, 2016), two high fidelity fuel performance codes, namely FRAPCON and BISON (Geelhood and Luscher, 2014; Hales et al., 2013), were used for comparative analysis. Using the Consortium for Advanced Simulation of Light Water Reactor (CASL) Virtual Environment for Reactor Applications (VERA) Core Physics Benchmark Progression Problem Specifications (Godfrey, 2014), an identical model was created in all three 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 and BISON (Yilmaz et al., 2016). The first step composed of running the model simulation in CTF and extracting the clad outer surface temperature, and then passing this information on to BISON and FRAPCON to be used as a boundary condition. BISON and FRAPCON would perform the simulation using this clad outer surface temperature, and provide gap conductance value and internal pin power distribution to CTF to be used as input to the fuel rod model. Finally, CTF executes the input deck using the two provided values. This procedure is utilized to achieve consistent comparisons. To gauge the agreement among CTF, FRAPCON, and BISON, two separate comparisons were done. FRAPCON and BISON were not compared directly since the primary purpose of this study is to evaluate the accuracy of corresponding informed CTF fuel performance models against higher fidelity codes. For this reason, the comparison was done between CTF

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http://dx.doi.org/10.1016/j.nucengdes.2017.07.025
Received 2 January 2017; Received in revised form 18 July 2017; Accepted 20 July 2017
0029-5493/

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
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%
BISON theoretical density input	95.0%
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

and FRACON, and between CTF and BISON.

2. Problem specifications

The 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 (HFP). Similarly, the core inlet mass flux was set to a value for an average fuel rod. The simulations were performed at three separate burnup steps: 0.0, 11.5, and 23.0 GWD/MTU. It was not possible to extract accurate data for zero burnup value from FRAPCON and BISON, therefore, for the zero burnup case, a burnup step of ~0.1 GWD/MTU was employed for comparison. The 15 comparison points can be found in Table 2. No burnable poison was used in the comparison models. Fig. 1 illustrates the subchannel configuration of the single pellet model, which was used for simulation.

3. Modeling strategy for code-to-code comparisons

3.1. Comparative analysis approach

The purpose of this study was to ascertain the predictive accuracy of the informed fuel rod model in CTF, thus the potential to inform this model using data from higher fidelity fuel performance models. Because of this objective, the comparative analysis between the corresponding informed CTF fuel rod models and high-fidelity fuel performance codes such as FRAPCON and BISON has to be made as consistent as possible. In this section, the general approach is described while in Sections 3.2 and 3.3 the specific procedures applied to CTF to FRAPCON and CTF to BISON comparative analyses are detailed.

Table 2
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

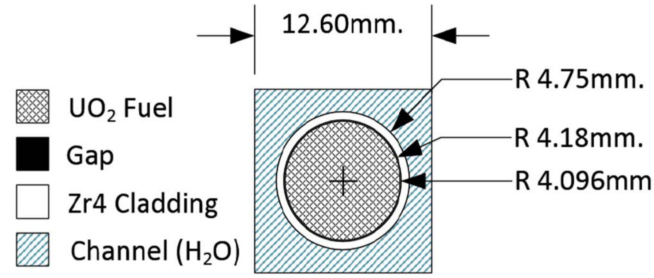

Fig. 1. Single pellet channel initial geometry.

In the continued development of CTF, an improved fuel thermal conductivity model has been added, which gives a correlation for fuel thermal conductivity as a function of burnup and gadolinium content (Yilmaz et al., 2016). Boundary conditions were applied to ensure that code-to-code comparisons demonstrate only the effects of power and burnup on the fuel temperature. CTF was first run at each power level to determine the outer cladding temperatures given the heat flux, flow parameters, and initial geometry. These temperatures were then used as boundary conditions for BISON and FRAPCON. This was performed to eliminate any discrepancies in temperature evaluation from the coolant convection models so that each code had the same temperature boundary. The fuel performance codes were evaluated at each power level, using each respective outer cladding boundary condition, and were run until the end burnup was achieved. The radial power factors (RPF), gap conductance values, and geometries were then taken from each fuel performance code, at each power and burnup level, and were evaluated in a second CTF run.

For the evaluation of these codes, comparisons were performed in pairs: FRAPCON vs. CTF and BISON vs. CTF. This was done due to differences in FRAPCON and BISON codes that created different gap conductance values at the same power and burnup values. This created 30 unique CTF cases; 15 paired with FRAPCON values and 15 paired with BISON values. For this process, a script was created for the FRAPCON model evaluations that constructed each input deck with the varying power and boundary conditions, executed the code, and post–processed the output.

The fuel performance codes reported significant cladding geometry changes in each case. The changes in fuel rod diameter affected the wetted perimeter, coolant surface area, and channel area such that CTF reported up to 0.5 degrees Kelvin difference in cladding surface temperature when compared to the initial CTF geometry. To maintain consistent outer cladding temperatures between the fuel performance codes and CTF, two separate techniques were used. Further specific modeling detail is discussed in the following sections.

3.2. FRAPCON model

FRAPCON did not allow for a displacement boundary condition, so an additional iteration was added to acquire new outer cladding temperature boundary conditions. For the comparison to FRAPCON, CTF was first run and the outer cladding temperatures were used in FRAPCON as an outer clad temperature boundary condition. After the first FRAPCON run, the geometry changes were implemented in the respective CTF runs along with the RPF and gap conductance values i.e. the FRAPCON fuel geometry, RPF values, burnup, and gap conductance values were then passed back to CTF for a second CTF iteration. The first FRAPCON iteration was compared to the second CTF iteration. The cladding radial geometry changes in FRAPCON could not be directly stopped in the same manner as BISON. The new outer cladding temperature computed by CTF was then used for a second FRAPCON run. Thus, a second FRAPCON vs. CTF comparison was completed where the FRAPCON cladding geometry was used in the second CTF iteration. The second comparison included updating the associated channel area,