Numerical Prediction of Dual-Cooled Annular Fuel Temperature During Control Rod Ejection Accident in OPR1000

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1. Introduction

A dual-cooled annular fuel concept for a light water reactor has been introduced by MIT for a significant amount of reactor power uprate. MIT proposed a 13x13 annular fuel array replacing the 17x17 solid fuel in the Westinghouse 4-loop plant, which could increase the core power up to 50% with the considerable changes in the major reactor components[1]. The Korea Atomic Energy Research Institute (KAERI) is also conducting a research to develop a dual-cooled fuel for its employment in an optimized pressurized water reactor in Korea, OPR1000. The dual-cooled fuel for the OPR1000 is targeted to increase the reactor power by 20% as well as reduce the fuel-pellet temperature by more than 30% without a change to the reactor components other than the fuel.

Numerous technical tasks exist for assessing the applicability of the dual cooled annular fuel to the power uprate in the OPR1000. One of the important tasks is to evaluate the performance of the annular fuel during the design basis events. Particularly, the fuel temperature and the peak cladding temperature (PCT) are the important variables during the control rod ejection accident (REA), since the rod averaged fuel enthalpy should be lower than its safety limit. The fuel enthalpy is known to largely depend on the fuel temperature.

This paper presents the predictions of the fuel and peak cladding temperatures during the REA. A general-purpose structural code, ABAQUS-6.8[2], and a computational fluid dynamics code, ANSYS CFX-11.0[3] were used to perform the numerical analysis of a heat transfer in the annular fuel as well as the solid fuel. The numerical predictions of the fuel maximum temperature (FMT) and PCT are compared against those predicted by a best-estimate system transient analysis code, MARS[4].

2. Numerical Method

2.1 Numerical Model and Boundary Condition

The solid and dual-cooled annular fuels consist of a fuel pellet(UO_2), a helium gap, and cladding(Zircaloy) as illustrated in Fig. 1. The dual-cooled fuel is configured with the annular pellet, the inner/outer claddings and the helium gaps in order to allow the coolant flow through the inner channel as well as the outer channel. For the numerical analysis of the heat transfer inside the fuel, the narrow gap along with the pellet and the cladding is included in the computational model because the temperature drop is expected to be very large in the gap. A conduction heat transfer is assumed in the helium gap using the equivalent thermal conductivity. Even though the gap width would change during the reactor operation, it is assumed to be constant in this study. A finite element model for the ABAQUS code and a finite volume model for the CFX code were constructed to simulate the heat transfer in the fuel.

A uniform heat generation rate is imposed at the hottest fuel (pellet) region, and a transient heat transfer to coolant is assumed at the outer surfaces of inner and outer claddings. The MARS code provided the time-dependent heat transfer coefficients and coolant temperatures at the core axial location where the FMT and PCT were predicted to occur during the REA. Since this study is focused on predicting the FMT and PCT of hot spot in the reactor core, a symmetric thermal boundary condition is used in axial and circumferential directions. The number of radial cells for the MARS, CFX and ABAQUS is 8, 25, 27 for the solid fuel, and 11, 26, 25 for the annular fuel, respectively.

2.2 Numerical Analysis

An unsteady heat transfer analysis is performed to predict the FMT and PCT during the REA using the ABAQUS and CFX codes. The initial constant heat generation rate in the fuel pellet was obtained by using the average linear power density and the three-dimensional peaking factor. Since the radial peaking factor was known to increase by a factor of 1.56 once the REA occurs, the heat generation rate during the REA is increased by the radial power distortion factor of 1.56. The initial steady state calculations before the REA were made, and then the transient heat transfer analysis was performed to simulate the REA conditions.

Iterative calculations were conducted to obtain converged solutions using a high resolution scheme. The iterations were terminated when both RMS residual of the governing equation is lower than 10^{-10}, and the monitored value of the temperature at a specified location is constant.

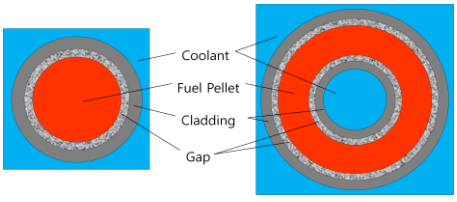

Fig. 1 Schematics of a solid fuel and a dual-cooled annular fuel.

3. Results and Discussion

Figs. 2 and 3 compare the FMT and PCT of the annular fuel during the REA which were predicted by the MARS, CFX and ABAQUS codes. All of the predictions for the FMT and PCT show an agreement of temperature within 3% and a time which the peak temperature reaches. The CFX code appears to predict a slightly higher FMT and the ABAQUS code predicts slightly lower local peaks of the PCT of the inner cladding. The largest differences are observed at the peak values of both the FMT and PCT.

