COMPARISON OF SUBCHANNEL AND AVERAGED CHANNEL THERMAL-HYDRAULIC DESCRIPTIONS ON COUPLED PIN-BY-PIN NEUTRONIC CALCULATIONS

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Best-estimate transient analysis of Light Water Reactors (LWRs) requires high accuracy code systems solving neutronics (NK), thermal-hydraulics (TH) and thermal-mechanics to model the core behavior. For long time, nodal diffusion methods for solution of the transport equation using assembly size computational meshes have been applied neglecting the details within the fuel assembly, or using "pin power reconstruction" techniques to predict those details.

Moreover, the multiphysics analysis has been commonly performed coupling those neutronic diffusion methods to thermal-hydraulic system codes using a nodalization of several fuel assemblies per computational node without taking into account the effects that this type of averaging can have on the results obtained.

This paper presents the work accomplished with the coupled system COBAYA4/CTF for a preliminary analysis of the effect of the different accuracy levels in the NK and TH domain. COBAYA4 is a neutronic code able to solve the diffusion equation at two resolution levels, nodal and pin by pin (PbP). CTF is a thermo-hydraulic code able to solve the coolant conservation equations also at two levels, channel (fuel assembly averaged solution) and sub-channel (real cooling channel) level. The coupled system COBAYA4/CTF is used through SALOME platform, i.e. SALOME is the software able to map conveniently the NK and TH meshes. This coupling allows combining different resolution levels for NK and TH problems. Therefore, the study of the effect of using different resolutions for the NK and TH nodalizations has been performed applying the system to a fuel assembly with selected boundary conditions.

I. INTRODUCTION

The sophisticated software platforms that are being developed nowadays (NURESAFE, CASL) (Chanaron, et al., 2015)(CASL, 2013) allow simulating complex multi-physical phenomena in a coupled fashion and using even multi-scale approach (Chanaron, et al., 2015).

Safety analysis simulations are typically carried out through the use of nodal diffusion codes. Those codes require macroscopic cross sections homogenized over large spatial zones consisting of a fuel assembly or one quarter of the assembly. Hence only the node-averaged power distribution is computed and pin-power reconstruction methods based on the use of assembly-wise form factors (Gomez-Torres, et al., 2014) have to be applied in order to estimate the pin powers.

PbP analysis requires macroscopic cross sections homogenized at pin-cell level. This type of solution conserves partially the local heterogeneity of the fuel assembly.

COBAYA is a multigroup neutronic diffusion code that is able to solve the core problem at two resolution levels, nodal and pin-by-pin, at different conditions, i.e. steady state or transient calculations originated by control rod movement, boron concentration changes or evolution of the thermo-hydraulic conditions.

The nodal solver employed in COBAYA is based on the Analytic Coarse-Mesh Finite-Difference Method (ACMFD) (Aragonés, et al., 2007). The pin-by-pin solver included in COBAYA is based on the transport-corrected finite mesh fine difference diffusion method (FMFD) (Herrero, et al., 2009).

In order to perform steady-state analysis at not negligible power level or transient calculations, the NK code will require information on the fuel temperature distribution, the moderator density and temperature distribution and boron concentration. So to obtain those distributions in the coolant, a thermo-hydraulic code has to be coupled.

In case of COBAYA, the thermo-hydraulic code used to calculate the temperature and density distributions is CTF. CTF is the improved version of COBRA-TF developed by the Reactor Dynamics and Fuel Management Group (RDFMG) from North Carolina State University under CASL consortium. CTF is a 3D core thermal-hydraulic code for LWR vessel and core analysis. It uses a two-fluid, three-fields modeling approach and solves three momentum conservation equations, four mass

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conservation equations, and two energy conservations equations (Salko, 2015). CTF is able to solve the TH problem at two levels, assembly averaged channel level and sub-channel level.

Two types of coupling methods can be applied to a NK/TH system, internal and external. Internal coupling is commonly faster than external but is more complex to implement and maintain. Usually important modifications have to be performed in the original codes to be coupled making a complex task to update any of the two codes. External coupling is easier to implement, but an external mechanism must be involved to fit the spatial geometry and map the two codes meshes.

COBAYA4 has been coupled with CTF through an external coupling making use of the SALOME platform for integration of multiphysics software (Chanaron, et al., 2015). The coupling interface for both codes uses *Medcoupling* library available in the platform to carry out the interpolation task in order to exchange fields of variables (Cuervo, et al., 2016).

One of the advantages of coupling using *Medcoupling* library is the flexibility of using different resolution levels for the two codes. So, different combinations of NK and TH resolutions can be studied just indicating to the library the type of mesh that is going to be solved by each code.

