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PIN LEVEL NEUTRONIC – THERMALHYDRAULIC TWO-WAY-COUPLING USING DYN3D-SP3 AND SUBCHANFLOW

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ABSTRACT

Nowadays several Reactor Dynamic Codes, (RDC) are able to solve the diffusion equation or even the transport equation (SP3 approximation) considering feedback parameters coming from the thermalhydraulic (TH) core behavior. These kinds of codes (DYN3D, PARCS, among others) usually contain a 1D two phase flow thermalhydraulic model capable to pass them assembly averaged feedback parameters. At fuel assembly base this nodal coupling is completely a two way coupling. The Neutronic part calculates the mean power of the whole assembly and passes it to the TH part in order to actualize the heat source. In turn, the TH model passes the assembly-based feedback parameters to the neutronic code for actualizing the nodal cross sections. The process will be repeated until convergence. At pin level, the current situation is somehow different. Although the neutronic solver can pass the pin power distribution in every sub – node (pin distribution), the 1-D TH model will average the pin power distribution to assembly-based scale and will give back assembly averaged feedbacks to the neutronic part for cross sections up-date (one and a half way coupling), leading to information loss in the calculation. A new coupled program system DYNSUB was developed by coupling DYN3D-SP3 and SUBCHANFLOW at pin level. DYNSUB was used to analyze stationary PWR minicore problems at pin-level. The comparison of the Keff predicted by DYNSUB with the one calculated by DYN3D-SP3 (coarse TH solution) shows small differences of up to 26 pcm. Differences up to 4.5% were found in the radial distribution of the pin power. The local safety parameters such as cladding and fuel temperature predicted with DYNSUB shows larger deviations compared with the ones obtained with DYN3D-SP3. These differences may increase when analyzing transients.

Key Words: Coupling, Neutronic, Subchannel Codes, Reactor Dynamic Codes, pin-by-pin solutions.

1. INTRODUCTION

Coupled neutronic / thermal hydraulics simulation codes for safety investigations of Light Water Reactors (LWR) are mainly based on nodal solutions allowing a limited degree of further spatial resolution of the fuel assembly to the cell (pin) level. Hence several strategies have been

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searched in order to extend the methodologies for a more detailed and physical sound prediction of the pin power. The pin power reconstruction method offers a very fast calculation of pin power distribution via a combination of the analytical solution of the diffusion equation plus the use of form functions taking into account internal heterogeneities. Another option is the use of solvers based for instance in the transport approximation SP3 that is able to predict the local power at pin level. In both cases the coupling with the thermal hydraulic (TH) model is performed by a one and a half way coupling, i.e. the neutronic solver gives a detailed pin power distribution but the TH solver (usually a one dimensional solver) predicts nodal averaged values (fuel assembly level) for the calculation of feedback parameters. Doing so important local information is lost. Consequently, a more precise and realistic description of both TH and neutronic domains at the same spatial scale is needed to catch the increasing heterogeneities of modern LWR core loadings.

There are two alternatives to replace the one dimensional thermal hydraulic solvers: computational fluid dynamic codes like ANSYS CFX, StarCD or subchannel codes such as COBRA [4], FLICA [5] and SUBCHANFLOW. Latter category of codes are selected at Karlsruhe Institute of Technology (KIT) for detailed TH simulation coupled to neutronic solvers because they are fast running codes with dedicated fuel rod models.

Section 2 describes the two codes, DYN3D-SP3 [1, 2] and SUBCHANFLOW [3], which will be coupled at pin level. Using an appropriate subchannel code, it is possible to allocate the pin power in every axial node of every rod for a later calculation of pin based XS's with pin based feedback parameters. In Section 3, the strategy for moving from one and a half way coupling to a two way coupling is described. Section 4 describes the features of the new DYNSUB program. In Section 5 the test problem to be analyzed by DYNSUB as well as the results obtained for a steady state simulation will be described. Finally the conclusions are given in Section 6.

2. TOOLS USED IN THE 2-WAY-COUPLING

To reach the goals of a pin-by-pin simulation, the DYN3D-SP3 neutron kinetics codes and the 3d thermal hydraulic SUBCHANFLOW code were selected for coupling.

2.1. DYN3D-SP3

DYN3D is a **DYN**amical **3-D**imensional code for the simulation of thermal reactor cores [1, 2, 7, and 8]. The 3-dimensional neutron kinetics models are based on a nodal expansion method for solving the two-group neutron diffusion equation in hex-z or rectangular x,y,z-geometry. Modern core loading include MOX fuels, larger fuel cycle length, higher burn-up, part-length rods, water rods, etc. which is very challenging for nodal diffusion codes. Thus, nodal diffusion methods were extended to include many energy groups, and a simplified transport approximation (SP3). To enhance the prediction capability of DYN3D a new version was developed, called DYN3D-SP3. It includes a one dimensional thermal hydraulic model (FLOCAL) to describe the two phase flow and thermal behavior of fuel rods. The fuel elements are simulated by parallel coolant channels with equal pressure drop and no cross flow.

2.2. SUBCHANFLOW

SUBCHANFLOW [3] is built on the bases of the legacy subchannel programs COBRA-IV-I [4] and COBRA-EN [5]. The old programming methods are substituted by using the modern Fortran 95 language. The thermo-physical properties of coolant and solid materials are summarized in separate modules. All arrays are dynamically allocated depending on input data, which is problem specific. The portability of the code is assured by avoiding functions that depend on operating systems. Consequently SUBCHANFLOW can be compiled under WINDOWS, LINUX or other UNIX systems without problem. The input deck is designed as a text based user interface using comprehensive keywords and simple tables. A manifold output is created to be used with different post processing tools e.g. to generate simple curves or more extensive three dimensional diagrams. In opposite to the COBRA family of subchannel codes, SUBCHANFLOW uses rigorously SI units internally in all modules. Coolant properties and state functions are implemented for water using the IAPWS-97 formulation (The International Association for the Properties of Water and Steam). In addition, property functions for liquid metals (sodium and lead) are available, too. The code can handle both rectangular and hexagonal fuel bundles and core geometries. As boundary condition the total flow rate or a channel dependent flow rate can be selected. It is possible to distribute the flow automatically to the parallel channels depending on the friction at the bundle inlet. In addition a pressure difference boundary can be applied for steady state calculations. Fluid temperature at the inlet and pressure at the outlet have to be prescribed as boundary conditions. SUBCHANFLOW takes profit of many valuable empirical correlations related to pressure drop, heat transfer, void generation, etc., collected over the last decades. Consequently it does not follow the general trend to describe two phase flow by simulating the processes on a micro-scale basis e.g., separate conservation equations for liquid droplets, films or vapor bubbles.

In SUBCHANFLOW a three equation two phase flow model i.e. a mixture equation for mass, momentum and energy balance is used. The constitutive relations are expressed as mixture equations for wall friction and wall heat flux as well as a slip velocity relation. The numerical solver is based on the pressure difference method of COBRA-IV-I and COBRA-EN. It is fully implicit and does not have any Courant time step limitation. All transients are based on a steady state calculation done before. In the numerical solution, each external iteration step proceeds axially level by level starting from the bottom. Consequently strictly upward flow can be handled, only. For strongly buoyant driven flows convergence will not be obtained.

