

Review of CTF's Fuel Rod Modeling Using FRAPCON-4.0's Centerline Temperature Predictions

Aysenur Toptan,^a Robert K. Salko,^b Maria N. Avramova^a^aNuclear Engineering Department, North Carolina State University, Raleigh, NC 27695^bOak Ridge National Laboratory, CASL Division, Oak Ridge, TN 37831

atoptan@ncsu.edu, salkork@ornl.gov, mnavramo@ncsu.edu

INTRODUCTION

Coolant Boiling in Rod Arrays–Two Fluid (COBRA-TF), or CTF¹ [1], is a nuclear thermal hydraulic subchannel code used throughout academia and industry. CTF's fuel rod modeling is originally developed for VIPRE code [2]. Its methodology is based on GAPCON [3] and FRAP [4] fuel performance codes, and material properties are included from MATPRO handbook [5]. This work focuses on review of CTF's fuel rod modeling to address shortcomings in CTF's temperature predictions. CTF is compared to FRAPCON which is U.S. NRC's steady-state fuel performance code for light-water reactor fuel rods. FRAPCON calculates the changes in fuel rod variables and temperatures including the effects of cladding hoop strain, cladding oxidation, hydriding, fuel irradiation swelling, densification, fission gas release and rod internal gas pressure. It uses fuel, clad and gap material properties from MATPRO. Additionally, it has its own models for fission gas release, cladding corrosion and cladding hydrogen pickup. It allows finite difference or finite element approaches for its mechanical model.

In this study, FRAPCON-4.0 [6] is used as a reference fuel performance code. In comparison, Halden Reactor Data for IFA432 Rod 1 and Rod 3. CTF simulations are performed in two ways; informing CTF with gap conductance value from FRAPCON, and using CTF's dynamic gap conductance model. First case is chosen to show temperature is predicted correctly with CTF's models for thermal and cladding conductivities once gap conductance is provided. Latter is to review CTF's dynamic gap conductance model. These Halden test cases are selected to be representative of cases with and without any physical contact between fuel-pellet and clad while reviewing functionality of CTF's dynamic gap conductance model. Improving the CTF's dynamic gap conductance model will allow prediction of fuel and cladding thermo-mechanical behavior under irradiation, and better temperature feedbacks from CTF in transient calculations.

THEORY

CTF employs a finite difference form of the conduction equation. The difference equations are formulated using the "heat balance" approach accommodating unequal mesh spacing, material properties, internal resistances, and radial power profiles. The finite difference nodes of the conduction equation are modeled as control volumes connected by thermal resistances. Formed set of linearized equations is solved by Gaussian elimination. Temperature distribution is obtained in the fuel rod, and fuel centerline temperature is calculated by

¹RDFMG version of COBRA-TF, being developed in conjunction with ORNL in CASL's VERA-CS

Hermite interpolation.

The user can either specify constant properties of fuel, gap and cladding in CTF's input deck or allow CTF to calculate fuel thermal conductivity as function of temperature, burnup and gadolinia content; gap conductance using its dynamic gap conductance model; and cladding thermal conductivity as a function of temperature. In this study, main focus is to review the CTF's dynamic gap conductance model, which can be summarized into two categories; thermal and mechanical aspects of the gap.

Thermal Aspects CTF allows two options for specification of gap conductance; user-defined gap conductance and dynamic calculation of the gap conductance. The dynamic gap conductance model calculates the gap conductance as a summation of conduction through the fill gas, solid-solid conductance through contact, and radiation. The convective heat transfer in the gap is ignored due to a thin gap approximation. Surface deformations of fuel pellet and cladding are encountered in calculation of the gap conductance.

Mechanical Aspects The changes in the gap thickness are due to fuel and cladding differential thermal and irradiation-driven expansion and contraction. CTF assumes that the fuel is centered in the cladding as a perfect cylinder. When there is a physical contact between fuel pellet and cladding, the minimum gap thickness is set to a mean surface roughness value as the surface roughness will maintain a minimum gas layer. The criterion for the pellet-clad contact is either the gap thickness is less than 3.6 times the summation of the fuel and clad inner surface roughnesses or contact pressure is greater than zero. The gap thickness is calculated mechanistically including phenomena affecting the gap thickness; fuel and clad thermal expansions, fuel relocation due to cracking and elastic deformation of the cladding.

