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Original Article

CTF/DYN3D multi-scale coupled simulation of a rod ejection transient on the NURESIM platform

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ABSTRACT

In the framework of the EU funded project NURESAFE, the subchannel code CTF and the neutronics code DYN3D were integrated and coupled on the NURESIM platform. The developments achieved during this 3-year project include assembly-level and pin-by-pin multiphysics thermal hydraulics/neutron kinetics 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 models of the minicore. In the first simulation, both codes model the core with an assembly-wise resolution. In the second simulation, a pin-by-pin fuel-centered model is used in CTF for the central assembly, and a pin power reconstruction method is applied in DYN3D. 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.

1. Introduction

One of the main objectives of the EU-funded project NURESAFE [1] was the delivery of fully integrated multiphysics applications. In the NURESAFE framework, the subchannel code CTF, and the neutronics code DYN3D were integrated and coupled on the NURESIM platform. The developments achieved during this 3-year project include assembly-level and pin-by-pin multiphysics thermal hydraulics (TH)/neutron kinetics (NK) coupling. In order to test this coupling, a PWR rod ejection transient is simulated on a MOX/UOX minicore. The transient is simulated using two different models of the minicore. In the first simulation, both codes model the core with an assembly-wise resolution. In the second simulation, a pin-by-pin fuel-centered model is used in CTF for the central assembly, and a pin power reconstruction method is applied in DYN3D.

2. Code description

In this section, a brief introduction of the CTF and DYN3D code is given. The NURESIM platform is also introduced.

2.1. The DYN3D reactor simulator

DYN3D [2] is a reactor core simulator developed at Helmholz Zentrum Dresden Rossendorf (HZDR), Germany. It is applied to perform steady-state and transient analysis in LWR for the geometry of hexagonal or square fuel assemblies.

Using flux factorization, the three-dimensional (3D) diffusion equation for two energy groups in a node is split into a two-dimensional (2D) equation in the 2D plane, and a one-dimensional equation for the axial [3]. The two equations are coupled by transverse buckling. In the 2D plane, the diffusion equation is solved using a nodal expansion method. The method is based on a 2D expansion of the intranodal fluxes. Exponential functions and polynomials up to the second order are used in each group.

Recently, the code was extended to solve the simplified transport equation (SP3). This development, described in the literature [4,5], was made to increase the accuracy of direct pin-by-pin calculations, and to assist in innovative reactor concepts (in particular, the molten salt reactor, the high-temperature gas-cooled reactor, and the sodium fast reactor).

The DYN3D pin power reconstruction method [6] 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

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of the neutron flux in chosen assemblies. The neutron flux is approximated by an analytical solution of the 2D diffusion equation in each axial layer of the selected assembly.

DYN3D is well validated for LWR transient analysis on international benchmarks, such as the TMI Main Steam Line Break benchmark [7] and the BWR Turbine Trip benchmark [8].

DYN3D was one of the first codes integrated on the NURESIM platform. During the NURESAFE project, the code interface with the NURESIM platform was upgraded to the Interface for Code Coupling (ICoCo) standard. The interface allows for mesh refinement up to the pin-by-pin level (where the pin power reconstruction is applied), which leads to the code being suitable for this study.

2.2. 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 [9].

The code uses a two-fluid modeling approach with consideration for three separate, independent flow fields: fluid film, vapor, and liquid droplets. Both subchannel and 3D Cartesian forms of nine conservation equations are available.

COBRA-TF has been improved and updated at the North Carolina State University (NCSU), USA by the Reactor Dynamics and Fuel Management Group (RDFMG) and subsequently rebranded as CTF. Improvements to the code include:

- transition from FORTRAN 77 to FORTRAN 90 source code;
- enhanced user-friendliness with improved error checking, free-format input deck, and development of a preprocessor [10];
- quality assurance utilizing an extensive VV matrix [11];
- turbulent mixing, void drift and direct heating model improvements [12];
- enhanced computational efficiency by implementation of new numerical solution schemes and parallelization options [13]; and
- improved physical model and user modeling documentation [12].

CTF was selected for this study because it ensures flexible modeling of the fuel bundle, from assembly-wise to pin-by-pin modeling. This capability is necessary for the hybrid modeling used in this work.

