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nTRACER/COBRA-TF Coupling and Initial Assessment

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1. Introduction

High-fidelity core calculations through a direct whole core calculation code require realistic modelings of not only nuclear reactions, but also thermal-hydraulics (T/H) behaviors. The nTRACER [1] direct whole core calculation code being developed at Seoul National University (SNU) has an internal T/H module to determine the temperature and density fields in the reactor. However, this module is based on a quite simplified model and considers only axial flow. The weakness of not-considering radial flow was overcome by coupling the MATRA (Multichannel Analysis for steady-state and Transient in Rod Array) [2] code with nTRACER [3]. MATRA can generate more realistic and detailed T/H field information for nTRACER, but it is a legacy code and does not have an efficient parallel computing capability.

On the contrary, the COBRA-TF (Coolant-Boiling in Rod Arrays – Two Fluids, CTF) [4] subchannel code, which was developed for the T/H analysis of Light Water Reactor (LWR) vessels, has a good parallel computing capability based on the Message Passing Interface (MPI). Moreover, it employs a two-fluid, three-field (i.e. fluid film, fluid drops, and vapor) modeling approach that is superior to the homogeneous equilibrium model of MATRA. In addition, it has other unique features such as the Boron tracking model which would be valuable in the neutronics aspect. Since these features of CTF would help more realistic core calculations, CTF has been coupled with the time-dependent 3D discrete ordinates neutron transport code TORT-TD [5] and the diffusion based coupled code system ATHLET-QUABOX/CUBBOX [6] by Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) of Germany [7,8].

Likewise, to enhance the calculation accuracy, execution speed, and general applicability of nTRACER in the transient calculations as well as in the steady-state calculations, the coupling of CTF with nTRACER was planned and carried out under a joint agreement between SNU and GRS. This paper presents the details of the coupling between nTRACER and CTF and the initial assessment of the coupled code with the calculation results obtained for a 2x2 assembly checkerboard problem with nonuniform inlet boron distributions.

2. Coupling CTF with nTRACER on LINUX

The coupling of CTF with nTRACER was conducted on the LINUX environment in which the shared library feature is available such that separate compilation of the CTF module and the nTRACER module is possible. In order to specify the flow channel conveniently for the CTF calculation using the nTRACER input deck, a CTF input generator was written and the mapping scheme between the neutronic and T/H meshes was established as presented below.

2.1 Coupling with Shared Library

There are several ways to couple different codes including the following two:

1) to compile and link the codes together to build one executable by making a static library for a module,
2) to generate a shared library for one code which can be dynamically loaded when the main executable requires it.

The second way is easier to maintain and compile each code separately although it is a little inconvenient to carry the library file along the executable. Even a compiler that is different from the one being used for the compilation of the main executable can be used. Since the official CTF package is compiled with the GNU Fortran whereas nTRACER is compiled with the Intel Fortran compiler, the second way was adopted in this work by using the shared library capability available on LINUX.

A shared library is a large collection of the object files and can be used in dynamic linking such that it is loaded and linked with the executable only when a subroutine in the library is called from the main executable. Only the minimum work is carried out by the linker when the program is compiled. It checks only if the required subroutines are in the shared library. The majority of linking task is performed when the program is started or the subroutines are called during the execution.

One thing to note in using the shared library feature is that the data sharing using the Fortran 90 modules between two subroutines belonging to the different codes is not practical. Rather the data should be transferred to the other by the subroutine arguments when calling a subroutine belonging to the shared library. Thus, the variable arrays containing the fuel rod power, coolant channel temperature density and temperature, and fuel temperature which are defined in CTF are identified and transferred to nTRACER as subroutine arguments.

2.2 Mapping Scheme in nTRACER and CTF

In general, subchannel analysis codes employ channel-centered cells while neutronics codes take pin-centered cells. This difference in the mapping should be taken care of when the data are transferred from one code to the other. Fortunately, CTF has the capability to convert the T/H field information from the subchannel-centered values to rod-centered cell values so that it is easier to couple CTF with a neutronics code than other subchennel codes. The indexing scheme for the rod-centered cells of CTF is, however, different from that of nTRACER in that nTRACER uses assembly-wise pin cell indexing while CTF uses core-wise global pin cell indexing. Moreover, for the assembly gap regions, nTRACER assigns additional cells whereas CTF does not. A subroutine was written in nTRACER to take care of the difference in the rod cell indexing scheme and assign temperature and density to the gap cells in nTRACER. Note that the fuel temperature distribution is normally determined in CTF and is transferred to nTRACER. Thus, nTRACER can use either these CTF fuel temperature data or its own fuel temperature calculation results that are obtained by solving the heat conduction equation given the bulk coolant temperature conditions transferred from CTF.

