Enhancement of MARS with an Advanced Fuel Model by Coupling FRAPTRAN

Hyong Chol Kim*, Young Jin Lee , Sam Hee Han
NSE Technology Inc.
**Corresponding author: hckim@nsetec.com*

1. Introduction

The thermal-hydraulic system code MARS has an option for coupling with the three-dimensional kinetics codes for detailed core transient calculations [1,2]. In this study, MARS has been further enhanced to have an advanced fuel rod model by coupling the FRAPTRAN code [3].

FRAPTRAN calculates heat conduction, heat transfer from cladding to coolant, elastic-plastic fuel and cladding deformation, cladding oxidation, fission gas release, and fuel rod gas pressure. FRAPTRAN is used for analyzing the fuel response under postulated accidents such as reactivity-initiated accidents (RIAs) and loss-of-coolant accidents (LOCAs), and also for analyzing and interpreting experimental results. Burnup-dependent variables such as fuel densification and swelling, and cladding creep and irradiation growth may be considered by incorporating FRAPCON [4] steady-state depletion calculation results as the initial conditions.

2. Methods of Code Coupling

2.1 General Framework of Code Coupling

The fuel performance modeling features of the FRAPTRAN code are integrated into the MARS code by coupling the two codes as shown in Fig. 1. During transient calculations, MARS calls FRAPTRAN which has been formatted into a DLL (Dynamic Link Library) form.

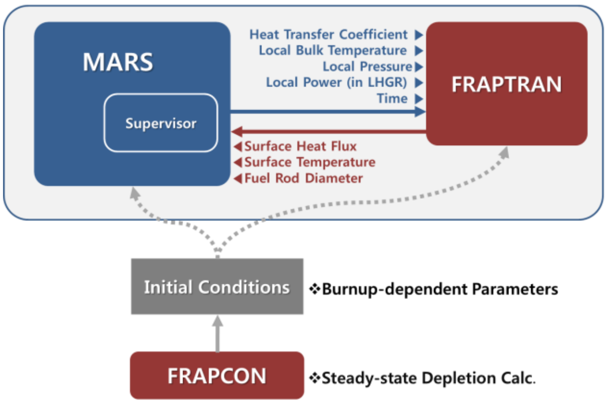

Fig. 1. Integrated code system.

During transient calculation, the MARS code provides the coolant parameters and rod power to FRAPTRAN calculation as boundary conditions. Burnup dependent parameters generated by FRAPCON can be used to initialize the burnup dependent variables for the transient calculation in MARS and FRAPTRAN.

2.2 Transfer Variables between Codes

FRAPTRAN calculation requires rod power history, axial power shape, cladding surface heat transfer coefficients, coolant temperature and pressure as boundary conditions. In the coupled calculation, these data are provided by MARS at each time step. Rod power history and axial power shape are calculated from the linear heat generation rates computed by MARS. FRAPTRAN then calculates and provides cladding surface temperature, surface heat flux, and cladding outer radius displacement to MARS for the next time step.

The axial node structures of fuel rods in both codes must be identical to ensure computational consistency.

2.3 Time Stepping

Transient time is passed from MARS to FRAPTRAN but the each code advances the time using its own time step. In general, the time step of MARS is smaller than the recommended time step of FRAPTRAN. As such, MARS controls the time stepping and FRAPTRAN follows the MARS time stepping using its own time step. The FRAPTRAN carries out its calculation to update the transfer parameters only when its current transient time is less than or equal to the current MARS transient time. It is important that the maximum time step of MARS should not be larger than the time step of FRAPTRAN for any given time period. FRAPTRAN returns to MARS without actual calculation when its transient time is larger than that passed from MARS.

2.4 Code Modifications

The main routine of FRAPTRAN is re-formatted as a DLL subroutine having the arguments of the transfer variables described in Section 2.2. Subroutines frap, crank6, heat, power, powrmp, store6, and prntot were also modified accordingly. In the first time step, artificial power ramping was necessary to gradually close the gap between fuel and cladding from the cold state and thus to avoid a computational error from thermal imbalances.

For MARS, TransientAdvanceM, HeatStrSolve, and HydroSolveM modules were analyzed and restructured for ease of modifications. Subroutines InputDataProcess, TransientAdvance, TimeStepControl, HeatStrAdvance, and HydroSolve were modified and new subroutines were added.

