Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-19, 2023

Effect of two way thermal hydraulic-fuel performance coupling on whole core depletion

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1. Introduction

Benchmark data is available for an operational nuclear power plant [1], which provides cycle depletion data for Multiphysics codes analysis and validation. Neutron kinetics (NK) codes calculate the flux and power distribution during the depletion cycle, while thermal hydraulics (TH) codes evaluate moderator temperature and density. Fuel performance (FP) codes analyze the behavior of fuel with time, such as enthalpy, temperatures, and pellet clad mechanical interaction. All of these phenomena are interconnected, and single physics codes incorporate simplifications to model other physics phenomena in a conservative manner. NK/TH coupling has produced reasonably accurate results, and thus, most of the coupling frameworks use these two coupled codes. FP codes not only model the dynamic gap conductance and change in fuel thermal conductivity with burnup but also the formation of the oxide layer on the clad surface.

Various strategies are employed for the convergence of coupled codes. It is impractical to couple computationally intensive Monte Carlo and Lattice transport NK codes with FP codes (in addition to TH code). In this study, a nodal code is utilized as an NK code, making it feasible to couple both TH and FP codes. Previous research has shown that coupling the FP code with the nodal code has a more significant impact than coupling the TH code with the nodal code [2].

The focus of this research is to compare one-way coupling of FP with TH code and two-way coupling between TH and FP codes. Parameters such as average coolant temperature, oxide surface temperature, and cladding hydrogen concentration are considered for comparing the two different coupling approaches.

2. Methodology

The methodology for this research involves the use of MPCORE, a Multiphysics coupling framework developed at Ulsan National Institute of Science and Technology, to externally couple the different physics modules. MPCORE creates container arrays of all the variables that need to be exchanged between modules, allowing for in-memory transfer of data between modules without the need for file read and write operations. The parallel implementation of modules in MPCORE also allows for efficient use of available resources. The modules coupled in MPCORE are:

1. **NK:** RAST-K, a nodal code that uses cross-sections generated from the STREAM lattice code, is used as a NK solver.
2. **TH:** CTF (Coolant boiling in rod arrays-Two Fluid), a two fluid, three field subchannel code for modeling heat transfer from cladding to coolant, is used as a TH module. CTF can use its own simplified heat conduction solver or use the clad outer surface temperature provided by an external code.
3. **FP:** Fuel Rod Analysis Programming Interface (FRAPI) is used in MPCORE, which can dynamically select between FRAPCON and FRAPTRAN in depletion and transient analysis, respectively.

Two types of coupling, one-way and two-way, are compared in this research for TH and FP modules.

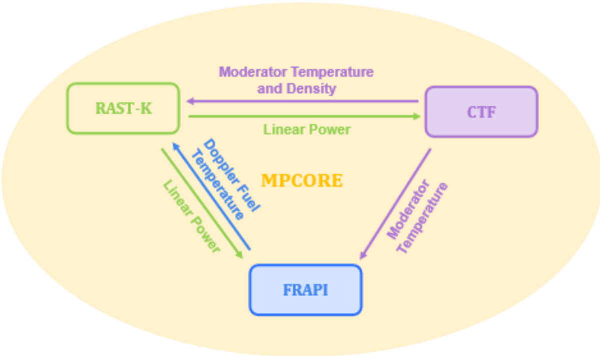

Fig. 1. One-way coupling between modules in MPCORE

2.1. One-way coupling

In some studies, one-way coupling has been employed between TH and FP modules where FP module does not transfer any data to TH module. Therefore, TH module uses its own simplified fuel thermal conductivity correlations. TH module calculates the boundary conditions such as clad or coolant temperature for FP module and provides coolant information to NK module.

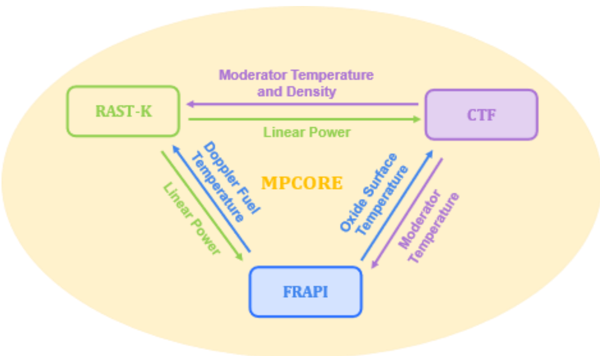

Fig. 2. Two-way coupling between modules in MPCORE

2.2 Two-way coupling

In two-way coupling, the TH module is only used for coolant-related parameters, while FP module is used for fuel, gap, and clad thermal conductivity. The oxide surface temperature is provided by the FP module to the TH module. The TH module provides the coolant temperature and pressure to the FP module to be used as a boundary condition.