3. FROM ONE AND A HALF TO TWO WAY COUPLING

For a detailed transport solution at pin level with DYN3D-SP3 pin based cross sections (XS) are needed. If the solution is a time dependent one, then the XS must be generated in advance for the expected range of thermal hydraulic parameters such as fuel temperature, coolant density, boron concentration, etc. The one dimensional thermal hydraulic module, FLOCAL, is able to predict these feedback parameters at a nodal level i.e. averaged over one fuel assembly. As it can be seen in Figure 1, the neutronic solution is a detailed one while the TH solution calculates nodal averaged values at fuel assembly level. By this approach detailed information is lost.

To increase the degree of detail in the thermal hydraulic solution, a transition from a one dimensional to a multidimensional solver at component level like the subchannel codes is urgently needed. Considering a thermal hydraulic subchannel code a real two way coupling with a detailed neutronic solver may be possible. Hence the subchannel code SUBCHANFLOW was selected for the coupling with DYN3D-SP3. By this approach, it is possible to allocate the pin power in every axial node of every rod for a later calculation of the pin based XS's with pin based feedback parameters in every rod and in every axial layer avoiding the averaging process.

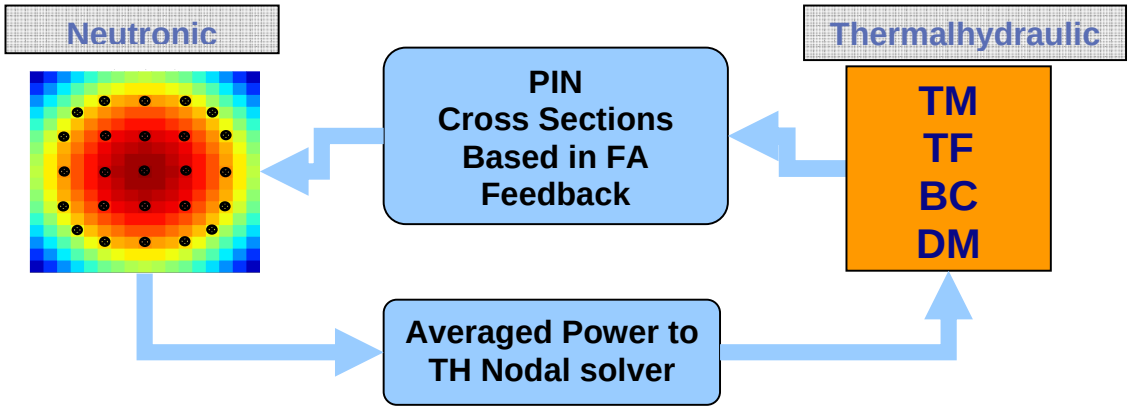

Figure 1. One and a Half Way Coupling of DYN3D – SP3

In the Figure 2, the two-way coupling scheme implemented in the new code DYNSUB by coupling SUBCHANFLOW and DYN3D-SP3 is illustrated for a fuel assembly. The pin power distribution is calculated with DYN3D-SP3 for every node in the geometry (pin based scale). The calculated pin power is passed over to the thermal hydraulic part, where it is allocated in each axial node of the rods and of the subchannels considered in the SUBCHANFLOW fuel assembly representation.

Special attention must be paid in the transfer of the feedback parameters. The mesh used usually in the subchannel codes has a different division compared with the neutronic one. In the case of SUBCHANFLOW, the power coming from the neutronic code can be directly allocated in the radial and axial rod power distribution. However, some of the feedback parameters, e.g. moderator density and temperature, void fraction, among others, are calculated in every subchannel, making necessary the use of a weighting method for having just one feedback value for every pin.

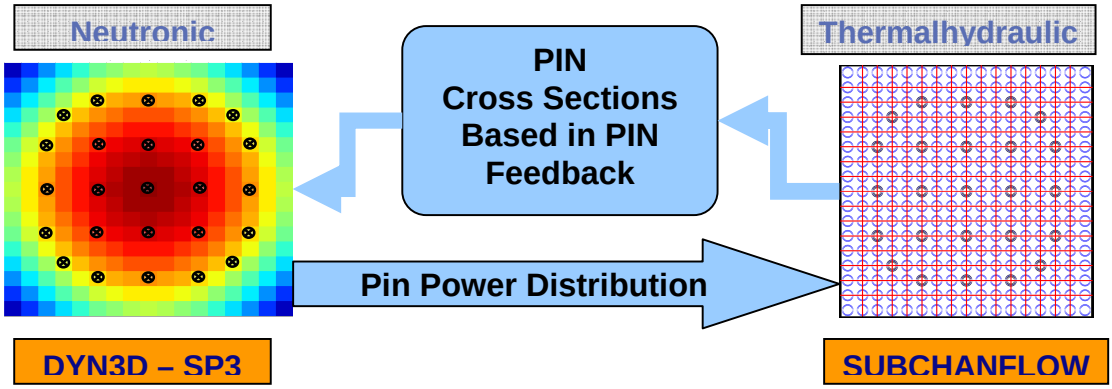

Figure 2. Diagram of a Two-Way for every axial layer.

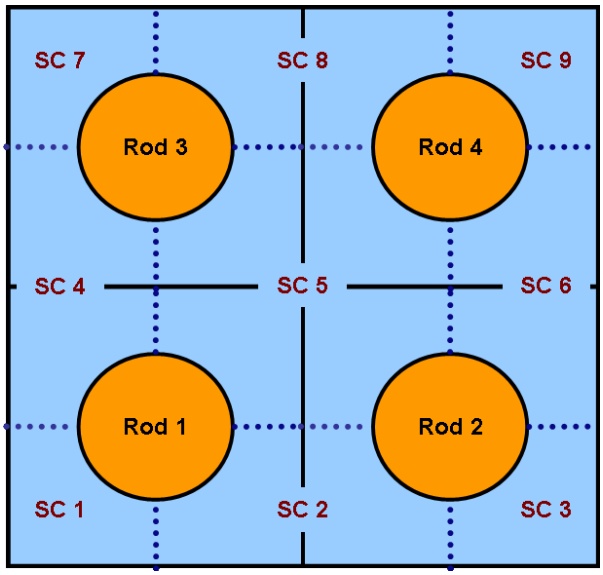

Figure 3. Bundle of 4 fuel rods with 9 subchannels.

In Figure 3, a bundle of four rods with 9 subchannels (SC) has been defined; furthermore the neutronic mesh (black full line) and the thermalhydraulic mesh (blue dotted line) are showed. The radial mapping between the neutronic and thermal hydraulic is as follows: 4 subchannels corresponds to one neutronic node. Hence the TH feedback parameters (FP) for each of the neutronic nodes must be calculated based on the corresponding 4 subchannels before they are transferred to the neutronic part.

