Development and Assessment of ESCOT Pin-Wise Thermal-Hydraulics Coupling in a Direct Whole Core Calculation Code nTER

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1. Introduction

High-fidelity multi-physics simulation with coupled neutronics and thermal-hydraulics (T-H) codes for whole core of light water reactors has become a critical issue when performing thorough core design analyses. Considering the compensating relationship between accuracy and computational time, a drift-flux model based pin-level core T-H code ESCOT (Efficient Simulator of Core Thermal-Hydraulics) [1] has been coupled to a direct whole core calculation code nTER (Neutron Transport Evaluator for Reactors) [2]. The ESCOT subchannel code was developed by Seoul National University – Reactor Physics Laboratory (SNURPL) and employs a 4-equation drift-flux model and SIMPLEC algorithm. The nTER code is a deterministic transport code developed by the Korea Atomic Energy Research Institute (KAERI) with the cooperation of the Korea Hydro and Nuclear Power Central Research Institute (KHNP-CRI) and employs 2D-1D scheme with planar method of characteristics (MOC) and axial P_N implemented within the 3D CMFD framework. Both codes are highly parallelized with MPI, their domain can be decomposed assembly-wise in the radial direction and plane-wise in the axial direction.

nTER has its own simple internal T-H solver which is for closed channels, involving no pressure drops. For the nTER code, the single channel corresponds to the entire assembly. Therefore, the nTER standalone calculation in feedback mode provides a single average coolant temperature per assembly which is used to calculate the pin-wise fuel temperature profiles. ESCOT is capable of a more accurate prediction of cross-flow, spacer-grid effects and fuel temperature in contrast to the simple internal T-H solver. In particular, the ESCOT fuel heat conduction model accepts subpin level power, burnup and gadolinium fraction and uses the same solid properties of the fuel performance code FRAPCON [3] for a realistic estimation of the fuel temperature profile.

nTER/ESCOT platform adopts a sequential coupling scheme (non-linear Gauss-Seidel method) accelerated and stabilized through the Anderson acceleration method [4], the flowcharts of both codes are shown in Fig. 1.

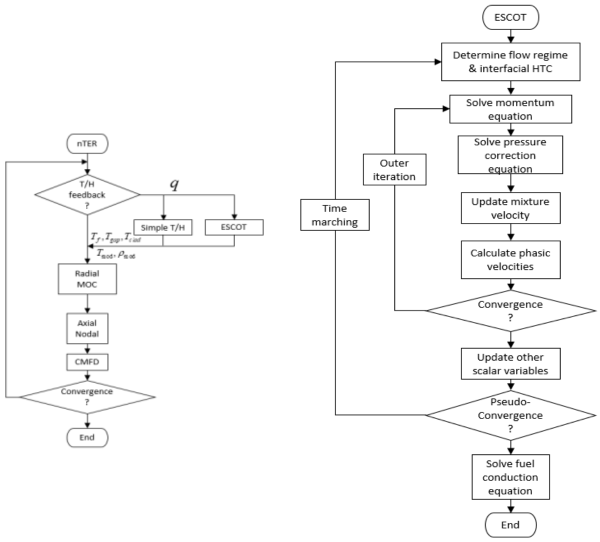

Fig. 1: flowcharts of the nTER (*left*) and ESCOT (*right*) codes.

2. Assessment of the nTER/ESCOT Coupled Platform

A series of 3D calculation tests with different symmetry option and different boundary conditions have been performed to test accuracy and performance of the nTER/ESCOT coupled platform. Although ESCOT fuel conduction model allows burnup dependent properties, the gap conductance does not have a correlation directly depending by the fuel burnup. For these analyses a constant value of gap conductance is used (10 kW/m^2/K) [5].

The performed tests have been split in feedback and burnup analysis. The feedback calculations were carried out both from VERA benchmark model and YG3 core model while the depletion analysis has been performed using only the YG3 models.

All the following calculations show a comparison between nTER standalone with activated Simple T-H model and nTER/ESCOT coupled platform where nTER standalone is used as reference.

2.1. Feedback Calculations

<u>VERA</u>

The analyzed tests were Problem 3, 4 and 5. Problem 3 copes with single assembly problem and the adopted radial boundary condition was pure reflection. Problem 4 analyzes checkerboards; this analysis has been carried out with pure reflection and also using the colorset boundary condition. Problem 5 is a full core model.

