M&C 2017 - International Conference on Mathematics & Computational Methods Applied to Nuclear Science & Engineering, Jeju, Korea, April 16-20, 2017, on USB (2017)

CTF / DYN3D Multi-Scale Coupled Simulation of a Rod Ejection Transient on the Salomé Platform

Yann Périn,* Kiril Velkov*

*Gesellschaft fuer Anlagen- und Reaktorsicherheit (GRS) gGmbH, Garching bei Muenchen, Germany
Yann.Perin@grs.de, Kiril.Velkov@grs.de

Abstract - *In the framework of the EU founded NURESAFE project the subchannel code CTF and the neutronics code DYN3D were integrated and coupled on the Salomé platform. The developments achieved during this three-year project include assembly level and pin-by-pin multi-physic TH/NK coupling. In order to test this coupling, a PWR rod ejection transient was simulated on a MOX/UOX minicore. The transient is simulated using two different versions of the models. In the first simulation, both codes model the core with an assembly-wise resolution. In the second one, a pin-by-pin fuel-centered model is used in CTF for the central assembly and in DYN3D the pin power reconstruction method is applied. The analysis shows the influence of the different models on global parameters such as the power and the average fuel temperature but also on local parameters such as the maximum fuel temperature.*

I. INTRODUCTION

In the framework of the EU founded NURESAFE project [1] the subchannel code CTF and the neutronics code DYN3D were integrated and coupled on the Salomé platform. The developments achieved during this three-year project include assembly level and pin-by-pin multi-physic TH/NK coupling. In order to test this coupling, a PWR rod ejection transient was simulated on a MOX/UOX minicore. The transient is simulated using two different versions of the models. In the first simulation, both codes model the core with an assembly-wise resolution. In the second one, a pin-by-pin fuel-centered model is used in CTF for the central assembly and in DYN3D the pin power reconstruction method is applied.

II. CODES DESCRIPTION

In this section a brief introduction of the CTF and DYN3D codes is given. The Salomé platform is also introduced.

1. The DYN3D reactor simulator

DYN3D [2] is a reactor core simulator developed at the Helmholz Zentrum Dresden Rossendorf (HZDR), Germany. It is applied for performing of steady state and transient analysis in LWR for hexagonal or square fuel assemblies' geometries. The diffusion equation is solved using a nodal expansion method. Pin-by-pin simulations are possible using either a pin power reconstruction method or the recently developed multi-group simplified transport (SP3) capabilities.

2. The CTF Thermal-Hydraulics subchannel code

Coolant-Boiling in Rod Arrays | Two Fluids (COBRA-TF) is a 3D Thermal/Hydraulic simulation code designed for LWR subchannel analysis [3]. It has been improved and updated at the North Carolina State University (NCSU), USA by the Reactor Dynamics and Fuel Management Group (RDFMG) and subsequently re-branded as CTF.

3. The Salomé platform

The Salomé platform is an open-source software co-developed by EDF, CEA and OpenCascade. Originally created for CAD applications, it has since evolved into a platform for code coupling in the framework of a series of three consecutive European Commission founded projects: NURESIM (2006-2008), NURISP (2009-2011) and NURESAFE (2013-2015).

III. DESCRIPTION OF THE INTEGRATION AND COUPLING ON THE PLATFORM

1. General Description

Codes can be integrated on the platform as "components". In the case of a full integration, single code's functions can be called and processed from the platform (e.g. initialize code, read input, perform steady-state, etc.). When coupling the codes on the Salomé platform, they do not directly communicate with each other but rather through the platform. The Salomé platform is coded in C++, therefore, the component's interfaces are preferably written in C++. However, most of the codes applied in the nuclear industry are written in Fortran. This is the case for CTF and DYN3D. Therefore the codes' interface should be able to interoperate C++ with Fortran libraries. The Salomé platform also features an internal Python console, in which all loaded components' functions can be called. Furthermore, the whole platform environment, including the components, can be loaded into an external Python console and executed there.