The FP for every neutronic node is given by means of the following Equation 1:

$$\overline{FP}_{ij} = \frac{\sum_{k=1}^{4} FP_k * A(SC_k)}{\sum_{k=1}^{4} A(SC_k)} \quad (1)$$

Where:

FP_k : Is whatever Feedback Parameter calculated per subchannel *k* (moderator density or temperature, void fraction, etc…).

$\overline{FP}_{ij}$: Mean value of the Feedback Parameter transferred to the neutronic mesh.

$A(SC_k)$: Flow area of subchannel *k*.

4. DYNSUB A NEW TWO –WAY – COUPLING CODE

Following the two-way approach a new coupled code, DYNSUB, was generated by coupling DYN3D-SP3 and SUBCHANFLOW. Several modifications of the source of both codes as well the creation of new routines were necessary.

In DYNSUB, the module DYN3D-SP3 acts a master and SUBCHANFLOW as a slave. In this case the one dimensional TH module, FLOCAL, was completely replaced by SUBCHANFLOW via a Dynamic Link Library. In the Figure 4 the strategy followed for DYNSUB is shown.

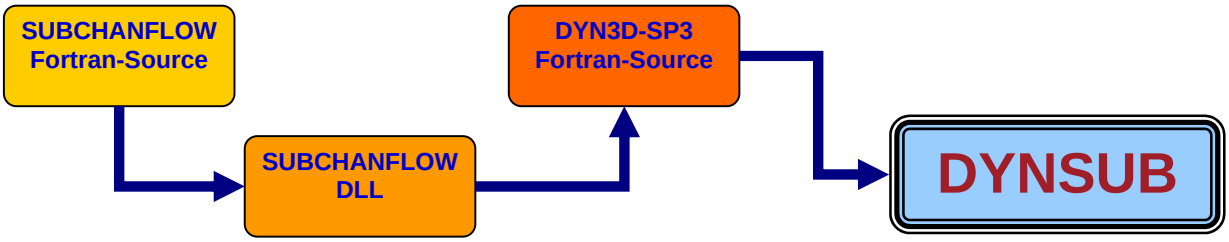

Figure 4. DYNSUB Coupling Scheme

In the next subsections, the main changes in both codes and also the additional subroutines generated for the coupling are described.

4.1. Main Changes in SUBCHANFLOW

To replace FLOCAL with SUBCHANFLOW several changes were required. The main idea of the coupling was the use of SUBCHANFLOW as a library. For doing so, several changes were done as listed hereafter:

- A slave program is not allowed to break a run but to send an error message once a problem is founded. Any "stop" in the source of SUBCHANFLOW will break the run. For this reason the replacement of "stops" by "returns" in the source of SUBCHANFLOW with the respective error message was performed.

- The thermal power fraction in every node of SUBCHANFLOW was calculated based in an axial profile combined with a radial profile. This was not favorable for the implementation of the two-way coupling. Changes were implemented in order to receive the power distribution in every node of the 3D problem representation.

- Modularization of SUBCHANFLOW by grouping it in a certain number of external SUBROUTINES. Each SUBROUTINE is dealing with a specific task in order to make it available in the master program.

- SUBCHANFLOW was compiled as a Dynamic Link Library (DLL) using preprocessor directives. Then it was added to the DYNSUB project for a later linkage to obtain the new executable of DYNSUB.

- Creation of an additional output file (Feedback.dat) for passing the feedback parameters to DYN3D-SP3.

4.2. Main Changes in DYN3D-SP3

DYN3D-SP3 is the master program. The main changes were related with the substitution of the TH module FLOCAL by SUBCHANFLOW by means of calling the external functions of the DLL containing SUBCHANFLOW.

Furthermore changes to several subroutines were done to take into account the new treatment of the feedback parameters predicted by SUBCHANFLOW in a very detailed resolution.

- The main subroutine of DYN3D-SP3 was modified in order to include the commons of the SUBCHANFLOW DLL, the calls to the SUBCHANFLOW modules. Additionally an internal option to select either SUBCHANFLOW or FLOCAL was implemented.

- New subroutine to deal with the allocation of detailed 3D feedback parameters. In the original DYN3D-SP3 the memory allocation is done for the nodal i.e. assembly-wise feedback parameters (same value for every node inside the assembly). In DYNSUB, the allocation must be done in a pin based scale (different values for every node in the assembly),

- The subroutines dealing with the calculation of cross sections were also modified in order to have interpolation of cross sections with the new pin based feedback parameters.

4.3. The New DYNSUB Program

The coupled of the two codes (DYNSUB), needed also the creation of new subroutines mainly related with the communication between them. The communication between them is done via data files. This option provides an easy way for checking the data passing from one code to the other.

A list of new subroutines and a short description of them is given in Table I.

Table I. Description of the new subroutines in DYNSUB

Subroutine	Description
rectbundle.f	Based in the data of DYN3D-SP3 input file, the initial tables for SUBCHANFLOW (channels, channel_neighbors, rod, rod_channels, spacers, and power_map) are automatically built.
dyn2sub.f	Passes the pin power distribution from DYN3D-SP3 to SUBCHANFLOW via actualization of the input table power_map at every iteration step.
sub2dyn.f	Passes the feedback parameters from SUBCHANFLOW to DYN3D-SP3 via the intermediate file Feedback.dat.

A simplified view of the flowchart is showed in Figure 5. Two options for initialization were considered and studied in order to improve the convergence process.

The first option DYNSUB 1 (right part of the diagram) consists of an initialization of cross sections with fixed feedback parameters along the core (same feedback parameters for all the nodes as it is usually done in DYN3D-SP3 stand alone version). These cross sections together with the flat initial neutronic flux are used to get the first calculation of power distribution. The power distribution is then given to SUBCHANFLOW for the first calculation of real feedback parameters, and at the end everything is prepared for starting the convergence loop DYN3D-SP3 –SUBCHANFLOW, in which the actualization of cross sections in the (yellow box DYN3D-SP3), based in the new feedback parameters coming from SUBCHANFLOW is performed.

The second option (left part of the diagram) differs from the first just in the first step. Instead of using fixed feedback parameters, they are calculated with SUBCHANFLOW using a flat power distribution. Here SUBCHANFLOW needs to be run two times (DYNSUB 2).

The interesting point here is to analyze the impact of the two initialization ways in the convergence process as it will be discussed in the section of results. In the Figure 5 the coupling via the two auxiliary files “Table_power_map.txt” and “Feedback.dat” is shown.