First of all, no difference in k-eff is shown for the same problem run with different symmetry option and same boundary condition. The eigenvalue difference between nTER standalone and nTER/ESCOT never exceeds 25 pcm with the axially integrated power RMS and maximum error differences relatively small for Problem 3 and 4 which reach 0.33% and 1.30% in case of Problem 5 (see Fig. 2). The number of fix point iterations (neutronics-T-H) was always equal to 6. TABLE I shows a summary of every performed calculation.

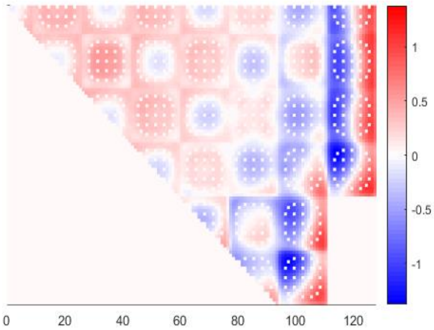

Fig. 2: axially integrated power difference between nTER standalone and nTER/ESCOT for Problem 5 (symmetry angle: 45).

TABLE I: Summary of the feedback calculation results for VERA benchmark problem.

	Sym Angle	k-eff		Rel. ΔP (%)	
		Simple T-H	**ESCOT(pcm)**	**RMS**	**Max**
Prob. 3 SA	45	1.16812	1.16823(-11)	0.09	0.23
	90	1.16812	1.16823(-11)	0.09	0.23
	360	1.16812	1.16823(-11)	0.09	0.23
Prob. 4 3x3	45	0.98329	0.98343(-14)	0.14	0.33
	90	0.98329	0.98343(-14)	0.14	0.34
Prob. 4 3x3 *colorset*	45	0.98592	0.98570(22)	0.10	0.29
	90	0.98592	0.98570(22)	0.10	0.29
Prob. 5	45	0.99093	0.99114(-21)	0.33	1.30
Prob. 5 *CBC*	45	1199.01	1200.22(-1.21)	0.33	1.31

It is not a case that for the Problem 5 the maximum error difference increases up to 1.30% inside peripheral assemblies; in fact the standalone calculation is assuming an average temperature in every assembly which makes less physical the prediction of the power at the boundary (see Fig. 3).

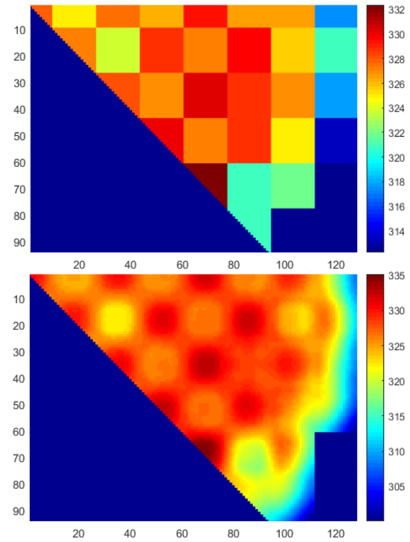

Fig. 3: outlet coolant temperature distribution for nTER standalone calculation (*top*) and nTER/ESCOT coupled platform (*bottom*).

For Problem 5 the critical boron concentration (CBC) search was performed too. The CBC for this problem results in 1199.01 ppm for nTER standalone and 1200.22 for nTER/ESCOT. The axially integrated power error difference has a similar trend to the feedback calculation, with an RMS of 0.33% and a maximum of 1.31% again located inside peripheral fuel assemblies.

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The feedback calculations related to YG3 concerns the A0 single assembly (UO_2 enrichment 1.30%) and the full core. For these calculations the Xenon equilibrium option was also activated. In this case the eigenvalue difference is within 3 pcm. The axially integrated power RMS error between nTER standalone and nTER/ESCOT has a low value (0.10% for the single assembly calculation and 0.33% for the core calculation).

In this case the number of fix point iterations was 4 for the single assembly calculation and 6 for the core calculation.