Data exchange on the platform is performed directly through memory using a dedicated data structure: MEDCoupling. The MEDCoupling format was developed by EDF and CEA to answer the challenges of data exchange for multi-physics simulations. The goal was to design a standardized approach that could be used to exchange data between codes. The MEDCoupling data model has two components:

- Mesh: The mesh contains the geometry of a domain which is represented by a set of cells and nodes. In this study, 3D surface mesh (3D space, 2D cells) and 3D mesh (3D space, 3D cells) are applied.

- Fields: The fields are the results that the codes actually exchange. They can be set on the mesh cells or nodes.

Fields can be either intensive or extensive:

- Intensive data does not depend on the volume of the physical system represented. Examples of intensive data are: moderator density, power density, temperature or pressure.
- Extensive data is proportional to the volume of the physical system represented. Examples of extensive data are: mass flow and power. A set of interpolation tools for the MEDCoupling format is available on the platform.

2. Integration and Coupling of CTF and DYN3D

The integration of DYN3D on the platform was performed at the HZDR during the previous EU projects NURESIM and NURISP and is not presented here.

CTF was fully integrated on the platform during the NURESAFE project. With the newly developed API (Application Program Interface), single CTF functions can be called from the platform. The methods in the API can be divided into two groups: code control and data exchange. The code control methods usually:

- Initialize the code (including input processing),
- Perform a steady-state convergence,
- Initialize the transient calculation
- Control the transient calculation
- Finalize the simulation

It is possible during transient simulations to check at each time step the proposed time step size in each code and to set manually the time step size.

The functions generating the 3D MEDCoupling mesh are called automatically during the initialization phase. The radial mesh generation function in both codes supports quadratic and hexagonal fuel geometries. In DYN3D, when the pin flux reconstruction option is activated, a mesh refinement is automatically performed. It is also possible to mix assembly scale and pin scale in CTF, i.e. use a refined mesh for a hot spot analysis for example.

In its latest version, the CTF input contains the position of the center (and the width) of each channel (and thus fuel rod) in the radial plane. This information is enough to generate a 3D model in the case of regular quadratic geometries. In CTF, the assembly level and the pin level are treated differently. For the assembly-wise modeling, the same mesh is used for both fluid and thermal meshes. For the pin-by-pin modeling, the thermal mesh is disjointed (since the fuel pins don't touch each other) and can even contain holes (e.g. where control rod guiding tubes are located). The algorithm can automatically select the correct model by checking the fuel pin object multiplication coefficient. If it is bigger than one, an assembly-wise mesh is assumed. At the pin scale, it is possible to model the thermal-hydraulics with rod-centered or the coolant-centered models (see Figure 1).

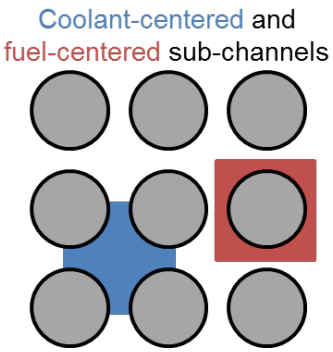

Fig. 1. Coolant Centered vs. Pin centered Modeling

The developed algorithm automatically selects the correct model by checking the channel and the fuel rod maps contained in the input. If their sizes are the same, the rod-centered model is assumed, otherwise, the coolant-centered is applied. It is possible to use both assembly and pin scale, i.e. use a refined mesh for a hot spot analysis. However, in that case, called hybrid modeling, only the rod-centered model is allowed for the pin scale.

It is possible after each steady-state convergence or each time step to exchange the following fields on the generated mesh:

- Fuel Doppler temperature,
- Moderator density,
- Moderator temperature,
- Boron concentration,
- Power (mesh and integral)

CTF does not have a steady-state mode. Pseudo steady-state simulations are used instead, during which no perturbation in the model occurs and the time step size for the fuel heat conduction can be artificially increased in order to accelerate the convergence. A function that checks the convergence is available. Before starting the actual transient simulation, the heat conduction time step multiplication factor is reset to 1.0.