The FMT increases to a peak value at about 3 sec after the REA occurs. This is because the REA increases the reactor power and the radial power distortion. The maximum increases of the FMT and PCT are estimated at 640 K and 400-430 K. The PCT increases significantly approximately 1.7 sec after the REA when the departure from nucleate boiling (DNB) is expected to occur. Fig. 4 illustrates the temperature contours at the initial condition (t=0 sec) and the peak FMT (t=3.1 sec).

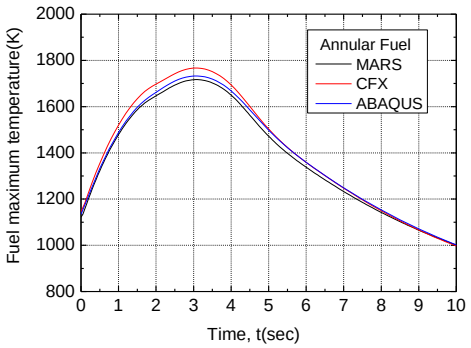

Fig. 2. Predictions of the annular fuel maximum temperature during the REA.

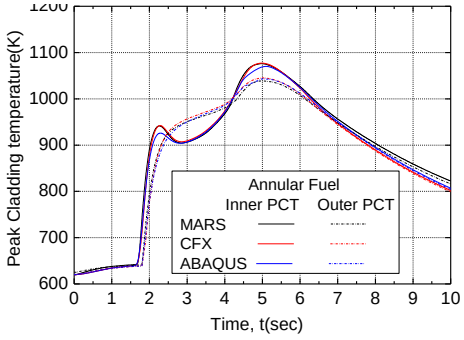

Fig. 3. Predictions of the annular fuel peak cladding temperature during the REA.

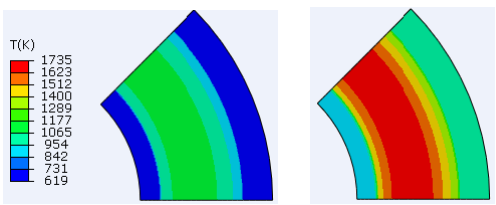

Fig. 4. Temperature contours of the annular fuel before and after the REA, i.e., t=0 sec and t=3.1 sec.

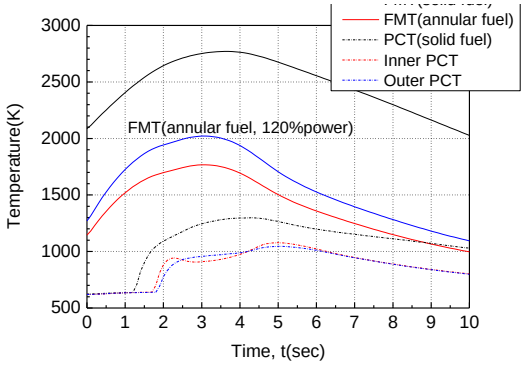

Fig. 5. Comparison of solid and annular fuel maximum and peak cladding temperatures during the REA.

Fig. 5 compares the FMT and PCT for the solid and annular fuels during the REA. The FMT at the 120% rated power for the annular fuel is also shown in Fig. 5. The FMT value of the annular fuel is 1000 K lower than the solid one at the rated power and 800 K lower even at the 120% power. It is however noted that the maximum increase in the FMT is approximately 640 K for both the solid and annular fuels. The faster increase of the solid fuel PCT indicates the DNB occurrence earlier than the annular fuel after the REA. The PCT values of the inner and outer claddings of the annular fuel are at least 200 K lower than the solid fuel PCT after the DNB.

4. Conclusions

Using the MARS, ABAQUS and CFX codes, the fuel maximum temperature and peak cladding temperature during the REA in OPR1000 were predicted for the dual-cooled annular fuel and solid fuel. The temperature predictions agree within 3%, and the time for the maximum FMT and PCT was also in agreement. The annular fuel showed a 1000 K lower FMT and a 200 K lower PCT during the REA with respect to those of the solid fuel. However, the maximum increase in the FMT during the REA is approximately 640 K for both the solid and annular fuels.

REFERENCES

[1] M. S. Kazimi, Introduction to the Annular Fuel Special Issue, Nuclear Technology, Vol. 160, pp.1-168, 2007.
[2] Dassault Systemes Simulia Corp., ABAQUS 6.8, 2008.
[3] ANSYS Inc., ANSYS CFX, Release 11.0, 2006.
[4] J. J. Jeong *et al.*, Development of a Multi-Dimensional Thermal-Hydraulic System Code, MARS 1.2.1, Annals of Nuclear Energy, Vol. 26, pp.1611-1642, 1999.