3. Coupling Strategy in MPCORE

The coupling strategy employed for TH/FP is presented in Fig. 1 and Fig. 2 . The NK/FP and NK/TH coupling approaches are identical in both one-way and two-way coupling. Both approaches utilize the fuel temperature calculated by FP and the coolant temperature calculated by TH, which are both obtained by NK. The convergence of the modules is achieved through the Picard method, with the critical boron concentration (CBC), linear power, temperature values (fuel, cladding, oxide, moderator), moderator density, and film heat transfer coefficient values being converged at each burnup step. The Gauss-Seidel approach is used to execute each module after receiving updated data from the other modules [3] . The overall flow scheme for MPCORE is depicted in Fig. 3 , and at the beginning of the program, input files for all modules are generated by a Python script. RAST-K solves for the flux and power distribution, which is then passed on to FRAPI. FRAPI solves the heat conduction of the fuel-gap-clad and oxide layers and provides the oxide surface temperature to CTF. CTF computes the coolant temperature, pressure, density, and provides feedback to other modules.

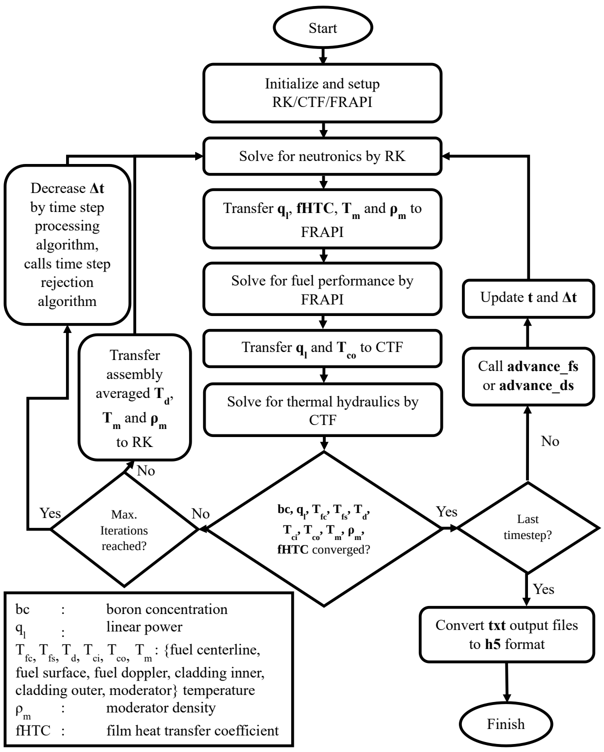

Fig. 3. Flow scheme MPCORE

4. Benchmark modeling details

The VERA benchmark [1] provides the Watts Bar reactor cycle 1 data, which is used in this study. However, replicating the exact cycle depletion in computational codes can be challenging due to the difficulty in following the power history of the actual power plant. To address this issue, appropriate power history has been provided by the benchmark team for simulation purposes.

MPCORE allows all Multiphysics modules to have different axial meshes. RAST-K calculations are performed using a three-dimensional quarter-core model with 54 axial meshes and four nodes for one assembly. Cross-sections are generated differently for spacer grid and no-spacer grid regions. Equilibrium xenon calculations and CBC searches are conducted for every burnup point. FRAPI and CTF use 24 equally spaced axial meshes. The spacer grid does not affect the fuel rod internally, and CTF has explicit information on the spacer grid location. Linear interpolation is used by MPCORE to transfer data between the codes. The FP module uses 5 radial meshes for the fuel region and 3 radial meshes for the cladding region. FRAPI uses a dynamic gap conductance model, which is especially important for multicycle cases as burnt fuel has high conductance from the start while fresh fuel has low conductance.

5. Results and Discussion

Cycle 1 depletion is analyzed using the MPCORE framework, and the results of one-way and two-way coupling are compared. As burnup and temperature increase, the thermal conductivity of fuel decreases while the gap conductivity increases due to gap closure. The coolant temperature is higher in one-way coupling because of the high fuel thermal conductivity in CTF. FRAPCON considers burnup-dependent conduction correlations, and in contrast to CTF, it allows for different gap widths in each axial mesh of every fuel rod.