The time step control in CTF is very flexible: At each time step, it is possible to check the CTF proposed time step size. The time step size can also be set manually. After a time step is solved, it can either be validated or repeated (with a different size). Therefore, it is possible in theory to implement a semi-implicit time coupling on the platform. During the NURESAFE project, only an explicit coupling approach has been implemented and tested.

For transient simulations, explicit time step synchronization is used. The time step size is the smallest one proposed by CTF. This solution increases the computation time but improves the stability. No stability problems were encountered in any of the performed within the frame of NURESAFE project coupled simulations.

After a time step is validated, it is possible to extract the following fields on the fluid mesh: moderator density, moderator temperature and boron concentration; and fuel temperature on the thermal mesh.

An example of a fuel temperature field of an hybrid mesh (assembly-wise + pin-by-pin) is provided in Figure 2.

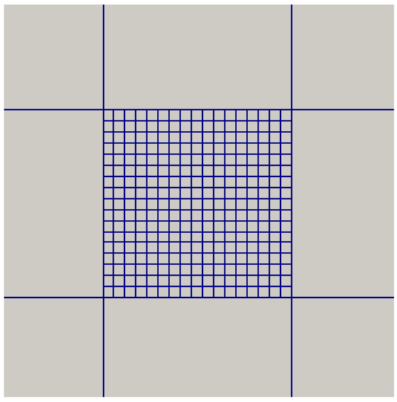

Fig. 2. Example of an hybrid mesh

IV. MODEL DESCRIPTION

A control rod ejection in two PWR minicore at HZP are simulated. The minicore is based on the MOX/UO2 Core Transient Benchmark [4]. The minicore consists in a 3x3 fuel assembly arrangement surrounded by reflector (see Figure 3). The central assembly where the control rod is inserted is UOX with a 4.5% enrichment. It is surrounded by 6 UOX assemblies with a 4.2% enrichement and 2 MOX assemblies with a 4.3% enrichement. The MOX assemblies are placed in order to get an asymmetric core. All fuel assemblies are fresh (no burnup).

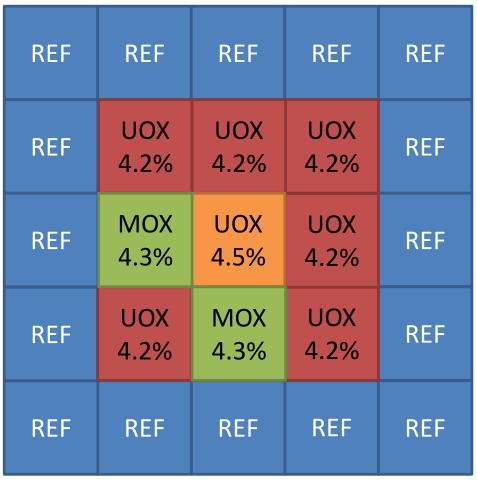

Fig. 3. Representation of the Minicore

1. Neutronics Model

The DYN3D model is always assembly-wise. In the hybrid case however, the pin power reconstruction is used in the central assembly where the control rod is ejected and the maximum power observed.

The DYN3D pin power reconstruction method features two steps: a homogeneous flux reconstruction step and a heterogeneous correction by means of a form function. The so-called method of successive smoothing is applied for the reconstruction of the neutron flux in chosen assemblies [5]. The neutron flux is approximated by an analytical solution of the two-dimensional diffusion equation in each axial layer of the selected assembly. The nodal average values of four assemblies are used to construct corner values by linear extrapolation and a subsequent smoothing step. The resulting interpolated flux functions fulfill the two-dimensional diffusion equation in the interior of the node.

The cross-section libraries for DYN3D were generated jointly at IRSN and UPM during the NURESAFE project using the lattice code APPOLO2 [6]. The are presented in the so-called NEMTAB format. The parameters are moderator density (50.0, 300.0, 600.0, 700.0, 800.0, 865.8 kg/m3), fuel temperature (473.15, 973.15, 1373.15 and 1773.15 K) and boron concentration which is here fixed at critical conditions.

The form functions, presented in Figure 4, were generated at the same time as the macroscopic cross-sections. However, unlike the cross-sections, the form functions are only depending on the burnup and the control rod insertion.