The mechanical properties of UO₂ are from MATPRO-11 handbook [5]. Metallurgical and chemical status of the fuel, gap and cladding is not encountered in CTF. More information about the dynamic gap conductance model can be found in CTF's Theory Manual [1].

VERIFICATION

The aim is to compare predicted result with simple hand-calculation. CTF is thermal-hydraulic subchannel code, and provides better prediction of clad outside as a boundary condition to fuel performance codes. This study verifies that CTF is capable of calculating the fuel centerline temperature once all properties are provided to CTF correctly, which could be through look-up tables.

A simple case is chosen without any source, viscous dissipation and pressure effect in a single channel. The problem is steady-state and one-dimensional. A constant linear power rate is applied along the fuel length. The fuel thermal conductivity and gap heat transfer coefficients are kept constant. Parameters are perturbed as given in Table I.

TABLE I: Input model parameters.

Symbol	Description	Unit	Value
q'	Linear power rate	kW/m	5-30
\dot{m}	Inlet mass flow rate	kg/s	0.1-0.5
D_f	Fuel pellet diameter	m	0.007-0.009
t_g	Gap thickness	m	0.00002-0.000065
t_c	Cladding thickness	m	0.0002-0.000824
k_f	Fuel thermal cond.	W/m-K	5.0-25.0
h_g	Gap conductance	W/m ² -K	1000-4000

Fig. 1 shows the agreement between the analytical results and CTF predictions. The results are in good agreement. CTF temperature predictions are in good agreement with analytical results. The maximum discrepancy is found to be 0.2% in fuel centerline temperature.

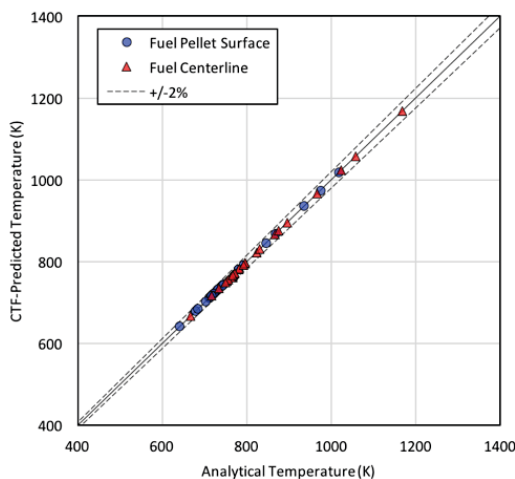


Fig. 1: CTF-predicted temperature vs. analytical temperature

COMPARISON

CTF's dynamic gap conductance model is tested with Halden experimental and FRAPCON-4.0 simulation results for UO₂ fuel. First, the gap conductance is specified in CTF from FRAPCON-4.0 to show temperature profile is predicted correctly with CTF's models for thermal and cladding conductivities. CTF has options for fuel thermal conductivity as a function of burnup, temperature and gadolinia content. This feature is recently added to CTF. Then, CTF's dynamic gap conductance model is turned on to examine existing status of CTF's fuel rod modeling. For the assessment, following Halden test cases are selected as: IFA432 Rod 1 and Rod 3 through of the reactor's life (i.e., as a function of burnup). Those rods are chosen to be representative of test cases with and without any physical contact between fuel-pellet and clad

while reviewing functionality of CTF's dynamic gap conductance model.

CTF Input Model Description Pressure–pressure inlet and outlet boundary conditions are specified. The mass flow rate is set to $\sim 1 \times 10^{-5}$ kg/s, which is very near zero. CTF input decks are created based on the simulated results via FRAPCON-4.0. The radial power distribution and burnup values are defined in CTF from FRAPCON-4.0 simulations for the selected Halden IFA test cases; IFA432 Rod 1 and Rod 3. The specifications for the test cases are provided in Table II.