The main routine of MARS was modified to have a “Development Model Control” option for activating the FRAPTRAN coupling. When this option is ON, a new subroutine “Frapinit” is activated to read “frap_mars.map” file which contains the input for specifying the MARS Heat Structure corresponding to the fuel rod modeled by FRAPTRAN. Pressure and temperature of the boundary volumes specified by the MARS input for the selected Heat Structure are transferred as the boundary conditions for FRAPTRAN calculation.

HeatStrAdvance routine was modified to call the new subroutine “Frap_Tran1D” which calls the FRAPTRAN instead of the existing “Transient1D” when the coupling option is ON.

3. Results of Calculations

3.1Verification of FRAPTRAN-DLL

To confirm that FRAPTRAN-DLL was developed correctly, a preliminary verification process shown in Fig. 2 was performed.

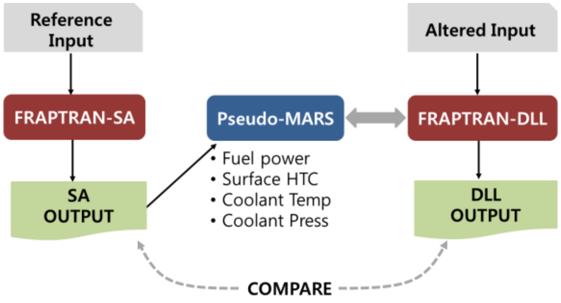

Fig. 2. FRAPTRAN-DLL verification process.

A reference calculation was performed using the original FRAPTRAN with a sample input. In Fig. 2, this original FRAPTRAN is indicated as “FRAPTRAN-SA(Stand-Alone)” to differentiate it from FRAPTRAN-DLL. During the FRAPTRAN-SA calculation, a file is generated to store the data of fuel power, cladding surface heat transfer coefficients, coolant temperature, and coolant pressure for each axial node and each time step.

A Pseudo-MARS was programmed just to read the previously generated file and to call the developed FRAPTRAN-DLL with the call statement identical to that used in MARS for coupled calculation.

Then, the coupled calculations with Pseudo-MARS and FRAPTRAN with an altered input were performed and the two outputs from FRAPTRAN-SA and FRAPTRAN-DLL were compared. Line-by-line comparisons were carried out using the DIFF function of an editor. The two output results were practically identical even though the input has been altered drastically from the reference input.

Therefore, the developed FRAPTRAN-DLL has been verified to be correct for the intended use of coupled calculation with MARS.

3.2 Reference MARS Calculation for a LOCA sample

A large-break LOCA for OPR-1000 reactor was selected as the reference case [5]. Fig. 3 shows the cladding surface temperature of the hottest rod of the reference case. This case was calculated using the standard MARS input modified with a BOC (Beginning-of-Cycle) axial power shape extracted from a Nuclear Design Report (NDR) for the first fuel cycle of OPR-1000 reactor. This BOC core contains only fresh fuels and, therefore, does not require burnup consideration.

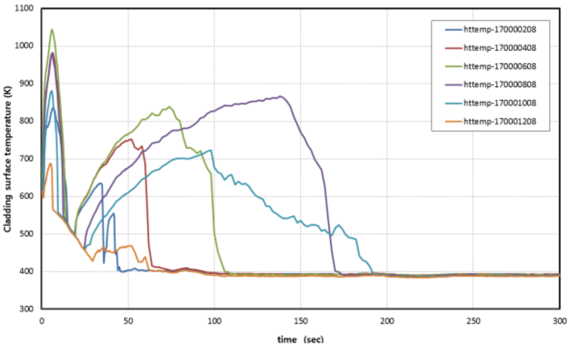

Fig. 3. Cladding temperature of the standard calculation.

3.3 Coupled Calculation by MARS and FRAPTRAN

The same case as described in the previous section was calculated using the MARS-FRAPTRAN coupled code system. Fig. 4 shows the cladding surface temperature of the hottest rod of this calculation. Results show that the blowdown peak is higher but the reflood peak is lower than those of the previous results.

The coupled calculation is very useful in such cases where the separate consecutive calculations of MARS and FRAPTRAN are difficult to carry out due to limitations in the maximum size of input data for power, pressure, temperature, and surface heat transfer coefficients. Also, it can eliminate many potential errors resulting from the laborious input preparation.