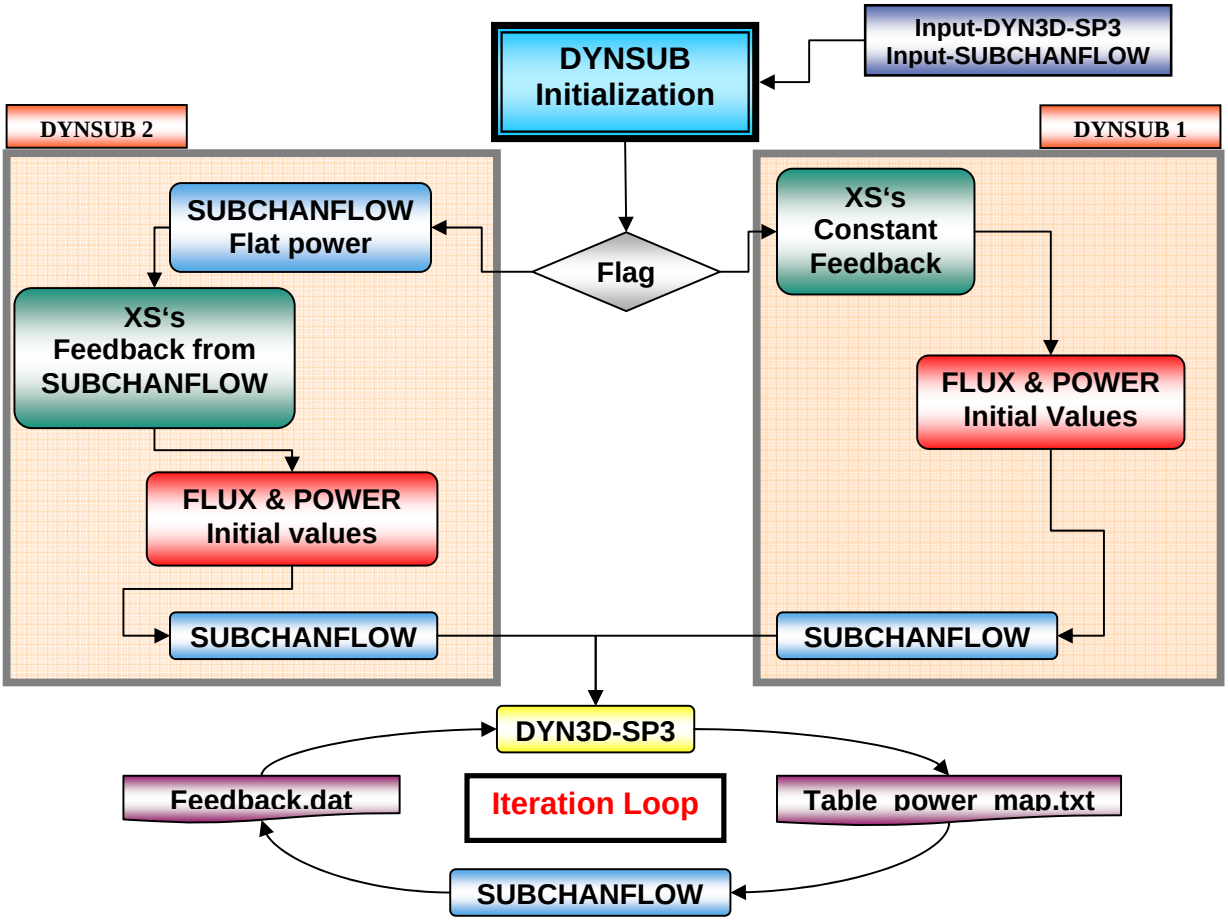

Figure 5. Flowchart of DYNSUB

5. RESULTS

For testing the performance of DYNSUB some test cases were studied based in the "OECD/NEA and U.S. NRC PWR MOX/UO2 core transient Benchmark" [9 and 10].

5.1. Definition of the Test Problems

Three steady state cases were considered in the static case in this paper:

A) One assembly UO2 at 4.5%
B) A minicore 3 x 3, with a central UO2 - 4.5% assembly and surrounded by 8 MOX - 4.3% assemblies.
C) A minicore 5 x 5, based exactly in the central section of the core configuration described in the Benchmark specification [9].

5.1.1. Operational conditions

A summary of some of the operational conditions for each case is given in Table II.

Table II. Operational conditions for the three cases considered.

	Case A	Case B	Case C
Number assemblies	1	9	25
Power level (MWth)	18.47	166.24	461.79
Inlet Temperature (°C)	287	287	287
Core Outlet Pressure (MPa)	15.375	15.375	15.375
Active flow (kg/sec)	82.12124	739.09116	2053.031
Fuel lattice, fuel rods per assembly	17 x 17, 264	17 x 17, 264	17 x 17, 264
Heated length (cm)	3657.6	3657.6	3657.6
Assembly pitch (cm)	21.41	21.41	21.41
Pin pitch (cm)	1.26	1.26	1.26
Radial boundary conditions	$\alpha = 1.0$	$\alpha = 1.0$	$\alpha = 1.0$
Axial boundary conditions	$\alpha = 0.5$	$\alpha = 0.5$	$\alpha = 0.5$
Number of axial nodes	17	17	17

The geometrical configuration for the UO2 and MOX fuel assemblies and the rest of details related with material composition and pin cell geometry specifications are available in ref [8].

5.1.2. Cross section structure

The Cross Sections library with 8 Group pinwise homogenized XS's used in the three cases is provided in the NEMTAB-like format used in the OECD MSLB benchmark [11]. The original library of the Benchmark problem was replaced with the library generated and validated in [1, and 12] for the development of DYN3D-SP3, which is based in the same operational conditions but differs in some of the lower energy cutoff of the 8 – group structure. Furthermore includes the P1 scattering table used in the SP3 transport approximation. In general, the 8 Group structured library contain branches in fuel temperature (3), moderator density (3) and boron density conditions (3) as well as 7 burn-up steps, to cover the expected range of core operating conditions. The moderator temperature effect is treated implicitly in the moderator density term assuming constant pressure of 15.5 MPa.

5.1.3. Results for the "Case A"

This case is the simplest one that can be analyzed. Figure 6 shows, in the upper subplot, the iteration process in the steady state for the calculation of Keff. In the lower subplot, the axial power profile is showed. Three different results are plotted. The DYN3D-SP3 result corresponds to the DYN3D-SP3 stand alone version (with FLOCAL). DYNSUB 1 and DYNSUB 2 are the

results with DYNSUB without and with initialization respectively (see Figure 5). Table III shows the Keff values and the pcm with respect the stand alone DYN3D-SP3 calculation. Furthermore the number of NK-TH iterations until convergence and the relative calculation CPU time with respect DYN3D-SP3 are showed.