TABLE II: Input Specifications for IFA432

<i>Rod</i>		
Fuel stack height	m	0.579
Coolant pressure	MPa	3.448
<i>Fuel</i>		
Material		UO ₂
Surface roughness	μm	85
Theoretical density	%	95.5
Pellet diameter		
Rod 1	mm	10.681
Rod 3	mm	10.528
<i>Cladding</i>		
Material		Zr-2
Outside diameter	mm	12.789
Wall thickness	mm	0.94
Surface roughness (inner)	μm	25
<i>Gap</i>		
Fill gas pressure	MPa	0.1
Fill gas composition		helium

Experimental data are extracted from FRAPCON's Integral Assessment Manual [7]. FRAPCON input decks are from the same manual as well. A burnup dependent fuel thermal conductivity is used in both codes. Radial power distribution, linear power rate and burnup are provided to CTF at each time-step from FRAPCON. Additional simulation specifications are as:

- CTF with gap conductance from FRAPCON; gap conductance value and rod dimensions from FRAPCON are provided to CTF at every time-step
- CTF's dynamic gap conductance model; CTF-predicted hot-state rod dimensions from previous time-step are provided to next-time step in CTF

Fig. 2 shows the average linear heat rate (left y-axis) and burnup (right y-axis) with respect to time for IFA432 Rod 1 and 3. The power history is provided to CTF. The clad outside (i.e., wall) temperature is set to a constant value in CTF from FRAPCON-4.0 simulations.

Results Fig. 3 show the measured and predicted fuel centerline temperature predictions at the lower thermocouple position for IFA432 Rod 1 and 3. Also, CTF-predicted fuel centerline temperatures are plotted against the FRAPCON-4.0 predicted fuel centerline temperature predictions for the specified IFA test cases in Fig. 4. CTF simulations are performed

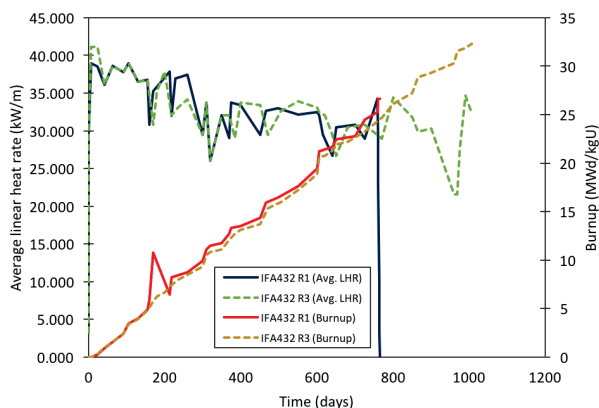


Fig. 2: Average linear heat rate and burnup vs. time

for two cases when (1) gap conductance values are provided from FRAPCON-4.0 at each time-step, and (2) CTF's dynamic gap conductance model is turned on. CTF centerline temperature predictions agree well with the FRAPCON-4.0 for first case, which indicates that CTF calculates fuel and cladding thermal conductivities correctly. For latter case, CTF simulations follow the similar trend as FRAPCON-4.0.

The gap conductance is dominated by the fill gas conductance in these simulations. Fig. 5 shows the fraction of the gap conductance due to the gas conductance. The effects of the radiation in the gap conductance is less than 4% for IFA432 Rod 1 and 0.04% for Rod 3. The contact between fuel pellet and cladding starts after around 400 days in Fig. 5, where CTF predictions start to deviate significantly from FRAPCON's predictions in Fig. 3.

Contact conductance between fuel pellet and clad is defined in terms of material properties and geometry of the interface. Interfacial pressure between the fuel and clad is generated by applied displacement, and is computed using the equilibrium stress, Hook's Law and the applied displacement. Main reason for the deviation in Fig. 3 is that FRAPCON has a more complicated mechanical model than CTF. It calculates the applied displacements including effects of several physics such as densification, swelling, relocation, creep etc. as compared to CTF. As an example, the effects of these physics on overall fuel surface deformation are shown for IFA432 Rod 1 and 3 in Fig. 6. For IFA432 Rod 3, total change in fuel radius is mainly governed by thermal expansion of the fuel. CTF takes into account only the effects of thermal expansion and fuel relocation due to cracking on the fuel radial deformation. This is why CTF's predictions are better in Fig. 4 for IFA432 Rod 3 as compared to Rod 1.

