Transactions of the Korean Nuclear Society Virtual Autumn Meeting
December 17-18

Pin level analysis of the NEA/OECD Main Steam Line Break Benchmark Exercise II

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1 Introduction

The main steam line break (MSLB) accident postulated in PWR safety analyses involves a considerable reduction of the inlet coolant temperature of one side of the reactor core which causes a considerable asymmetry in the radial flow conditions. Because of this asymmetry, the positive reactivity feedback effect introduced by the decrease of the coolant temperature appears non-uniform. Additionally, a stuck rod on the cold side is considered during the reactor SCRAM for conservatism in the analysis.

The Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) administered a three-exercise benchmark problem in order to assess the numerous coupled neutronics/thermal-hydraulics (T/H) [1].

This paper is devoted to the solution of the Exercise II which deals only with the core level phenomena and does not require system modeling since a set of time-dependent boundary conditions is provided. Therefore, a pin-by-pin Simplified P_3 (SP_3) finite difference based code coupled with a pin-level T/H solver is employed to solve the Exercise II.

In the next section, the fundamentals and the description of the used code are given. Section 3 provides the benchmark specifications while results are analyzed in Section 4. Finally, conclusions are drawn inside Section 5.

2 Description of the Calculation System

2.1 Pin-level Neutronics SP_3 Based Solver

In order to simulate a reactor core using three-dimensional (3D) SP_3 equation, a methodology called direct calculation with multi-level coarse mesh finite difference (CMFD) acceleration has been explored and successfully developed by Hwang J. T. in his M.Sc. dissertation [2] to solve transient problems with high computing efficiency retaining the accuracy.

In this methodology, the 3D problem is decomposed into multiple pin-wise one-dimensional (1D) finite difference method (FDM) problems along the axial direction. Since the problem of 1D FDM can be solved directly by the forward/backward substitution, the feasible performance in terms of computing time is achieved with limited resources. Also, with axially fine mesh structure, the fission distribution along the axial direction is more accurately calculated. The direct calculation is then coupled with two levels of 3D CMFD acceleration. The first one is the application of pin-level CMFD acceleration based on SP_3 equations while the second one is the application of assembly-level 3D CMFD acceleration based on diffusion theory (P_1). The code has its own simplified T/H module which is for closed channel and implies no pressure drops. Figure 1 shows the calculation flow of the code for the steady-state (*top*) and transient (*bottom*) cases. In case of transient calculations, a conditional update has been implemented for a small variation of the transport cross section (default value $\Delta\Sigma_{tr} > 0.1\%$).

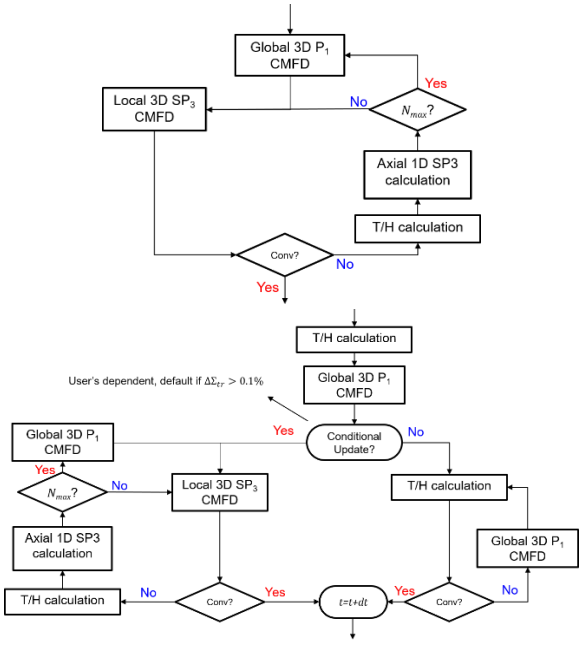

Figure 1. Calculation flow for the 3D/1D based SP_3 code, steady-state (*top*) and transient (*bottom*).

The code is highly parallelized with MPI. In particular, the calculation of the local and global 3D CMFD are parallelized following the basic framework of axial domain decomposition while the axial solution is radially parallelized. A more detailed description is provided in Hwang J. T. thesis [2].

2.2 Pin-level T/H Module

Accurate prediction of cross-flow, mixing effects, spacer-grid effects, fuel temperature and possible presence of local void fraction is necessary to faithfully model the coolant flow in the core of a nuclear reactor. This can be done by introducing the ESCOT code as T/H module [3].