There is a small difference between the results of one-way and two-way coupling in NK parameters. The maximum difference in boron concentration is 4 ppm. To validate the accuracy of the model, a comparison was made between two-way MPCORE coupling, MCS/TH1D [4] and RAST-K/TH1D nodal codes, as shown in Fig. 4. The largest discrepancy observed between MPCORE and MCS regarding the CBC is around 25 ppm. Initially, the results from the simple nodal code (RK) and MPCORE coupling were quite similar, but as the burnup increases, the difference increases due to dynamic gap conductance modeling in MPCORE. The normalized power distribution, as shown in Fig. 5, is also within the standard deviation of MCS results. After verifying the MPCORE modeling, other parameters are compared for one-way and two-way coupling.

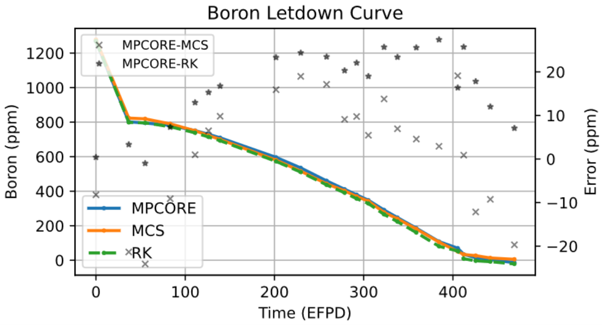

Fig. 4. Boron concentration cycle 1.

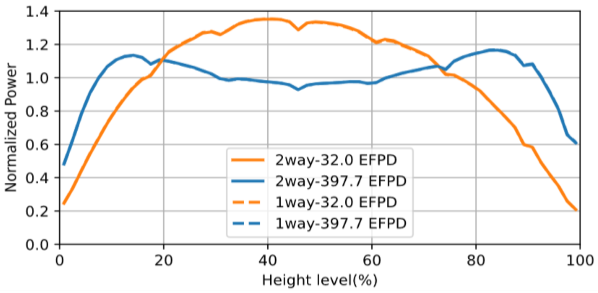

Fig. 5. Normalized radial averaged axial power distribution.

The figures (Fig. 6-8) display the core average parameter values obtained through two-way and one-way coupling. The difference is depicted in green color and is represented on the secondary y-axis. The difference is calculated using the formula:

$$Diff = \delta_{twoway} - \delta_{oneway} \tag{5.1}$$

Here, δ denotes the parameter average value at any given timestep.

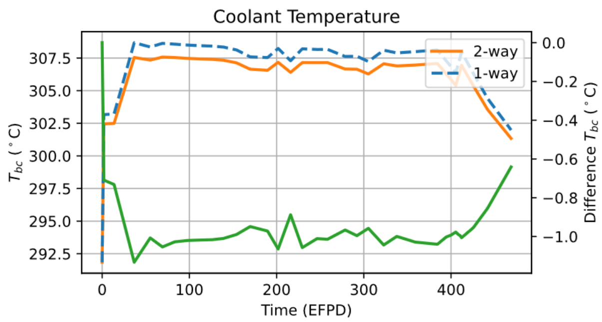

Fig. 6. Core averaged coolant temperature.

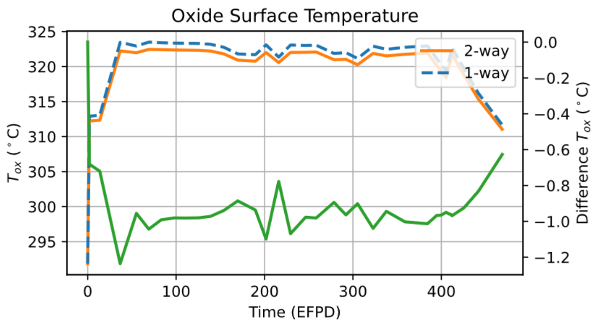

Fig. 7. Core averaged oxide surface temperature.

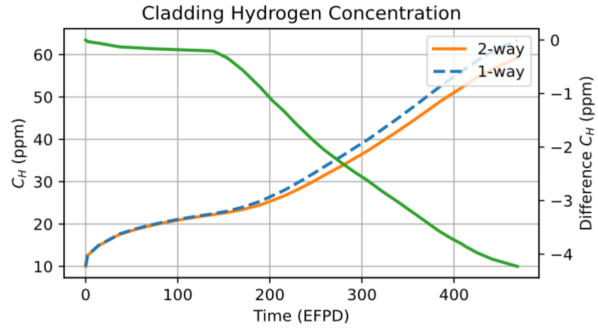

Fig. 8. Core averaged cladding hydrogen concentration.