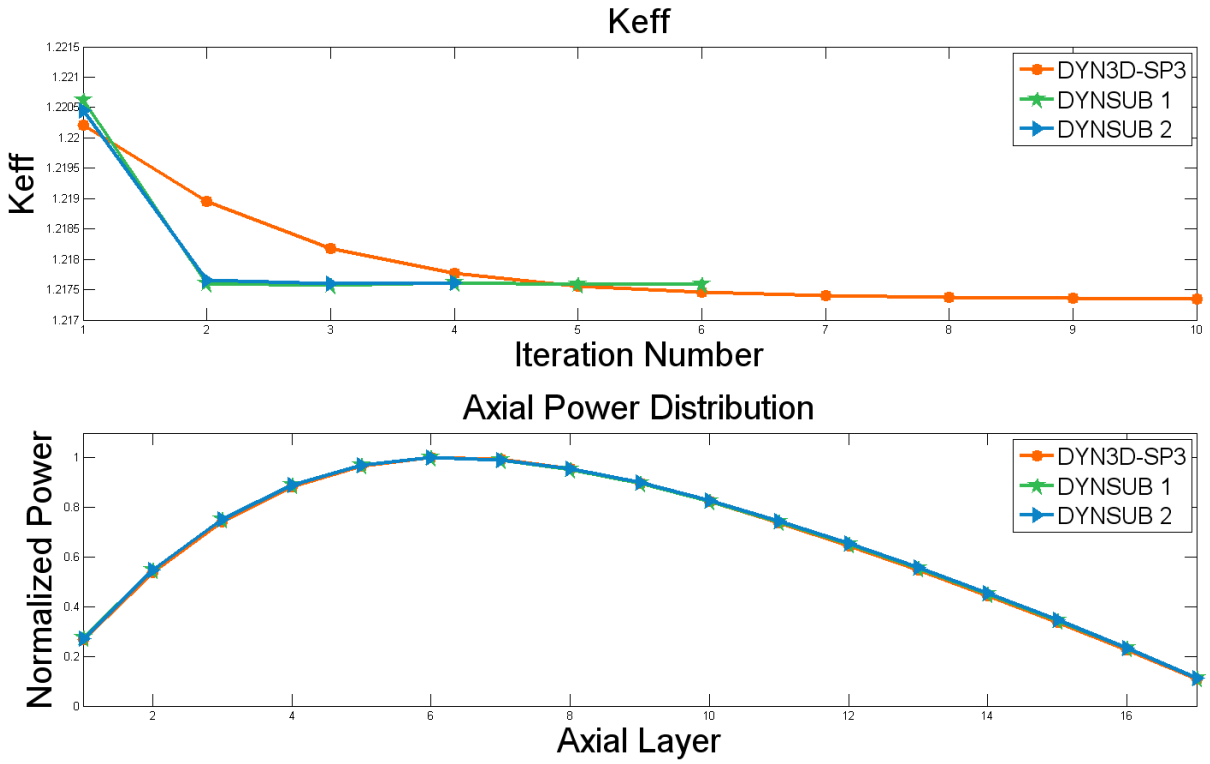

Figure 6. Results for "Case A", upper: Convergence of Keff, lower: Axial Power Profile.

Table III. Keff, Number of Iterations and Calculation Time for "Case A".

	Keff	pcm	No. Iteration	Relative CPU time
DYN3D-SP3	1.217346	----	10	1.000
DYNSUB 1	1.217581	23.5	6	1.031
DYNSUB 2	1.217609	26.3	4	0.994

The results of DYNSUB show good agreement with the already validated DYN3D-SP3 stand alone calculation. Although the calculation of SUBCHANFLOW lasts more than the 1D calculation of FLOCAL (as it was expected), the CPU time in the calculation can be even improved (DYNSUB 2) due to the faster convergence of the coupling resulting from a detailed initialization.

5.1.4. Results for the "Case B"

The next step was done adding complexity to the geometry and having a mix of fuel elements. An imaginary minicore 3 x 3 consisting of one central UO_2 FA and surrounded by 8 MOX FA's was chosen.

Again, Figure 7 shows, in the upper part, the NK-TH iteration process in the steady state for the calculation of Keff. In the lower part, the axial power profile is showed. Once again the DYNSUB calculation in both cases had better convergence.

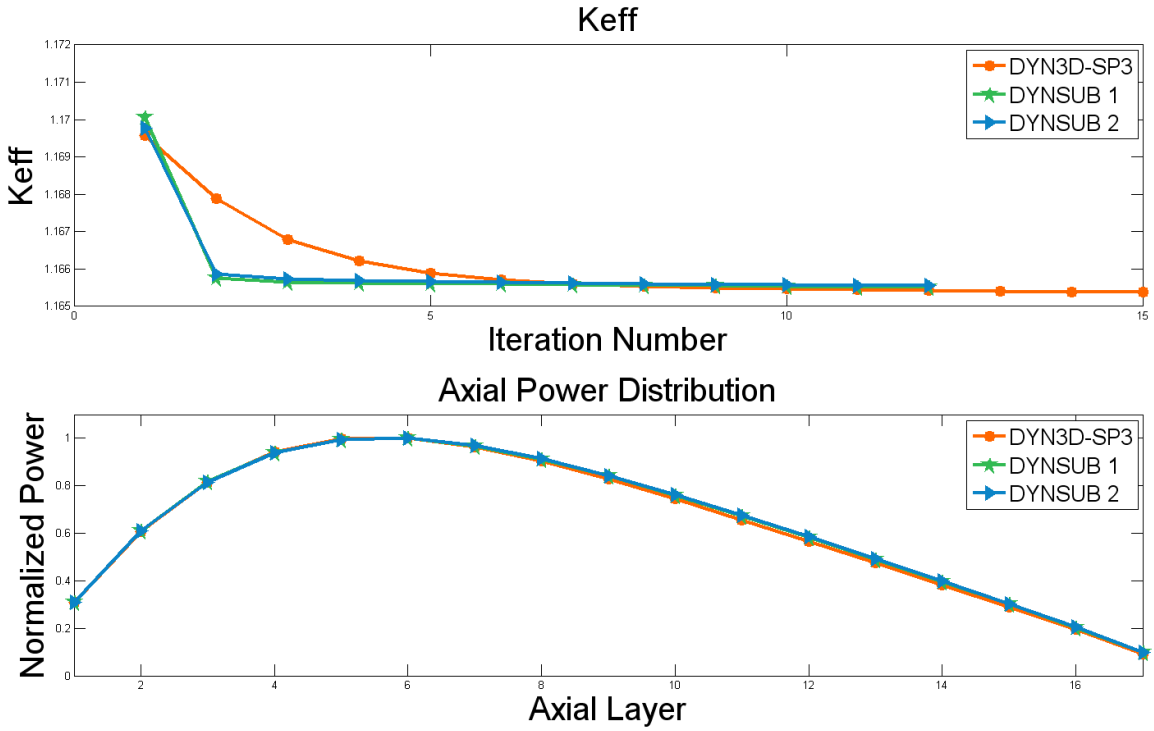

Figure 7. Results for "Case B", upper: Convergence of Keff, lower: Axial Power Profile.

Table IV. Keff, Number of Iterations and Calculation Time for "Case B".

	Keff	pcm	No. Iteration	Relative CPU time
DYN3D-SP3	1.165381	----	15	1.000
DYNSUB 1	1.165520	13.9	12	1.406
DYNSUB 2	1.165552	17.1	12	1.312

Although the effect of the initialization of DYNSUB 2 has no consequences in the total number of NK – TH iterations comparing with DYNSUB 1, in the internal iteration process of the

neutronic part, the effect of the initialization (DYNSUB 2) reduces slightly the number of internal iterations (in the first NK-TH iteration) resulting in a small decrease in the CPU time calculation, as it can be seen in Table IV and V.