The maximum error difference between the Simple T-H and the ESCOT calculation for the core simulation is around 1.30% and located in the peripheral assemblies. The CBC search was also performed for the YG3 core. The nTER standalone calculation has given 828.27 ppm while nTER/ESCOT 828.86 with RMS and maximum difference in axially integrated power comparable to the eigenvalue calculation (see Fig. 2). The summary of these calculations are shown inside TABLE II.

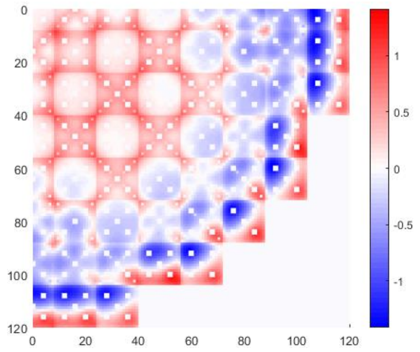

Fig. 4: axially integrated power difference between nTER standalone and nTER/ESCOT for YG3 core in case of activated CBC search mode (symmetry angle: 90).

TABLE II: Summary of the feedback calculation results for YG3 core.

	Sym Angle	k-eff		Rel. ΔP (%)	
		Simple T-H	ESCOT(pcm)	RMS	Max
SA	45	1.09625	1.09628(-3)	0.10	0.24
	90	1.09625	1.09628(-3)	0. 10	0.23
	360	1.09625	1.09628(-3)	0. 10	0.23
Core	45	1.14590	1.14588(2)	0.33	1.27
	90	1.14590	1.14588(2)	0.34	1.27
Core *CBC*	45	828.27	828.86(-0.59)	0.38	1.31
	90	828.27	828.86(-0.59)	0.38	1.31

2.2. Depletion Calculations

The depletion capability of nTER/ESCOT has been performed in boron search mode using 3D problems. Every calculation concerns models obtained by the YG3 core. The analysis examines single assembly, checkerboard and full core analyses. The simulated burnup cycle was 1 year, except for the assembly A0 were the cycle was set to 145 days since the CBC becomes negative after that step. To speed up the process, all the calculations have been performed with the octant symmetry.

The main common result in all these calculations is that the CBC difference between nTER standalone and nTER/ESCOT increases almost linearly from the initial step to the last one. If the problem contains gadolinium a spike is present between 130 and 200 days when the gadolinium is completely consumed as Fig. 5 shows. This picture shows the boron letdown curve for 1-year burnup of the YG3 reactor core. During the entire cycle the difference between the predicted CBCs never exceeded 20 ppm.

The colorset symmetry option was used for two checkerboard problems (C1A0 and C1C0). The maximum difference between nTER standalone CBC prediction and nTER/ESCOT decreases to values between 6 and 10 ppm. The axial power RMS error difference results around 0.95% for C1A0 and 0.27% for C1C0 while the 2D power RMS difference results in 0.12% for C1A0 and 0.11% for C1C0. Also the maximum and minimum difference results relatively low (about 0.5% and -0.25%) to confirm the fact that nTER standalone already provides a good approximation of problems without border effects.

For the YG3 reactor core octant simulation, the CBC difference never exceeds 10 ppm and the distance between nTER standalone and nTER/ESCOT increases linearly during the cycle (see again Fig. 5). The 2D power during burnup has an almost constant RMS error difference of about 0.35-0.40%, maximum of about 1.4% and minimum of about-1.1%. For a better understanding of the spatial trend of the axially integrated power at different burnup steps, two maps are shown in Fig. 7. These figures show the difference at beginning of life (BoL) and at the end of cycle (EoC) between the predicted axially integrated power provided by nTER standalone and nTER/ESCOT.

TABLE III shows a summary of the burnup calculations performed to assess the coupled platform nTER/ESCOT.

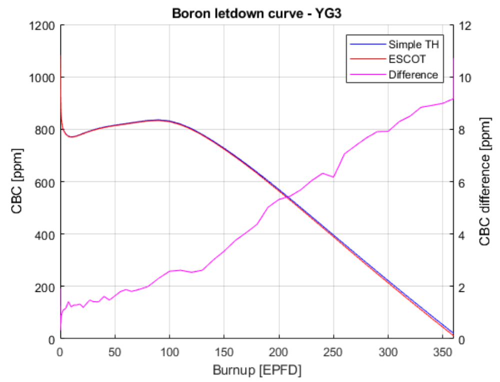

Fig. 5: boron letdown curve for YG3 core.