This means that even in the hybrid case, the thermal-hydraulic feedbacks are only considered at the assembly level in DYN3D.

0.905	0.973	0.992	1.000	1.005	1.005	1.007	1.008	1.006
0.973	0.987	0.998	1.004	1.015	0.987	1.017	1.017	0.986
0.992	0.998	1.010	0.985	0.995		0.988	0.988	
1.000	1.004	0.985		0.998	0.989	1.021	1.020	0.988
1.005	1.015	0.995	0.998	1.029	0.991	1.021	1.021	0.989
1.005	0.987		0.989	0.991		0.989	0.988	
1.007	1.017	0.988	1.021	1.021	0.989	1.020	1.020	0.988
1.008	1.017	0.988	1.020	1.021	0.988	1.020	1.020	0.989
1.006	0.986		0.988	0.989		0.988	0.989	

1.262	1.327	1.301	1.246	1.185	1.137	1.124	1.114	1.103
1.327	1.308	1.249	1.165	1.073	0.959	1.023	1.016	0.938
1.301	1.249	1.130	0.950	0.862		0.864	0.864	
1.246	1.165	0.950		0.781	0.797	0.893	0.900	0.824
1.185	1.073	0.862	0.781	0.818	0.788	0.882	0.889	0.816
1.137	0.959		0.797	0.788		0.817	0.827	
1.124	1.023	0.864	0.893	0.882	0.817	0.913	0.943	0.881
1.114	1.016	0.864	0.900	0.889	0.827	0.943	1.030	1.026
1.103	0.938		0.824	0.816		0.881	1.026	

Fig. 4. Form functions (1/4 of assembly) for the unrodded (top) and rodded (bottom) cases

2. Thermal-Hydraulics Model

Two thermal-hydraulics models are built in CTF. The first CTF model describes the minicore using an assembly-wise resolution. The reflector "assemblies" are also each modeled by a separate channel. In total, 25 channels are represented in the assembly-wise model.

The second CTF model describes the minicore with a hybrid resolution: one channel per fuel assembly, except for the central channel which is described with a pin-by-pin resolution (using a fuel-centered model). This maked for a total of 313 channels (24+289). When coupled with DYN3D, the

0.735	1.118	0.743
1.087	1.65	1.118
0.727	1.087	0.735

Fig. 5. Core radial relative power distribution

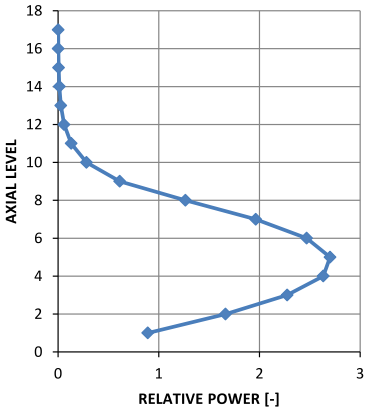

Fig. 6. Core axial relative power distribution

thermal-hydraulics feedbacks from the pin-by-pin part of the model are automatically averaged/merged by the interpolation tool.

V. RESULTS AND ANALYSIS

1. Steady-State

The control rod is initially inserted 170cm from the top of the active core (total core length = 365cm). The corresponding radial and axial power profiles are presented respectively in Figure 5 and Figure 6.

The pin power distribution in the central assembly is shown for two axial levels in Figure 7. On the top of the figure, the distribution at axial level 18, where the control rod in inserted, is displayed. On the bottom part, the distribution at axial level 4, without control rod, is displayed. The asymmetry introduced by the MOX assemblies can be clearly seen. The influence of the uncontrolled/controlled form functions presented in is also obvious.