2.3 Initial Assessment

A 2x2 assembly checkerboard with 16x16 pins in each assembly was solved to verify the coupled calculation feature. The nTRACER calculations were performed in two times: once with the internal T/H solver and the second time with the CTF T/H solver. The converged pin power distributions and coolant temperature distributions are compared by taking the CTF coupled case as the reference. Figs. 1 and 2 below show the comparison results for the coolant temperatures at the highest power plane and at the outlet.

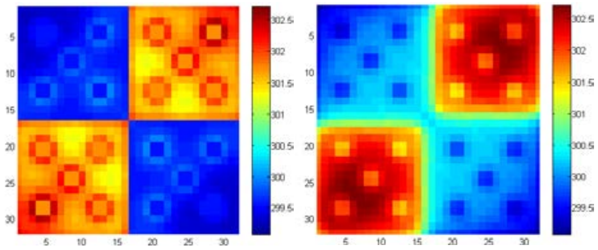


Fig. 1. Temperature distribution at the highest power plane with nTRACER internal T/H module (left) and with CTF (right)

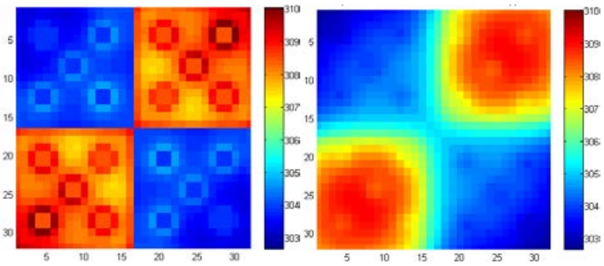


Fig. 2. Outlet temperature distribution with nTRACER internal T/H module (left) and with CTF (right)

As shown in the two plots, the unphysical discontinuity in the coolant temperature noted at the interface of the two assemblies in the result obtained with the internal T/H solver is smoothened in the CTF coupled calculation. The smoothening of the temperature distribution due to the flow mixing in the CTF coupled calculation becomes more obvious as the flow move upward.

The effect of the more realistic temperature distribution on the pin power is, however, not so significant as identified in Fig. 3, which compares the axially integrated pin power distributions. The difference in the pin power distribution is within the band of ±0.25%. The pin power obtained with the nTRACER internal T/H solver is mostly higher at the high power assemblies while it is lower in the low power assembly. This trend can be explained by the coolant temperature comparison for the highest power plane shown in Fig. 1. With the internal T/H solver, more pins have lower temperature in the high power assembly and the negative feedback effect causes higher power. However, this effect is not so large as identified by the other parameters shown in Table I.

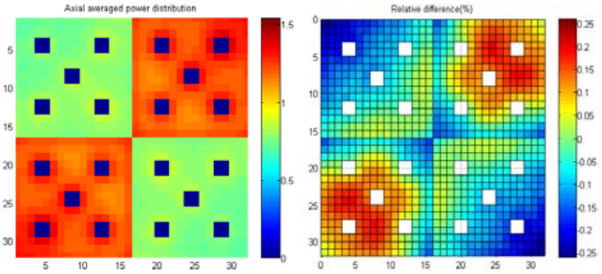


Fig. 3. Axially averaged pin power distribution with the CTF T/H solver (left) and relative difference (%, reference CTF) in the power distribution for the internal T/H solver (right)

Table I: Summary of calculated results

	nTRACER	CTF
k-eff	1.03988	1.04002
Peaking factor (pin)	1.3837	1.3822
Avg. outlet temp.	306.18 °C	305.97 °C
Max outlet temp.	310.02 °C	309.09 °C
Min. outlet temp.	303.25 °C	302.66 °C
Max. fuel temp.	559.4 °C	558.8 °C

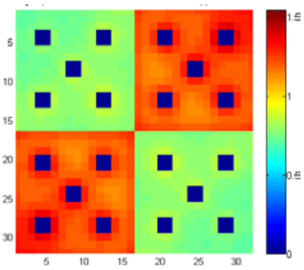
3. Examination of Boron Tracking Model in CTF

Previously nTRACER can model only uniform boron concentration in the coolant for the entire cells. However, there might be nonuniform boron distribution cases at some special transient conditions. CTF has a boron tracking model to deal with such cases and the boron concentration is calculated for each channel. Modifications needed to incorporate the nonuniform boron data in the nTRACER calculation were made and the new feature was examined for the checkerboard case with different boron concentrations in each assembly as the following:

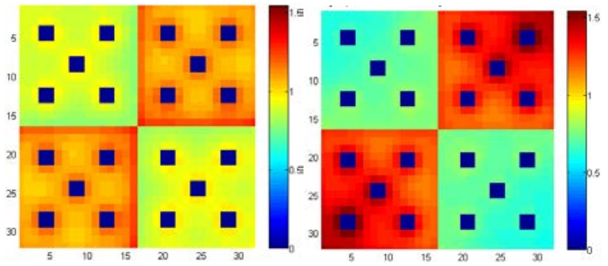
1) Case 1: Uniform 800 ppm boron concentration which is taken as the base case
2) Case 2: 0 ppm boron concentration at the low power assembly and 800 ppm at the high power assembly
3) Case 3: 0 ppm boron concentration at the high power assembly and 800 ppm at the low power assembly

Note that these cases are not realistic at all, but the calculations were carried out for the sake of theoretical examination.