Optimal resolution level for safety analysis seems to be the use of the NK code at pin-by-pin level and the TH code at subchannel level. This approach has a major disadvantage as high calculations times are needed for transient analysis.

Then, a compromise approach consisting on using different resolutions for NK and TH can be considered. It has been observed that the impact in calculation times of reducing the mesh cell size is much higher in the TH solution than in the NK one. Therefore, an optimal approach can be to run the case using pin-by-pin details for COBAYA and channel averaged analysis for CTF. It has been proven (Cuervo, et al., 2016) that this approach makes feasible to obtain the problem solution in a few hours in a desktop PC.

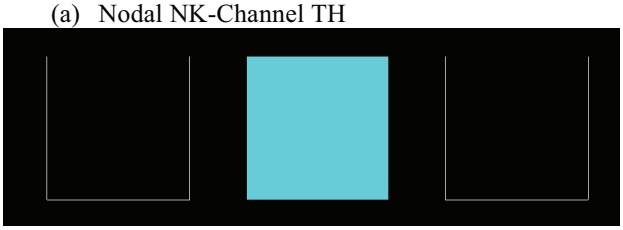
Nevertheless, the type of transients where this solution may be reasonable must be studied. And the first step is characterizing the effects that this approximation can have on the solution obtained with the coupled system COBAYA/CTF.

II. DESCRIPTION OF THE ANALYSIS

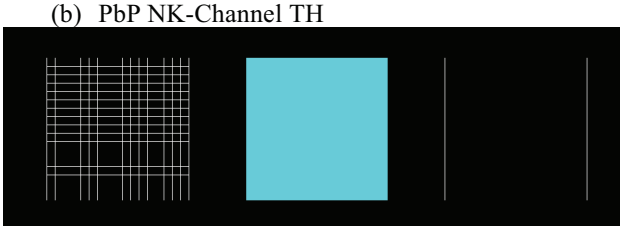
The selected test problem included a 4.5 w/o UO2 fuel assembly taken from OECD/NEA PWR MOX/UO2 core transient benchmark (8 groups libraries available for nodal and PbP) (Kozlowski, et al., 2006).

The impact of the different resolutions in NK and TH physics on the 3D fuel assembly steady-state calculations were analyzed using the combinations of meshes shown in figure 1. It must be explained that CTF solves also the heat transfer equation for the rod so a third mesh must be considered in the calculation that is shown in light blue in the figure.

(a) Nodal NK-Channel TH



(b) PbP NK-Channel TH



(c) PbP NK-Subchannel TH

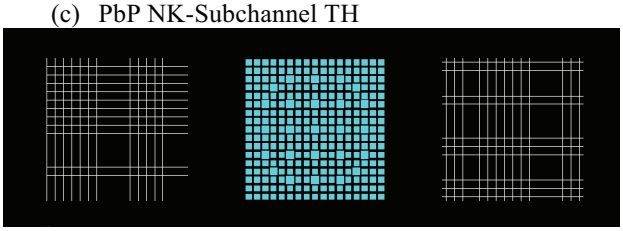


Figure 1: Different meshes used for the three combinations for NK-TH resolutions.

The assembly was first analyzed using reflective radial boundary conditions and vacuum axial boundary conditions for NK. In the case of TH, radial adiabatic boundary conditions were used. Axially steady-state flow conditions for inlet mass flow and enthalpy and outlet pressure were imposed extracted from the original benchmark. In this case a very flat power distribution is obtained when using pin-by-pin resolution.
In order to generate a strong gradient in the power distribution within the assembly, vacuum boundary conditions for NK were assigned at the south side of the assembly. Reflective conditions were still assigned to the rest of the sides. Under these conditions a stronger effect of the average channel approximation was observed.

Hot Full Power (HFP) 3D simulations were performed for the three combinations of resolution in NK and TH physics and the two different boundary conditions with COBAYA4/CTF.

III.RESULTS

A comparison of the multiplication factor, radial power peaking factor FdH and axial power peaking factor Fz are shown in the tables I, II and III respectively. The PbP/sub-channel results are taken as a reference solution.

Considering the multiplication factor, when using reflective boundary conditions, the solution for PbP/channel and PbP/sub-channel calculations are very close, being the difference 1 pcm. In case of nodal/channel, the difference with the reference solution is higher becoming 74pcm.

When using vacuum boundary condition in south side, the solutions of nodal/channel and PbP/channel are very different compared to PbP/sub-channel solution. In case of PbP/channel this difference becomes 630 pcm. The difference increases in nodal/channel calculation reaching 675pcm.

