Progress in Nuclear Energy xxx (2017) 1–15

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

Multi-physics code system with improved feedback modeling

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ARTICLE INFO

Article history:
Received 2 April 2016
Received in revised form
10 July 2016
Accepted 2 March 2017
Available online xxx

Keywords:
Doppler feedback
Fuel thermal conductivity degradation
Nuclear reactor multi-physics
CTF/TORT-TD
CTF/TORT-TD/FRAPCON-FRAPTRAN

ABSTRACT

Fuel temperature (Doppler) feedback modeling in the coupled sub-channel thermal-hydraulic/time dependent neutron transport codes system CTF/TORT-TD was improved by accounting for the burnup dependence of the fuel thermal conductivity. TORT-TD is a three-dimensional (3D) time dependent neutron-kinetics code based on the discrete ordinates (S_N) method. CTF is the Reactor Dynamics and Fuel Modeling Group (RDFMG) version of the sub-channel thermal-hydraulics code COBRA-TF (COlant Boiling in Rod Arrays – Two Fluid). A burnup-dependent fuel rod model, which takes into account the degradation of the fuel thermal conductivity at high burnups and the effects of burnable poisons, such as Gadolinium, was implemented in CTF. The model is applicable to UO_2 (uranium dioxide) and MOX (mixed oxide) nuclear fuels – it includes the modified Nuclear Fuel Industries (NFI) model for UO_2 fuels and the Duriez/Modified NFI model for MOX fuels. The in-pellet fuel temperature distributions predicted by CTF/TORT-TD were compared to reference CTF/TORT-TD/FRAPCON calculations, in which the fuel rods were modeled with the fuel performance code FRAPCON. These comparisons were carried out for a 4×4 pressurized water reactor (PWR) pin array at hot full power (HFP) steady state conditions. The CTF/TORT-TD fuel temperature predictions were consistent with the CTF/TORT-TD/FRAPCON results. This fact demonstrated that CTF with the new fuel thermal conductivity model can predict the temperature field within light water reactor (LWR) fuel rods as accurately as FRAPCON. Therefore, CTF/TORT-TD calculations can be carried out in fast scoping studies instead of the computationally expensive CTF/TORT-TD/FRAPCON calculations. The performed statistical analyses indicated an improved accuracy of fuel temperature calculations relative to the CTF/TORT-TD/FRAPCON reference numerical solution. Furthermore, better agreement between CTF/TORT-TD and CTF/TORT-TD/FRAPCON in calculated neutronic reactivity was found when fuel burnup effects were considered in CTF/TORT-TD. Therefore, the improved CTF/TORT-TD can be seen as a high fidelity multi-physics computational tool capable of providing accurate and efficient simulations for practical reactor core design and safety analysis.

1. Introduction

Models for degradation of the fuel thermal conductivity with burnup already exist in the fuel performance codes such as FRAPCON and FRAPTRAN-3.4 (Geelhood et al., 2010a, 2010b; Lusher and Geelhood, 2010), whereas most of the thermal-hydraulics codes still use simplified fuel rod models along with the 1979 MATPRO-11 material properties of unirradiated UO_2 (uranium dioxide). Modeling of the fuel thermal conductivity degradation (TCD) is of high importance for accurate predictions of the fuel temperature (Doppler) feedback and thus for reactor safety evaluations.

The modified Nuclear Fuel Industries (NFI) (Lusher and Geelhood, 2010) model for UO_2 fuel rods and the Duriez/Modified NFI model (Lusher and Geelhood, 2010) for MOX (mixed oxide) fuel rods were already implemented in the stand-alone CTF (Salko and Avramova, 2013). The two models take into account the degradation of the fuel thermal conductivity with high burnups and its dependence on the presence of burnable poisons such as Gadolinium, for example. The modified CTF was validated using the Halden fuel temperature measurements (Geelhood et al., 2010c). In addition, a CTF-to-FRAPCON-3.4 benchmarking was carried out (Yilmaz, 2014). It was demonstrated that overall CTF with the burnup-dependent fuel thermal conductivity models predicts the

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http://dx.doi.org/10.1016/j.pnucene.2017.03.007
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Please cite this article in press as: Yilmaz, M.O., et al., Multi-physics code system with improved feedback modeling, Progress in Nuclear Energy (2017), http://dx.doi.org/10.1016/j.pnucene.2017.03.007