Fig. 4 shows the power distributions of the three cases. As expected, the power increases at the assemblies having 0 ppm boron while it decreases at the assemblies having 800 ppm. Hence, Case 3 gives the most skewed power distributions. The same tendency is noted in the coolant temperature distribution at the outlet shown in Fig. 5.



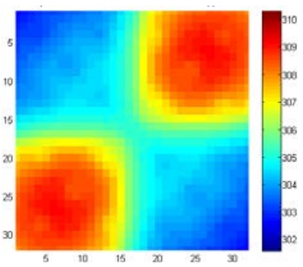
Case 1



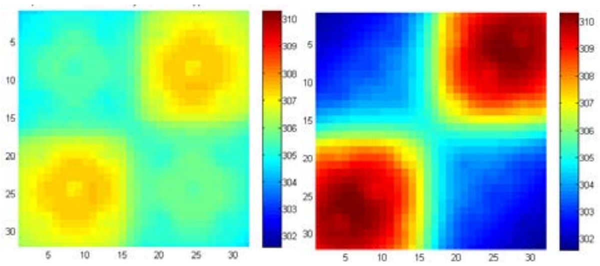
Case 2 Case 3

Fig. 4. Axially averaged pin power distribution by asymmetric boron cases

Table II summarized the results with a general comparison of the three cases. The effective multiplication factor (k-eff) is increased in both cases of partial boron reduction. It is observed that Case 3 yields a higher increase because removal of absorption in the high power assembly enhances more neutron generation. This case involves the highest peaking factor and maximum temperature as well as the lowest temperature. It is noted, however, that the average outlet temperatures in the three cases are almost same because total power remains the same.



Case 1



Case 2 Case 3

Fig. 5. Coolant temperature distribution at outlet by asymmetric boron inlet cases

Table II: Comparison of various calculated results for different boron inlet conditions

	Case 1	Case 2	Case 3
k-eff	1.04002	1.10701	1.11637
Peaking factor (pin)	1.3822	1.2916	1.5402
Avg. outlet temp.	305.97°C	306.01°C	305.96°C
Max outlet temp.	309.09°C	307.45°C	310.29°C
Min. outlet temp.	302.66°C	304.32°C	301.59°C
Max. fuel temp.	558.8°C	535.2°C	588.8°C

Fig. 6 illustrates the change in boron concentration along the axial direction. At the inlet, the distinct boundary of boron concentration is noted. However, as the flow goes up along the assemblies, boron starts to migrate around due to the diffusion and cross flow between channels. Therefore, a smeared distribution of boron concentration is observed at the outlet plane although the amount of diffused boron is not so large.

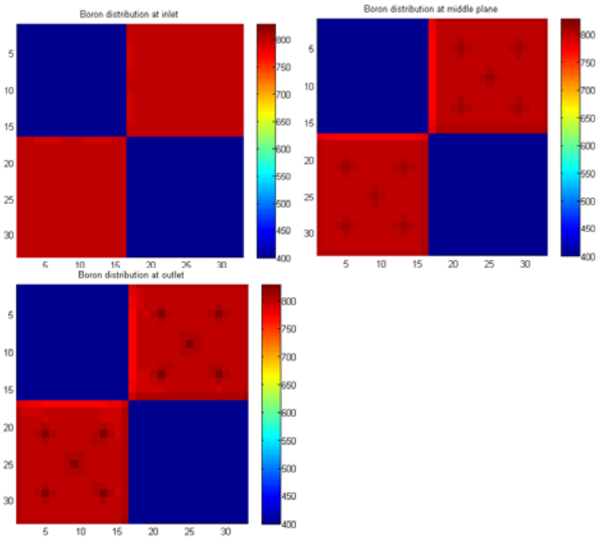


Fig. 6. Boron concentration change along the axial direction for Case 2; upper left - inlet, upper right - middle, bottom - outlet

4. Conclusions

Coupling CTF with nTRACER was done successfully in the LINUX environment utilizing the shared library feature that allows using two different compilers so that the compiler originally used for each code can be used. The initial assessment of the coupled code demonstrates that more realistic coolant temperatures are obtainable by using CTF. The change in pin power distribution is noted with the realistic flow distribution even though the change is insignificant. The calculation utilizing the boron tracking model of CTF is noticeable. It makes possible for nTRACER to handle nonuniform boron distributions which can be encountered during some transients.

Since further validation of the coupling is necessary, the coupling capabilities will be extended to transient applications where non-uniform distributions of inlet parameters such as boron concentration but also coolant temperature can occur. The evaluation and improvement of the parallel computing capability of the nTRACER/CTF, which will be needed for the simulation of full core problems, is under way.

ACKNOWLEDGEMENTS

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