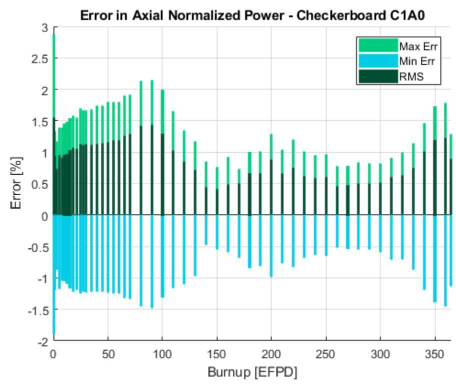

Fig. 6: error in axial normalized power for YG3 C1A0.

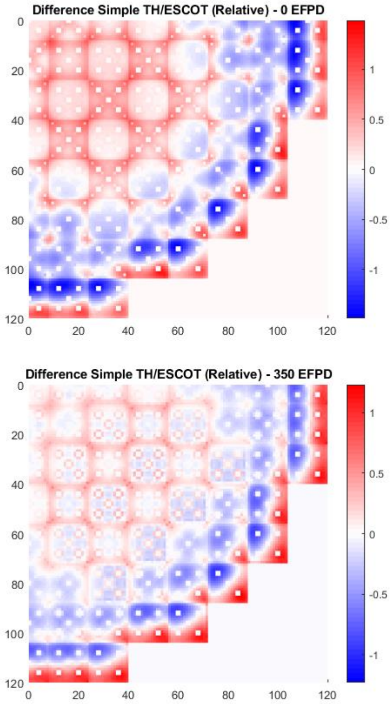

Fig. 7: axially integrated power difference for YG3 core at BoL (*top*) and EoC (*bottom*).

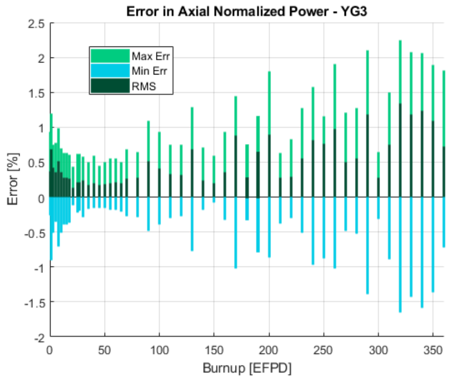

Fig. 8: RMS, MAX and MIN difference for each burnup steps of the YG3 reactor core.

TABLE III: summary of the burnup calculation results for YG3 core.

		CBC	Rel. ΔP (%)	
		MAX Diff (ppm)	**RMS**	**Max**
SA	**A0**	2	0.10	0.22
	B0	7	0.08	0.21
	C0	10	0.14	0.23
	D0	12	0.09	0.21
	D1	11	0.16	0.23
Checker board	**C1A0**	6	0.12	0.5
	C1C0	9	0.11	0.25
Core	**YG3**	7	0.37	1.4

3. Summary and Conclusions

The coupled neutronics-T-H platform nTER/ESCOT has been developed to perform high-fidelity whole core analyses. For the feedback analyses, the differences between nTER standalone and nTER/ESCOT have shown an eigenvalue gap smaller than 30 pcm. If the border effects of the simulated problem are not significant, nTER standalone and nTER/ESCOT have shown similar behavior in predicting the power in that the RMS error difference was always below 0.5% and the maximum never above 0.8%. For reactor problems the RMS error difference remains of the same of the single assembly and checkerboard problems (below 0.5%) while the maximum error difference has increased up to 1.2÷1.5% due to the better approximation of the coolant temperature inside the peripheral assemblies. The assessment of the depletion calculation has shown a difference in CBC large as 20 ppm. The CBC difference increased almost linearly with burnup. The axial power difference showed an RMS error changing within 0.5÷1.0% for single assembly, checkerboard and reactor core calculations. For the reactor simulation, the axially integrated power has shown an almost constant RMS error difference of 0.35% in every burnup step with again maximum error between 1.2÷1.5% concentrated at the boundary of the problem.

This new coupled code is a practical high fidelity tool which allows better simulation of coupled neutronics-T-H problems with more accurate prediction of cross-flow, spacer-grid effects and fuel temperature.

References

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