If an analysis of FdH is carried out, the same tendency than in multiplication factor can be observed. In this case nodal/channel radial peaking factor does not make sense as the power distribution within the assembly is flat. When using reflective boundary conditions the difference between PbP/channel and PbP/subchannel solutions is -0.1% indicating that power distribution is more pronounced in reference solution. Surprisingly, in the same case but with vacuum boundary condition FdH is 2.9% higher in PbP/channel than in PbP/subchannel indicating higher gradients in power in the average channel calculation. This may be explained by the different feedback that the average value of coolant temperature and density and rod temperature can have in the NK calculation producing an increase in the power where power is higher and a decrease where is lower and, therefore, magnifying the difference.

For Fz the tendency is what expected and opposite to FdH, being always higher for the reference solution. When the nodal/channel approximation is used and boundary conditions include vacuum in one side, Fz becomes 4.6% lower than reference solution. In case of running a PbP-channel calculation the factor is 2.7% lower than reference. This may be explained by the different feedback. At all the axial levels, the channel average coolant temperature and the channel average fuel temperature are lower than the coolant and fuel temperatures of the hottest fuel rod of the assembly. The channel average coolant density is higher than the coolant density in subchannels around the hottest fuel rod. Those differences between the average values and the subchannel values are higher at the top of the fuel assembly than at the bottom. The higher temperatures of coolant and fuel and lower densities of the coolant when performing the PbP/subchannel calculation reduce the reactivity at the top of the fuel assembly, reducing also the power at these axial levels and therefore increasing the peaking factor Fz.

TABLE I. Multipication factor

	Nodal NK – channel TH	Pin-by-pin NK – channel TH	Pin-by-Pin NK – subchannel TH
Reflective BC at all interfaces	1.21903 (+74 pcm)	1.21830 (1 pcm)	1.21829 (ref)
Void BC on the south side and reflective on the rest sides	0.97616 (+675 pcm)	0.97571 (+630 pcm)	0.96942 (ref)

TABLE II. Radial power peaking factors FdH (axially integrated)

	Nodal NK – channel TH	Pin-by-pin NK – channel TH	Pin-by-pin NK – subchannel TH
Reflective BC at all interfaces	1	1.017 (-0.1%)	1.019
Void BC on the south side and reflective on the rest sides	1	1.447 (2.9%)	1.406

TABLE III Axial power peaking factor Fz

	Nodal NK – channel TH	Pin-by-pin NK – channel TH	Pin-by-pin NK – subchannel TH
Reflective BC at all interfaces	1.539 (-1.1%)	1.555 (-0.1%)	1.556
Void BC on the south side and reflective on the rest sides	2.119 (-4.6%)	2.161 (-2.7%)	2.220

The radial power factors axially integrated for the three configurations using vacuum boundary conditions are showed in the Figure 2. In the nodal/channel case, power profile is plane since it is a nodal calculation. In the other two cases there is a strong gradient power profile in the fuel assembly. The difference in the power distribution can be observed in the north side of the assembly showing a darker red color in this area for the PbP/channel calculation (figure 2a).

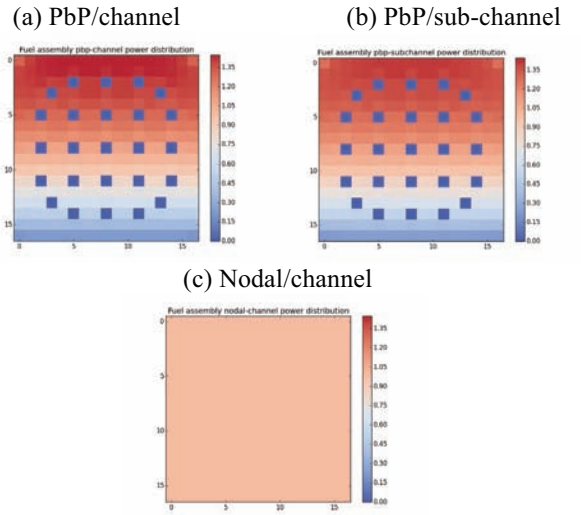


Fig. 2. Radial power distributions.

II. CONCLUSIONS

The paper presents a coupled COBAYA4/CTF analysis of a fuel assembly using combinations of different resolutions for NK and TH. The impact of using channel averaged or subchannel descriptions of TH problem has been studied.

It has been observed that, if a pin-by-pin calculation of the power distribution is performed and when this distribution is smooth, the differences using averaged channel or subchannels are negligible. This is not the case when the power distribution shows a deep gradient. In this case the multiplication factor reaches a higher value when running an averaged channel calculation becoming a difference of 650 pcm between both solutions. This means that reactivity in channel averaged calculation is higher being more conservative. This type of calculation also produces a more pronounced power distribution due to the different feedback yield by the two different descriptions of the TH problem. This effect is reflected in the higher value of the FdH obtained for the averaged channel calculation. On the other side, Fz is higher for the subchannel description of the assembly giving as a result a higher axial peak for this type of calculation.

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