In nuclear reactor fuel behavior computational simulations, one-way coupling can result in higher coolant temperatures throughout the cycle due to the absence of the burnup effect in thermal hydraulic codes. This can lead to higher oxide surface temperatures and affect the cladding hydrogen concentration. Hydride production in zircaloy cladding is one of the main limiting factors for extending life of nuclear fuel rods in core. Prior studies utilizing Multiphysics coupling analysis with BISON, grounded on the coupling outcomes of DECART and CTF, have highlighted the importance of precise computation of cladding hydrogen concentration [5]. This study has suggested that one-way coupling overestimates the cladding hydrogen concentration. Additionally, differences between one-way and two-way coupling results tend to increase with burnup, emphasizing the need for using two-way coupling in multicycle depletion simulations.

Fig. 9-11 illustrate the axial distribution of core wise parameters with solid lines showing two-way coupling results and dotted lines representing one-way coupling results.

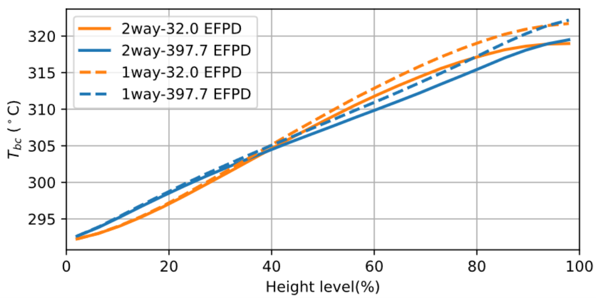

Fig. 9. Radial averaged bulk coolant temperature.

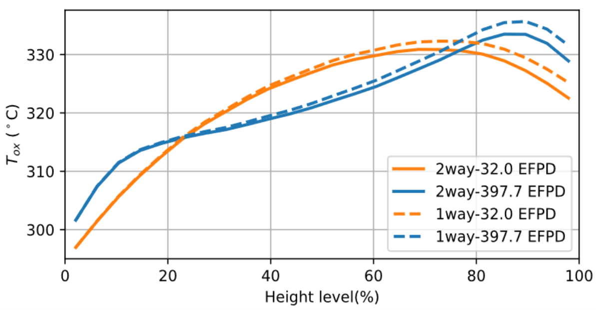

Fig. 10. Radial averaged oxide surface temperature.

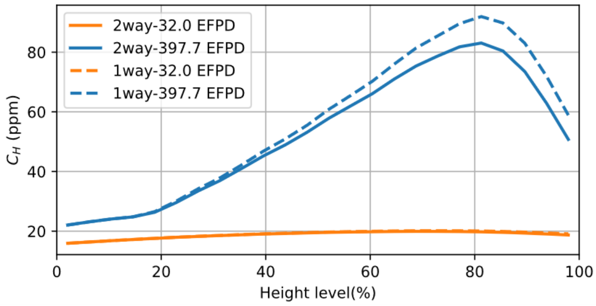

Fig. 11. Radial averaged cladding hydrogen concentration.

The temperature difference for both coolant and oxide layer increases as the height of the core increases. Due to high coolant temperatures during the entire cycle length, more hydrogen concentration is observed in the cladding layer. As a result, the cladding hydrogen concentration is almost similar in both coupling approaches at the beginning of the cycle, but the difference becomes more significant towards the end of cycle 1. The difference in cladding hydrogen concentration is more pronounced in the upper region of the core, where the one-way approach shows higher temperatures.

6. Conclusion

The effect of one-way and two-way coupling between FP and TH modules in the MPCORE Multiphysics framework has been investigated in this study. The STREAM/RAST-K two-step neutronics code was employed for the NK module, which generated nodal power followed by pin power reconstruction to give linear power for each axial mesh of the fuel rod. The TH and FP modules provided coolant and fuel temperature values for each pin. In one-way coupling, no data was transferred from FP to TH module, hence TH module used its simplified heat conduction solver for coolant characteristics. In two-way coupling, FP supplied oxide surface temperature to TH module and TH module gave coolant temperature to FP. The performance comparison was made for coolant temperature, oxide surface temperatures, and cladding hydrogen concentration. The parameter difference increased with burnup for both approaches and thus required the use of two-way coupling for multicycle depletion and transient analysis.

ACKNOWLEDGEMENTS

This research was supported by the project(L20S089000) by Korea Hydro & Nuclear Power Co. Ltd..

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