2.3. The NURESIM platform

The NURESIM platform [14] is based on the open-source software Salomé (http://salome-platform.org) which is 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 funded projects: NURESIM (2006–2008), NURISP (2009–2011), and NURESAFE (2013–2015).

The NURESAFE project, from which this work is extracted, had several main objectives:

- facilitate the coupling of different codes and solvers by using common data structures and generic functions (see the next section);
- generic pre-processing, post-processing, and coupling supervision;
- the accurate representation of physical phenomena in reactor and core physics, two-phase flow thermal hydraulics, and fuel modeling [15];
- multiscale and multiphysics capabilities of reactor safety computations [16]; and
- deterministic and statistical sensitivity and uncertainty analyses [17].

Over the three successive projects, many codes were integrated and coupled on the platform [1], covering the whole range of reactor physics: TH system codes (e.g., Cathare, ATHLET), TH subchannel codes (e.g., CTF, FLICA4), CDF codes (e.g., TRIO-U), neutronics codes (e.g., DYN3D, COBAYA4, and CHRONOS), and fuel performance codes (e.g., DRAKKAR).

3. Description of the integration and coupling on the platform

3.1. General description

Codes can be integrated on the NURESIM platform as "components". In the case of a full integration, single code functions can be called and processed from the platform (e.g., initialize code, read input, perform steady-state, etc.). When coupling codes on the NURESIM platform, the codes do not directly communicate with each other, but rather through the platform as illustrated in Fig. 1.

During the NURISP project, a standard API for code integration and coupling, the so-called ICoCo API, was developed. It is a pure abstract API defining a standard way for two physical codes to exchange information.

The NURESIM platform and the ICoCo API are 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 code interface should be able to interoperate C++ with Fortran libraries.

The NURESIM platform also features an internal Python console, in which all loaded component 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 called 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 consists of the following two components.

1. Mesh: The mesh contains the geometry of a domain that 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.
2. 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.

1. 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.

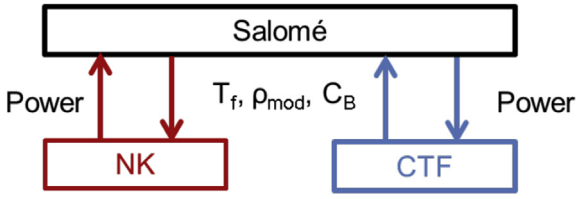

Fig. 1. Coupling on the NURESIM platform.

2. 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.

The parameters exchanged are shown in Fig. 1. DYN3D sends the volumic power to CTF. CTF sends the boron concentration (Cb), the fuel temperature (Tf), and the moderator density to DYN3D.

3.2. 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 application program interface (API), single CTF functions can be called from the platform. The functions in the API can be divided into two groups, code control and data exchange. The code control group typically handles:

- code initialization (including input processing);
- steady-state calculation;
- transient initialization;
- transient calculation; and
- code finalization.

CTF does not feature a steady-state mode, pseudo steady-state convergence is used instead. During a pseudo steady-state convergence, no perturbation in the model occurs and the time step size for the fuel heat conduction can be artificially increased to accelerate the convergence. A function that checks the convergence is called after each time step. Before starting the actual transient simulation, the heat conduction time step multiplication factor must be reset to 1.0.

The time step control in CTF on the platform 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 theoretically possible to implement a semi-implicit time coupling on the platform. However, during the NURESAFE project, only an explicit coupling approach has been implemented and tested as illustrated in Fig. 2.

In CTF the maximum time step is imposed by the Courant condition, which is proportional to the axial mesh size. In neutronics code, the maximum time step is often limited by the flux gradient between two time steps. Several options for the coupled time step size are possible. Usually, the smallest time step size

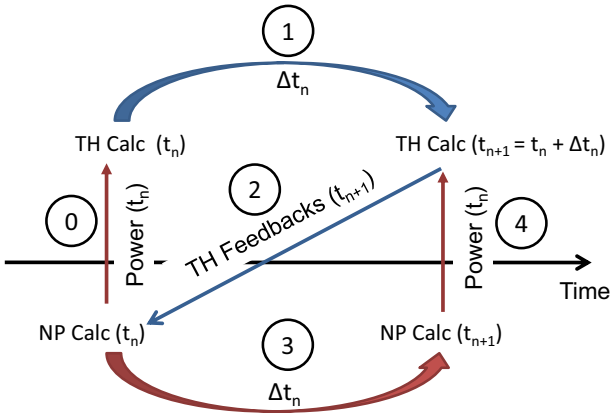

Fig. 2. Explicit time coupling algorithm.