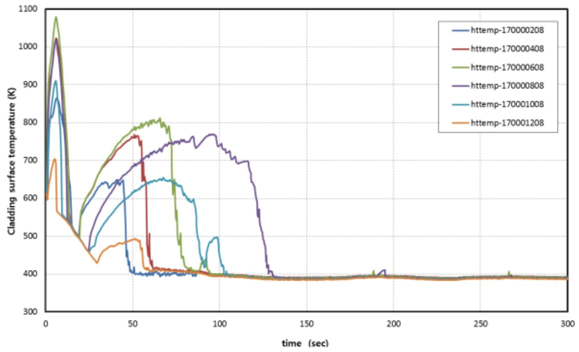

Fig. 4. Cladding temperature of the coupled calculation.

3.4 Coupled Calculation for a Core with Irradiated Fuels

The coupled code system is applicable for transient calculations for EOC (End-of-Cycle) cores which contains irradiated fuels. Depletion calculation for a fuel rod was carried out using the FRAPCON code with burnup history data taken from NDR and a restart file was written for FRAPTRAN calculation.

FRAPTRAN input specifies the duration time for which the subject rod experienced burnup up to the starting time of the transient. MARS input was modified to correctly describe the EOC axial power shape.

Fig. 5 shows the results for the EOC calculation. Results show that the temperature peaks are lower than those of the BOC calculation results.

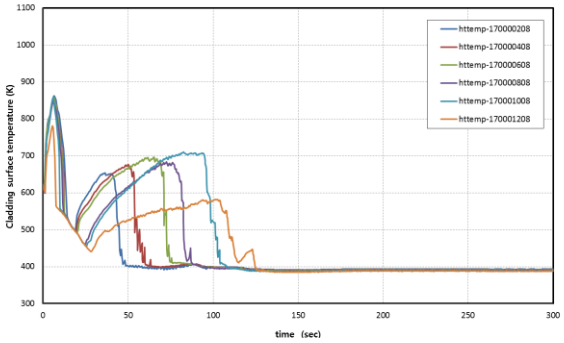

Fig. 5. Cladding temperature of the coupled calculation at EOC.

4. Conclusions

MARS has been coupled with FRAPTRAN to enhance its analysis capability and an integrated code system consisting of MARS-FRAPTRAN-FRAPCON has been established.

FRAPTRAN-DLL has been successfully verified and the coupled calculations have shown to provide reasonable results.

An EOC core loaded with irradiated fuels was analyzed with the integrated code system. The coupled code system has demonstrated its applicability to variety of applications such as assessing the effects of fuel thermal conductivity degradation with burnup.

MARS has been enhanced with the advanced fuel model of FRAPTRAN so that users can use the fuel rod performance evaluation capability in the transient analyses.

REFERENCES

[1] J. -J. Jeong, et al., “Development and Verification of “System Thermal-hydraulics - 3 Dimensional Reactor Kinetics” Coupled Calculation Capability using the MARS 1D Module and MASTER Code,” KAERI/TR-2232/2002, Korea Atomic Energy Research Institute, 2002.

[2] H. C. Kim, et al., Core Nodalization Effects in the Main Steam Line Break Analysis Using the MARS/PARCS Coupled Code, Transactions of the Korean Nuclear Society Spring Meeting, May 30-31, 2013, Gwangju, Korea..

[3] K. J. Geelhood, W.G. Luscher, J.M. Cuta, “FRAPTRAN 1.5: A Computer Code for the Transient Analysis of Oxide Fuel Rods,” NUREG/CR-7023, Vol. 1 Rev.1, Pacific Northwest National Laboratory, 2014.

[4] K. J. Geelhood and W. G. Luscher, “FRAPCON-3.5: A Computer Code for the Calculation of Steady-State, Thermal-Mechanical Behavior of Oxide Fuel Rods for High Burnup,” NUREG/CR-7022, Vol. 1 Rev.1, Pacific Northwest National Laboratory, 2014.

[5] “MARS Code Manual, Volume IV: Developmental Assessment Report,” KAERI/TR-3042/2005, Korea Atomic Energy Research Institute, pp.222-228, 2009.

ACKNOWLEDGMENTS

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KOFONS), granted financial resource from the Nuclear Safety and Security Commission (NSSC), Republic of Korea. (No. 1403009)