The relative CPU time for both versions of DYNSUB is in this case greater than the CPU time of DYN3D-SP3 stand alone. This difference of time, is however not very large taking into account that SUBCHANFLOW ran with 2916 subchannels and 17 axial nodes (total number of nodes: 49572). Some studies can be done in the future in order to improve the convergence process of SUBCHANFLOW and to reduce the CPU time of DYNSUB.

Table V. Internal NK iterations for DYNSUB 1 and 2, for the "Case B"

NK – TH Iterations	Internal NK iterations	
	DYNSUB 1	DYNSUB 2
1	912	893
2	147	147
3	76	77
4	53	54
5	52	53
6	52	52
7	52	52
8	43	44
9	41	42
10	40	41
11	18	19
12	15	15

Figure 8 shows the difference in percent in the pin power distribution for the hottest axial layer (axial layer 6) between DYNSUB 1 and DYN3D-SP3 stand alone (absolute value). The difference is for all the pins less than 2%. It is important here to notice that there is a greater deviation in the axial power profile in the superior axial layers (as it can be seen in Figure 7). Figure 9 shows the same difference in percent but now for the axial layer 15. The deviation in pin power distribution is in this case reaches values until 4.5%.

For trying to understand the differences in the superior axial layers, one more test was performed in order to estimate the effect of cross flow in the calculation. In SUBCHANFLOW comparing with the FLOCAL model of DYN3D-SP3, calculations with cross flow are possible and have been done in the past results. Table VI shows results for Keff deactivating the cross flow effect in SUBCHANFLOW in order to be able to analyze the influence of cross flow in the calculation. As it can be shown the Keff presents only small differences. The differences showed in Figure 8 or 9 are mainly the result of the two-way-coupling in the pin level and at least in the stationary case, the effect of cross flow is not so big.

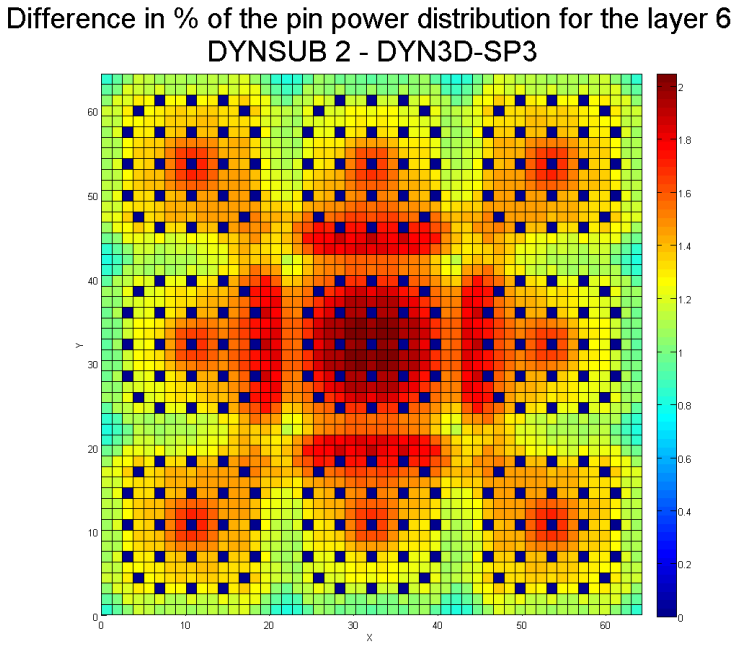

Figure 8. Pin Power distribution difference in percent for the axial layer 6.

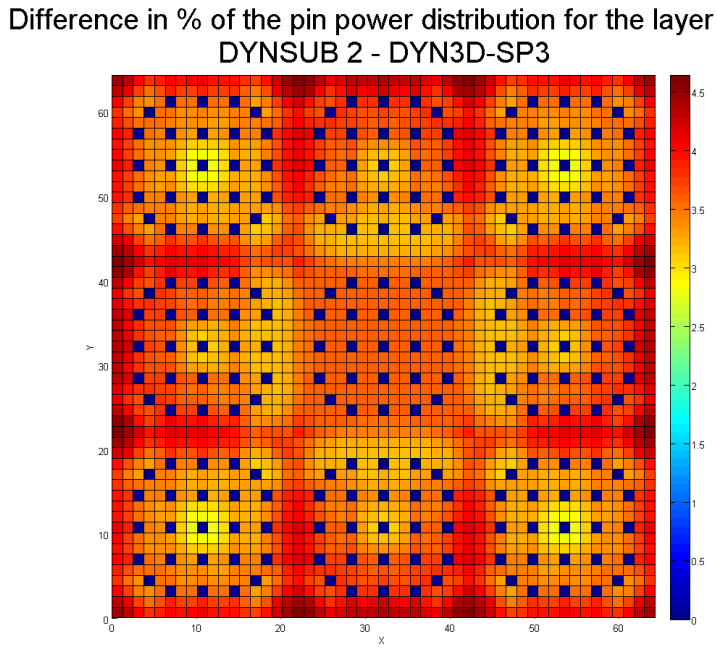

Figure 9. Pin Power distribution difference in percent for the axial layer 15.

Table VI. Keff for "Case B" without cross flow in SUBCHANFLOW

	Keff	pcm
DYN3D-SP3	1.165381	----
DYNSUB 1	1.165610	22.9
DYNSUB 2	1.165645	26.4

5.1.5. Results for the "Case C"

Trying to have a more realistic problem, another minicore 5 x 5, based in the quarter of core described in the Benchmark document [9] and showed in Figure 10 was modelled. In this case, the 25 central assemblies of the quarter core configuration defined the geometry under study. The different burn-up were also considered together with the operational conditions described in Table II. Table VII shows the difference in the Keff calculation.

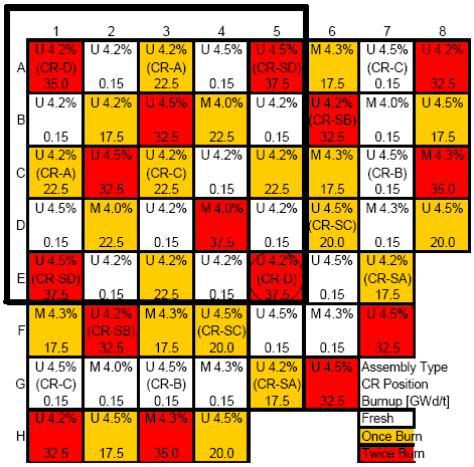

Figure 10. 5 x 5 minicore "Case C" (assemblies in the black box)

Table VII. Keff, Number of Iterations and Calculation Time for "Case C".

	Keff	pcm
DYN3D-SP3	1.128671	----
DYNSUB 1	1.128768	-9.7
DYNSUB 2	1.128771	-10

The effect of initialization is in this case not so important (22 iterations from DYN3D-SP3 vs 23 of DYNSUB 2). The computation time for this case is almost 3 times greater for the two versions of DYNSUB comparing with DYN3D-SP3, however it is very acceptable taking into account the

huge amount of nodes involved in the problem (8100 subchannels with 17 axial nodes each giving: 137700). Figure 11 shows the normalized pin power distribution calculated with DYNSUB (from now DYNSUB 1 will be named simply DYNSUB). The blue and black lines are the ones with the pin power peaks (blue and black point respectively). The green point shows the position of the pin with the smallest pin power contribution in the hottest assembly.