CONCLUSIONS

CTF's dynamic gap conductance model is reviewed. CTF fuel temperature predictions are compared with FRAPCON-4.0 predictions for the selected Halden test cases; IFA432 Rod 1 and 3. Those rods are chosen to be representative of test cases with and without any physical contact between fuel-pellet and clad while reviewing functionality of CTF's dynamic gap conductance model. CTF simulations are performed in two ways;

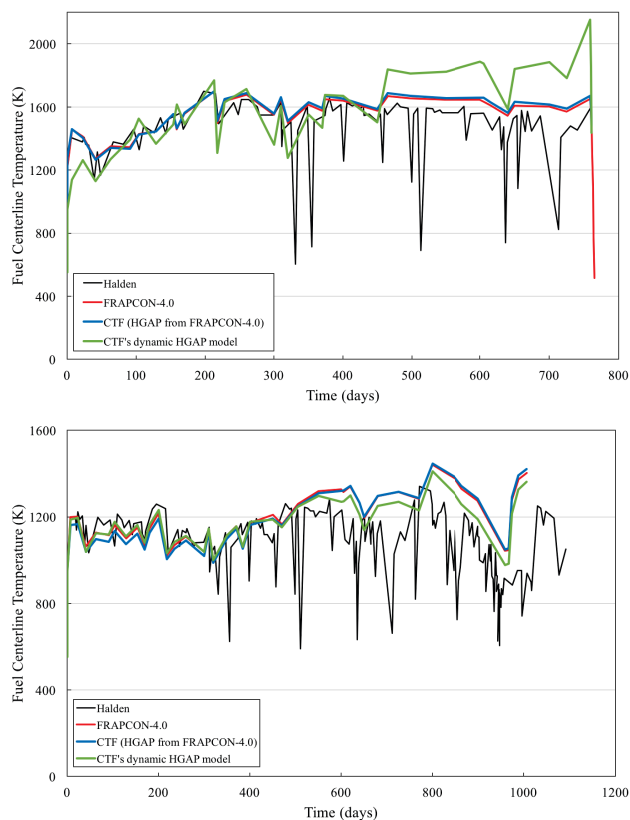


Fig. 3: Measured and predicted fuel centerline temperature for IFA432 Rod 1 and 3 at lower thermocouple position

informing CTF with gap conductance value from FRAPCON, and turning on CTF's dynamic gap conductance model. In the first case, the CTF's temperature predictions agree well with FRAPCON results. This indicates that CTF calculates fuel and cladding thermal conductivities accurately. For the second case, the fuel centerline predictions follow similar trends, yet CTF starts to deviate from FRAPCON significantly. Even thermal aspects of gap conductance in CTF is similar to FRAPCON, FRAPCON is superior in calculation of mechanical changes in gap. This study underlies need for improvement of mechanical model in CTF's dynamic gap conductance model. Improvement of CTF's model is particularly important for transient calculations in CASL's VERA-CS to provide accurate thermal feedbacks. Methodology to improve CTF's mechanical model is to add missing deformation models to CTF from MATPRO or develop new transient low-fidelity models using high-to-low fidelity modeling approach. In this case, BISON will be used as the high-fidelity fuel performance code.

ACKNOWLEDGEMENTS

This research is supported by and performed in conjunction with the Consortium for Advanced Simulation of Light Water Reactors (<http://www.casl.gov>), an Energy Innovation Hub (<http://www.energy.gov/hubs>) for Modeling and Simulation of Nuclear Reactors under U.S. Department of Energy Contract No. DE-AC05-00OR22725.