The ESCOT code is a pin-level core thermal-hydraulics solver which adopts the four-equation drift-flux model, the SIMPLEC algorithm, and a fuel conduction model using the empirical correlations of the FRAPCON code. ESCOT is highly parallelized with MPI, employing both axial and radial domain decomposition, and provides accurate yet fast pin-level core T/H solutions. Figure 2 shows the ESCOT code calculation flow for transient simulations.

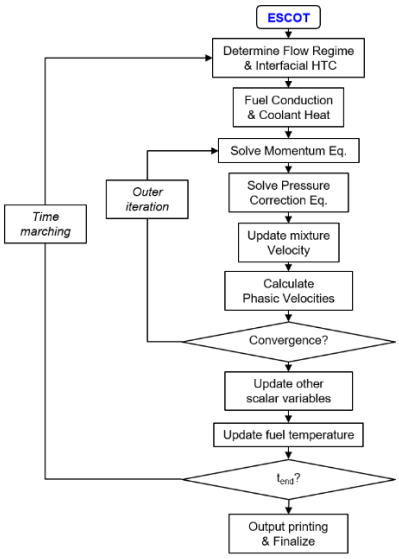

Figure 2. ESCOT code calculation flow for transient simulations.

2.3 *Coupling Methodology*

The two codes introduced in the previous sub-sections have been directly coupled since they share the same parallelism. In order to use both codes at their best, the MPI capability of splitting the communicator is employed. In this way, the ESCOT code can run using the assembly-wise domain decomposition scheme while the neutronics performs its calculation with planar-wise decomposition. Figure 3 details the general scheme of the parallelization topology.

Figure 3. Coupling topology between the neutronics solver and the ESCOT code.

Moreover, the parameters necessary to have a complete solution of a coupled neutronics-T/H problem are: the power, the fuel temperature, the moderator temperature and the moderator density. In the transient coupling, the moderator properties change slower than the fuel temperature. Therefore, for transient coupled calculations, the fixed-point iteration problem within the same timestep can be solved by only calculating the fuel temperature and by performing the entire ESCOT T/H calculation after the time-step has converged. The scheme is presented inside Figure 4.

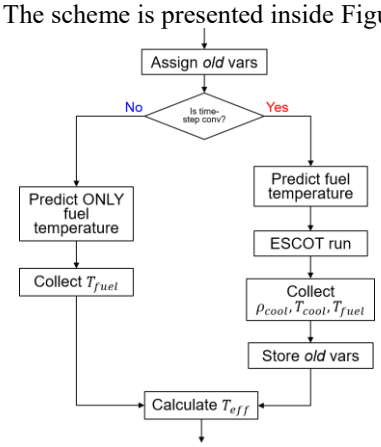

Figure 4. ESCOT interface for the transient coupling.

3 Description of the MSLB Benchmark Exercise II

The reactor core used for the MSLB Benchmark is based on the same model of the Three Mile Island one, with 241 assemblies of which 177 are fuel assemblies (FA) and a total power of 2,772 MW_{th}. A set of eighteen boundary conditions at 171 time-steps was provided for inlet temperature, inlet flow mass and outlet pressure according to the radial mapping provided inside Figure 5. The evolution of the coolant temperature for the eighteen inlet core sectors is also provided inside Figure 6.

The simulation of this transient covers a time of about 100 seconds. In this simulation, the reactor trip occurs at 6.65 seconds with a speed of 155.71 cm/sec. The core model has eight banks of control rods of which seven are explicitly modeled with a specific cross section file (1 to 7), while the last bank is modeled implicitly. As previously mentioned, one rod on the cold side is stuck out during this calculation (steady-state and transient). Its position is provided inside Figure 7 which also shows the radial mapping of the eight control rod banks. The initial position of every control rod bank is fully extracted except bank 7 which is 90% withdrawn.

438 unrodded and 195 rodded compositions were provided to solve this problem. These sets of cross sections (XS) were calculated assuming the core at 650 Effective Full Power Days, 5 ppm of boron and thirty branches including five effective fuel temperature points and six moderator density points. For a more detailed description of the benchmark specification, the reader may check [1].

This problem was formulated to validate assembly-wise solvers but here a pin-wise solver is used to analyze the scenario. Thus, the set of XSs provided by the benchmark has been assigned assembly-wise but the feedbacks are calculated pin-wise. In addition, the number of axial meshes was kept equal to the one recommended in the benchmark $Z = 26$. Some of the calculation conditions in which this analysis has been performed are provided inside Table 1.