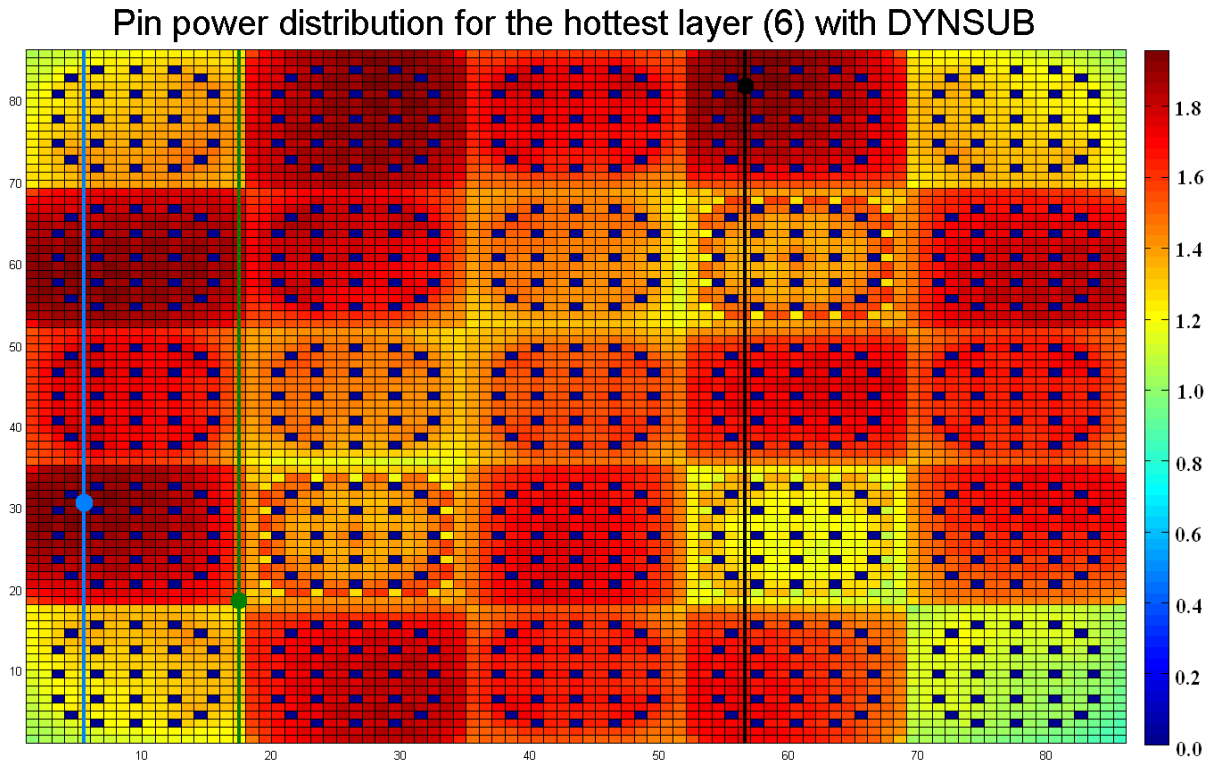

Figure 11. Normalized Pin Power Distribution for the hottest layer with DYNSUB 1 for "Case C".

In Figure 12, the pin power profile of the three lines showed in Figure 11 is showed for DYN3D-SP3 and DYNSUB. Small differences are found in the profile. The position of the two pin peaks (identified by the color of the line blue and black) coincide in both cases, however DYN3D-SP3 overestimate it in approx 2%. The biggest differences between the two calculations are found in the hottest assemblies, as it can be seen in Figure 13 where the difference in percent between DYN3D-SP3 and DYNSUB is shown. Although the differences are small (2%), some important details related with the safety parameters are now visible thanks to the use of a subchannel code. Figure 14 shows the differences in the axial temperature distribution for the hottest pin (blue point), coldest pin of the hottest assembly (green point) and one guide tube of the same assembly calculated with DYNSUB. Additionally, the assembly based averaged temperature distribution calculated with FLOCAL for the hottest assembly is shown.

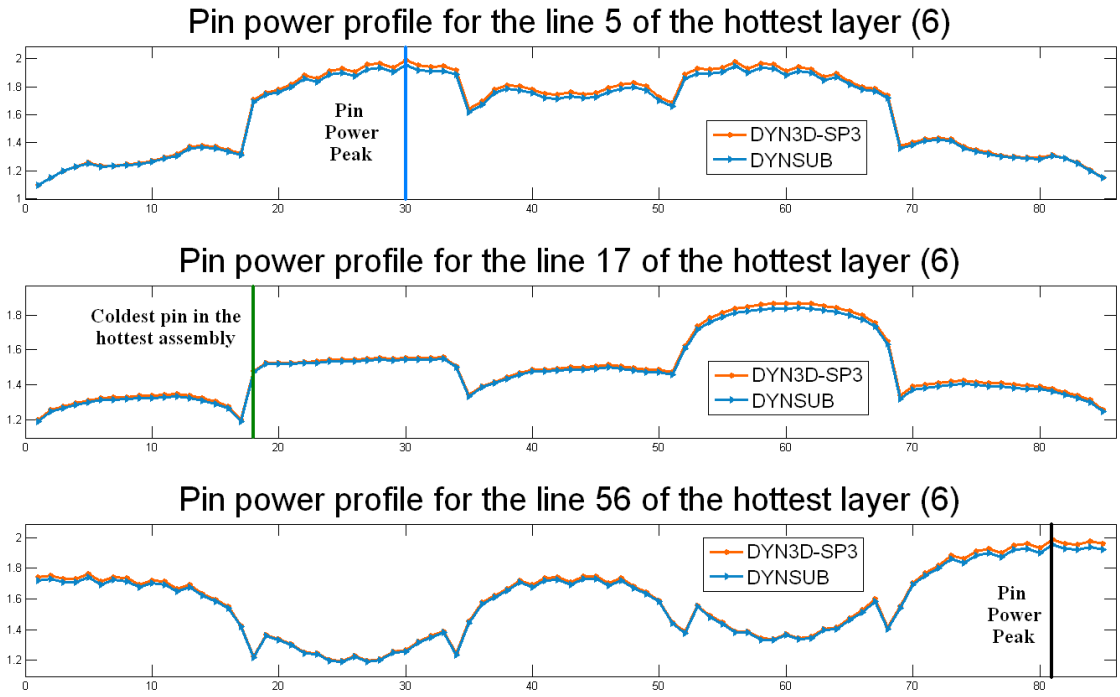

Figure 12. Pin Power profile for the rows 5, 17 and 56 in the hottest layer, "Case C".