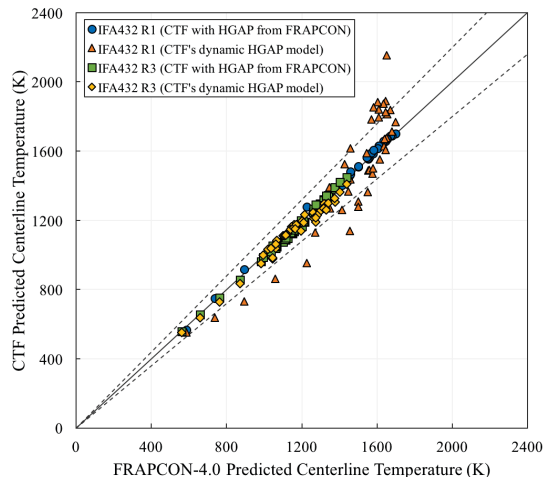


Fig. 4: CTF vs. FRAPCON-4.0 predicted fuel centerline temperature

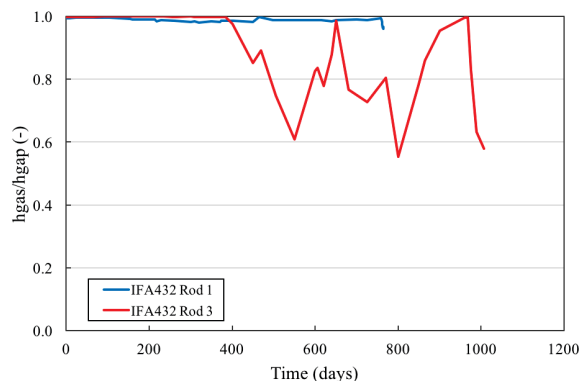


Fig. 5: Fraction of the gap conductance due to gas conductance for IFA432 Rod 1 and 3 based on FRAPCON-4.0 predictions

REFERENCES

1. RDFMG-CTF, "CTF - A Thermal Hydraulic Subchannel Code for LWRs Transient Analysis Theory Manual," Tech. rep., NCSU (2016).
2. C. STEWART, J. CUTA, A. KOONTZ, J. KELLY, K. BASEHORE, T. GEORGE, and D. ROWE, "VIPRE-01 A Thermal-Hydraulics Analysis Code for Reactor Cores: Volume 1, Mathematical Modeling," Tech. Rep. NP-2511, EPRI (1982).
3. C. BEYER ET AL., "GAPCON-Thermal 2: A Computer Program for Calculating the Thermal Behavior of an Oxide Fuel Rod," Tech. Rep. BNWL-1898, PNNL (1975).
4. J. DEARIEN ET AL., "FRAP-S3: A Computer Code for the Steady-State Analysis of Oxide Fuel Rods- Report I, Analytical Models and Input Manual," Tech. Rep. TFBP-TR-164, INEL (1977).
5. D. HAGRMAN, G. REYMANN, and R. MANSON, "MATPRO-Version 11 (Revision 1): A Handbook of Materials Properties for Use in the Analysis of Light Water Reactor Fuel Rod Behavior," Tech. Rep. NUREG/CR-0497,

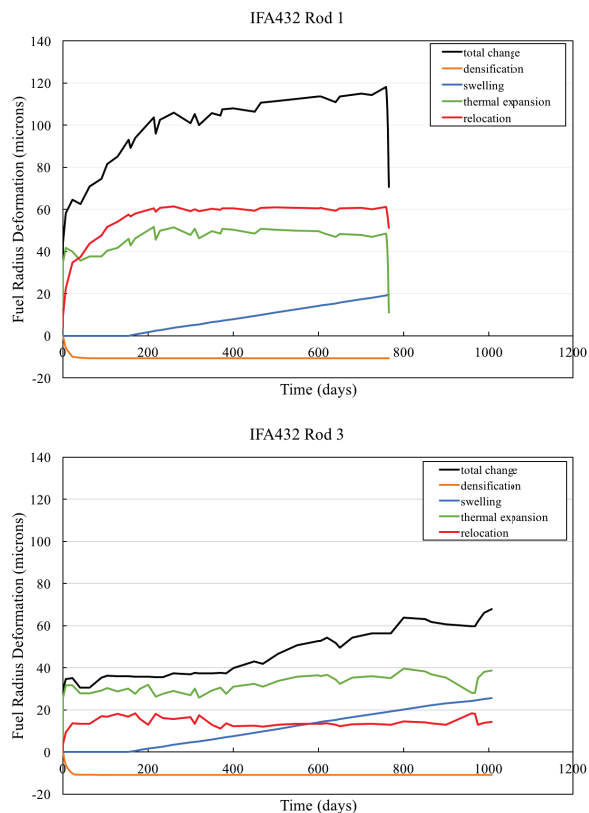


Fig. 6: Fuel surface deformation vs. time for IFA432 Rod 1 and 3

TREE-1290, INEL (1980).

6. K. GEELHOOD, W. LUSCHER, P. RAYNAUD, and I. PORTER, "FRAPCON-4.0: A Computer Code for the Calculation of Steady-State, Thermal-Mechanical Behavior of Oxide Fuel Rods for High Burnup," Tech. Rep. PNNL-19418, Vol.1 Rev.2, PNNL (2015).
7. K. GEELHOOD and W. LUSCHER, "FRAPCON-4.0: Integral Assessment," Tech. Rep. PNNL-19418, Vol.2 Rev.2, PNNL (2015).