Table 1. Calculation conditions for the solution of the NEA/OECD Benchmark Exercise II.

Time-step size [sec]	0.1
# of Time-steps	970
Ψ convergence criterion	10^{-6}
Conditional Update [%]	0.1
Decay Heat Model	Dunn Model [4]
# of MPI processes	177 (26 planes / 177 FA)

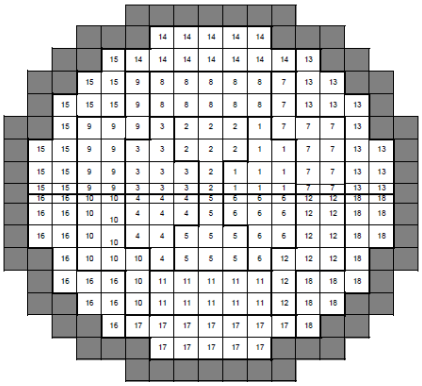

Figure 5. Radial mapping for the eighteen sets of boundary conditions.

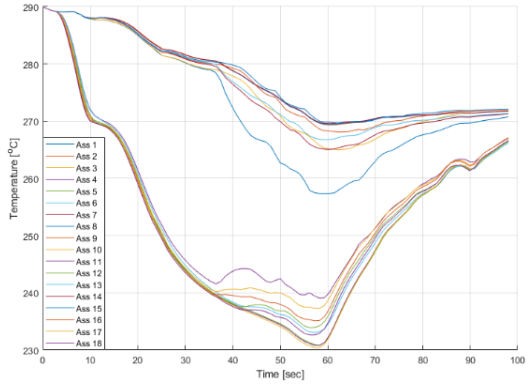

Figure 6. Evolution of the inlet coolant temperature for the eighteen core sectors.

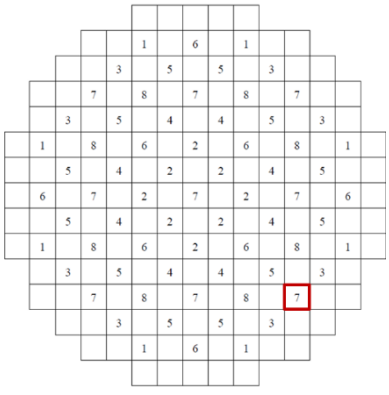

Figure 7. Control rod banks radial mapping and position of the stuck control rod.

4 Solution of the NEA/OECD MSLB benchmark Exercise II

In order to verify the accuracy of this new solver, the evolution of the global variables has been compared with a solution obtained with MASTER/COBRA in which the assembly-wise solution was performed [5]. The eigenvalue calculated in this simulation is 1.00647 while for the MASTER code was 1.00721, the difference is mainly due to the better nodalization of neutronics and T/H. Despite the 74 pcms of difference, the trends of the power and reactivity match well as Figure 8 shows. The maximum power after the SCRAM occurs at 57.800 seconds with a registered value of 30.9% while for MASTER/COBRA occurs at 57.790 seconds with a measured value of 32.9%; the maximum reactivity after the reactor trip reached -0.06 at 55.900 seconds while the calculated one with MASTER/COBRA was -0.03 at 55.475 seconds.

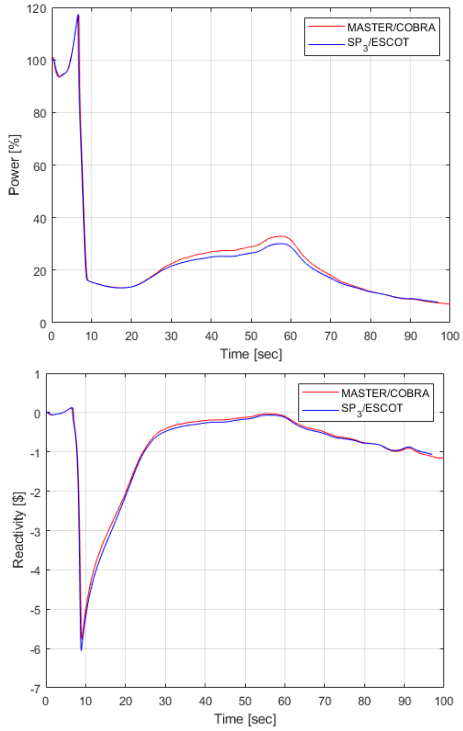

Figure 8. Evolution of power (*top*) and reactivity (*bottom*) during the transient calculated with MASTER/COBRA and the 3D/1D SP_3 code coupled with ESCOT.