2. Transient

The simulation starts from the HZP critical state. The control rod is ejected within 0.1s after 1s of simulation. The maximum reactivity insertion is 1.4$. The power response with the assembly-wise model and the hybrid one are compared in Figure 8. The modelisation has little influence on the

Fig. 7. Pin power distribution in the central assembly - At level 18 (Top) - At level 4 (Bottom)

maximum power. The hybrid model reaches a slightly higher power than the assembly-wise one (+0.7%). The hybrid model also gives a higher maximum power than the assembly-wise one (+3.1%). The difference is larger than for the core power because of the larger peaking factor introduced by the form function. At the end of the transient, the power is higher in the assembly-wise model (6.7%) and the average fuel temperature is accordingly larger (1.5%). The DNB ratio and cladding temperature are not shown because their behavior is not relevant for the safety during the transient.

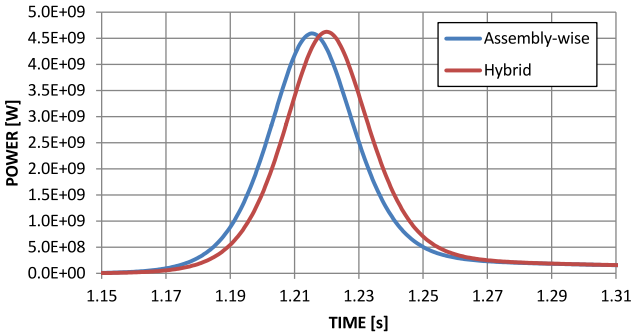

Fig. 8. Core power during transient

VI. CONCLUSIONS

The subchannel code CTF and the neutronics code DYN3D were successfully integrated and coupled on the Salomé platform. In order to test this coupling, a PWR rod ejection transient was simulated on a MOX/UOX minicore. Two different coupled models are tested on this transient. In the first model, the core is described in both codes with an assembly-wise resolution. In the second model, called hybrid model, an assembly-wise resolution is used except in the central assembly where a pin-by-pin fuel-centered model is used in CTF and the pin power reconstruction method is applied in DYN3D . The analysis shows the influence of the different

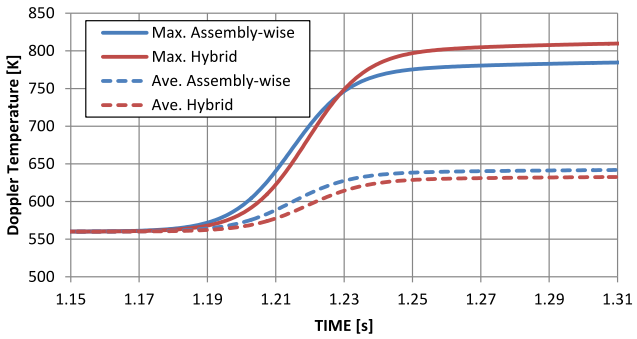

Fig. 9. Fuel temperature during transient

models on the minicore power, core average fuel temperature but also on the maximum fuel temperature.

VII. ACKNOWLEDGMENTS

This work was partly founded by the German Federal Ministry of Economics and Technology (BMWi) and by the European Commission under the 7th EURATOM Framework Program within the NURESAFE Project contract No. 323263.

REFERENCES

1. B. CHANARON, "7th Framework Programme - Simulation Platform for Nuclear Reactor Safety - Grant agreement for: Collaborative project - Annex I - Description of Work," Tech. rep. (2012).
2. U. ROHDE, "The reactor dynamics code DYN3D - models, validation and applications," *Progress in Nuclear Energy*, **89** (2016).
3. M. AVRAMOVA, "COBRA-TF Development, Qualification, and Application to Light Water Reactor Analysis," Tech. rep., The Pennsylvania State University (2003).
4. T. KOZLOWSKI and T. DOWNAR, "OECD/NEA and U.S. NRC PWR MOX/UO2 Core Transient Benchmark, Final Specifications," Tech. rep., OECD/NEA (2003).
5. H. FINNEMANN AND R. BÃŰER AND R. BÃŰHM AND R. MÃIJLLER, "Evaluation of Safety Parameters in Nodal Space-Time Nuclear reactor Analysis," in "Specialists Meeting on Advanced Methods for Power Reactors, Cadarache, France, September, 10-14," (1990).
6. R. SANCHEZ, "APOLLO 2: A user oriented, portable modular code for multi-group transport assembly calculations," *Nuclear Science and Engineering*, **100** (1988).