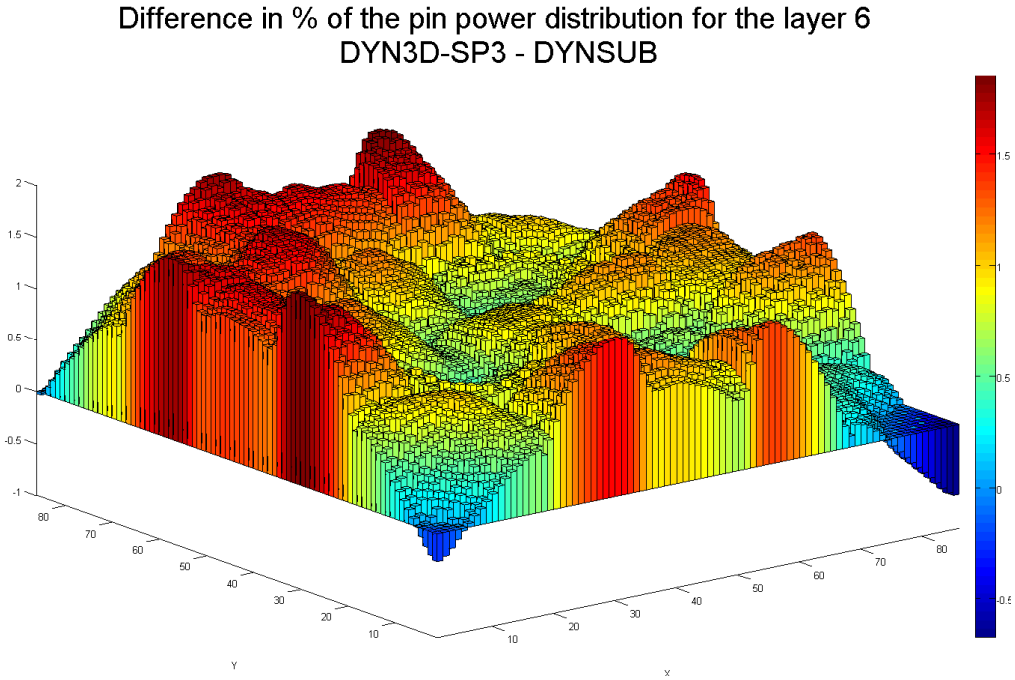

Figure 13. Pin Power Distribution for the hottest axial layer with DYNSUB 2, "Case C"

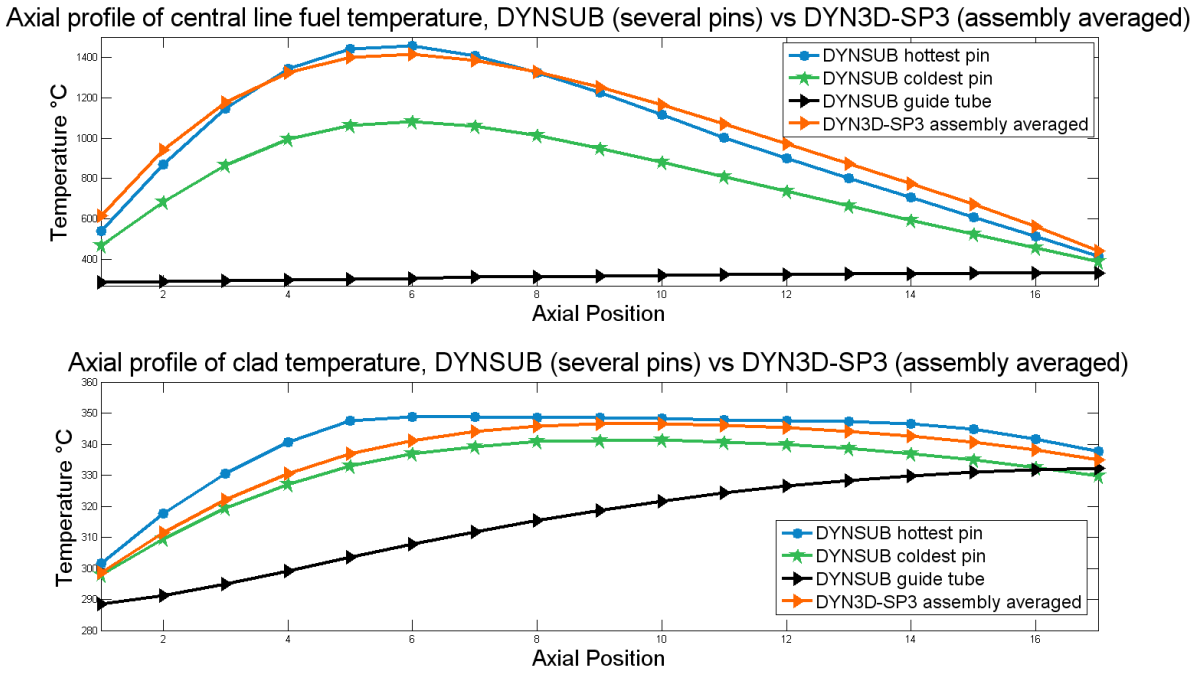

Figure 14. Axial profiles of temperature for fuel central line (upper) and clad (lower), for several pins with DYNSUB and assembly averaged with DYN3D-SP3

The maximal centerline temperature of the fuel with DYNSUB is greater than the predicted with DYN3D-SP3. For the cladding temperature the same behavior was found. The difference between the hottest pin and the assembly averaged value coming from DYN3D-SP3 is not as large as the difference between the coldest pin and the assembly averaged, where an overestimation has been predicted with DYN3D-SP3. Also the temperature distribution inside the guide tubes can be analyzed. It is important to notice that although the axial maximum temperature from DYNSUB is greater, the pin power peak is smaller. The reason could be the Doppler Effect.

Thanks to the new capabilities of DYNSUB local safety parameters e.g. fuel center line temperature, maximal cladding temperature, etc. can be directly predicted by the coupled code system eliminating the use of hot channel factors and thereby reducing the conservatism in numerical tools for design and safety.

6. CONCLUSIONS

DYNSUB is a new tool with a two-way-coupling methodology ready for steady state calculations. DYNSUB avoids the loss of information due to averaging, making possible to predict safety parameters more accurately.

For the three cases analyzed, the behavior of DYNSUB in steady state is in agreement with the results coming from the already validated stand alone version of DYN3D-SP3. Keff deviations up to 26 pcm, and percent differences up to 2% in the pin peak calculation were found, however larger deviations emerged when comparing the temperature profiles of particular pins against the averaged values coming from DYN3D-SP3.

The effect of initialization with SUBCHANFLOW (DYNSUB 2) showed a great impact in the convergence process and thus in the CPU time in the two simplest cases (A and B). DYNSUB 2 was able to solve the problem almost in the same time that DYN3D-SP3 but using a 3D Thermalhydraulic model (SUBCHANFLOW). For the Case C, the initialization effect had no impact. Several strategies can be investigated later in order to improve the convergence.

At least in the steady state, the effect of cross flow implies not too much deviation; however, this effect can be very important in the transient implementation. Also the differences in axial temperature profile may be significant when a transient is investigated. The time dependent DYNSUB version is under development and the validation work will be extended.

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