Recently, a correlation to evaluate the critical heat flux (CHF) has been added to the ESCOT code. The scheme to calculate the departure of nucleate boiling (DNB) follows the one implemented inside the COBRA code [6]. It essentially follows the Biasi correlation [6]. Figure 9 shows that the evolution of the minimum DNB ratio (MDNBR). During the entire scenario, the MDNBR always remains above 2.

A summary of the global parameters and a comparison between the two analyses is provided inside Table 2.

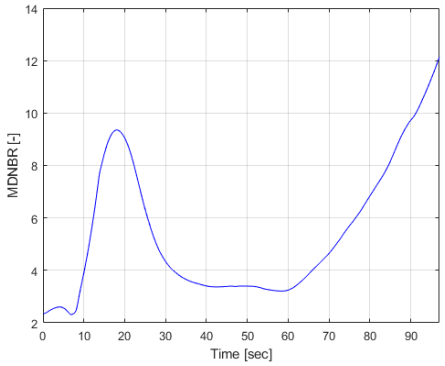

Figure 9. Evolution of the MDNBR during the transient.

Table 2. Summary and comparison of the Exercise II.

	3D/1D-ESCOT	MASTER/COBRA
k_{eff}	1.00647	1.00721(74)
Time of Max. Power	57.800	57.790
Max. Power [%]	30.90	32.90
Time of Max. Reactivity	55.900	55.475
Max. Reactivity [$]	-0.06	-0.03
Power at 97.0 seconds [%]	7.80	7.55

Simulating this problem with pin-level solvers allows the access to intra assembly data which were not available in previous analyses. Figure 10 shows the 2D axially integrated power at 6.0 and 57.0 seconds which represent the power maps just before the SCRAM and at the instant in which it the second peak is reached.

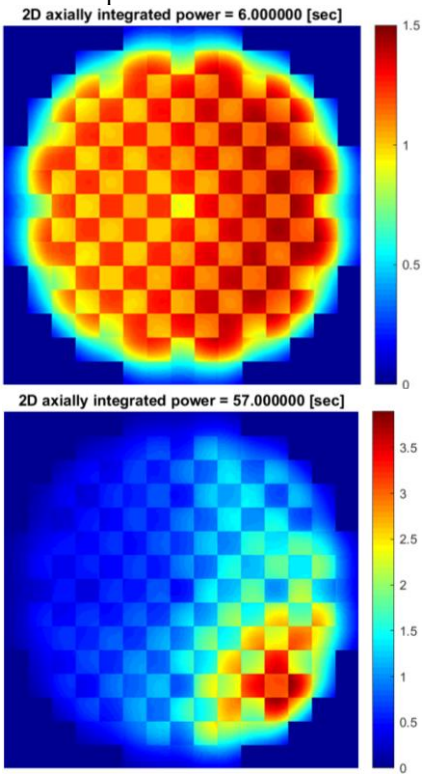

Figure 10. 2D axially integrated power measured at 6.0 (*top*) and 57.0 (*bottom*) seconds.

Moreover, the coolant temperature distribution at 57.0 shows also high asymmetry due to the boundary conditions and the stuck rod (see Figure 11).

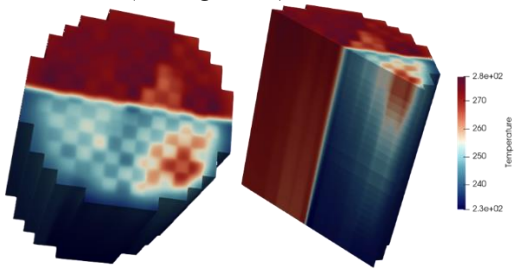

Figure 11. Coolant temperature distribution at 57.0 seconds.

5 Conclusions

The analysis of the Exercise II of the NEA/OECD MSLB benchmark has been performed at pin-level employing a SP_3 pin-by-pin finite difference solver coupled with the ESCOT code. The results of the calculation have been compared with a previous analysis performed with MASTER/COBRA. The comparison between the two simulations matches well for what concern the global variables but with this solution it has been possible to access the intra assembly parameters.

It turned out that the MDNBR is always bigger than 2, the reactor does not go back critical after the SCRAM and that the mixing effects lower down of about 2% the maximum core power of the second peak.

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