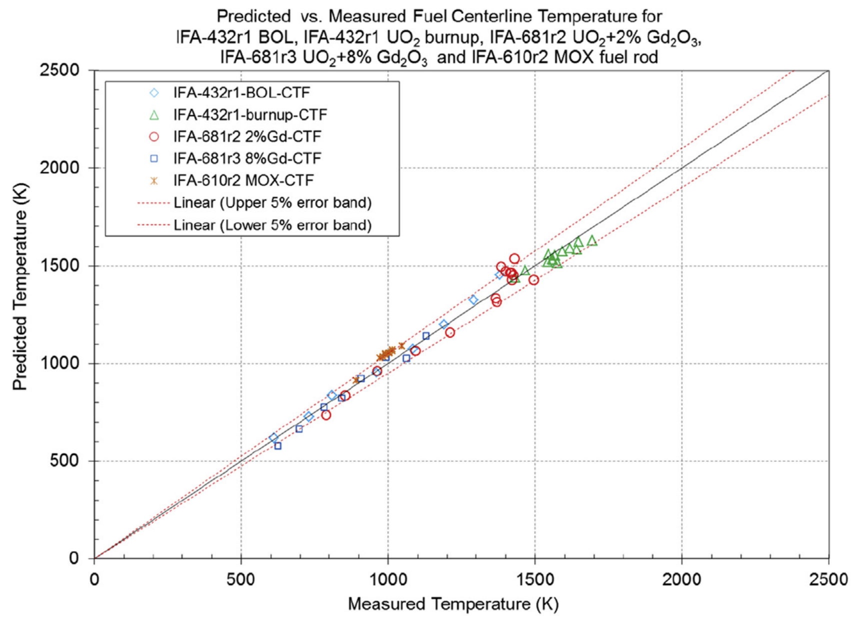

Fig. 1. Predicted vs. Measured Fuel Centerline Temperature for IFA-432r1 BOL, IFA-432r1 burnup, IFA-681r2 UO_2+2%Gd_2O_3, 681r3 UO_2+8%$Gd_2O_3$and IFA-610r2 MOX.

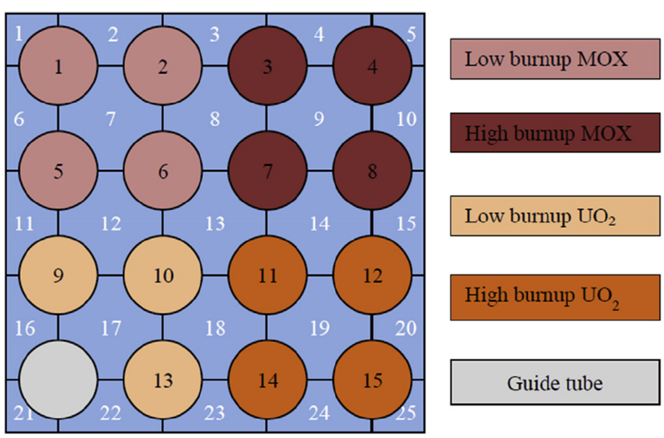

Fig. 2. 4 × 4 PWR Pin array and sub-channel Configuration.

Table 1
As-manufactured cold fuel dimensions.

Active length [m]	3.6576
Pin pitch [m]	0.0126
Fuel pellet radius [m]	0.003951
Inner clad radius [m]	0.004010
Outer clad radius [m]	0.004583
Clad-pellet gap thickness [m]	0.000059
Clad thickness [m]	0.000573

Halden experimental data within a 5% error band (Fig. 1).

The burnup-dependent fuel thermal conductivity model was also incorporated in the coupled sub-channel thermal-hydraulics/time-dependent neutron transport code system CTF/TORT-TD (Magedanz et al., 2015). The hot full power (HFP) steady state conditions were simulated for a 4 × 4 pin array (Fig. 2) extracted from the Purdue Pressurized Water Reactor (PWR) MOX benchmark (Kozlowski and Downar, 2007). The CTF/TORT-TD simulations

Table 2
Input parameters for UO_2 and MOX fuel types.

Cold plenum length [m]	0.22
Outer diameter of plenum spring [m]	0.007902
Diameter of the plenum spring wire [m]	0.001006
Number of turns in the plenum spring	20
Length of each pellet [m]	0.011003
Depth of pellet dish [m]	0.000280
Pellet dish shoulder width [m]	0.001036
Pellet surface roughness [m]	2.10^{-6}
Expected density increase during operation [kg/m^3]	100.0
Clad type	Zircaloy 4
Cladding inner surface roughness [m]	5.0038 10^{-7}
Initial gas pressure [Pa]	2.0 10^6
Coolant pressure [MPa]	15.5
Coolant inlet temperature [°K]	560.0
Coolant mass flux [kg/{m^2 s}]	3062.88
Linear power [kW/m] (axially uniform)	19.13
Time step interval size [days]	50
Burn time [days]	1000

Table 3
FRAPCON nodalization of the UO_2 and MOX rods.

Pellet radial nodes (equal cross-sectional area)	17
Axial nodes (equal length)	20

Table 4
UO_2 and MOX fuel characteristics.

	UO_2	MOX
U-235 enrichment [%]	4.25	0.202
PuO_2 content [%]	N/A	5.0
% of theoretical density	93.35	94.67

were performed with and without modeling of the fuel TCD and the results were compared to CTF/TORT-TD/FRAPTRAN predictions (Magedanz et al., 2015). The CTF/TORT-TD/FRAPTRAN sub-channel thermal-hydraulic/time-dependent neutron transport/fuel