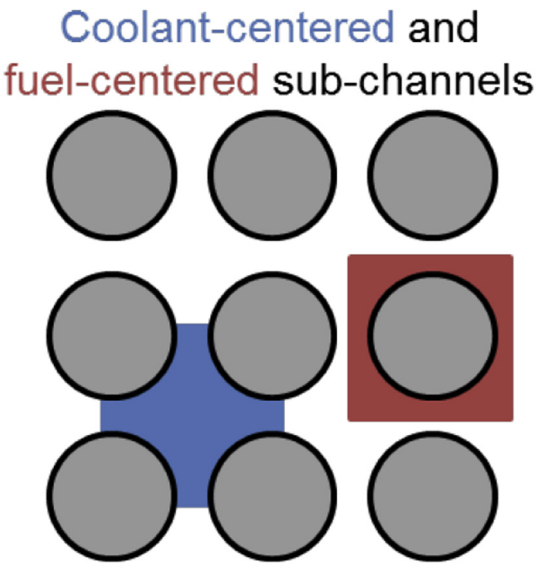

Fig. 3. Coolant centered versus pin centered modeling.

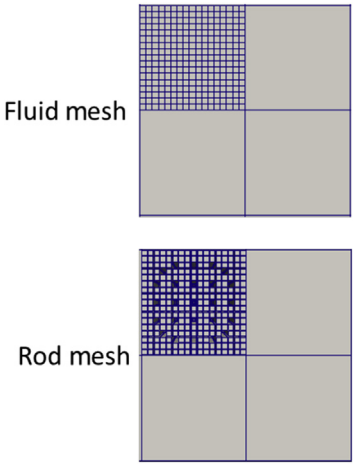

Fig. 4. Example of a hybrid mesh.

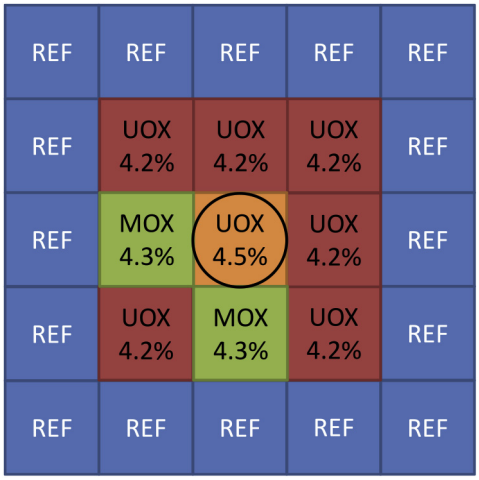

Fig. 5. Representation of the minicore.

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

0.735	1.118	0.743
1.087	1.65	1.118
0.727	1.087	0.735

Fig. 7. Core radial relative power distribution.

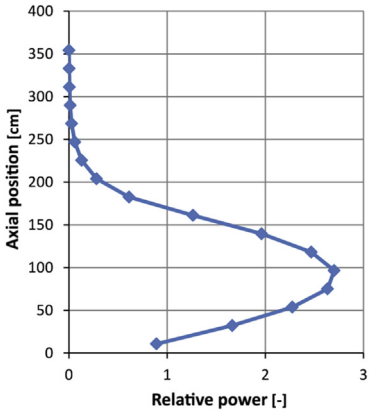

Fig. 8. Core axial relative power distribution.

proposed by CTF and DYN3D is used. This solution increases the computation time but improves the accuracy as well as the stability. No stability problems were encountered in any of the performed time steps within the frame of the NURESAFE project coupled simulations.

In the present study, a constant time step size of 1 ms is used to facilitate the comparison between the two models presented in the next section.

The functions generating the 3D mesh are called automatically during the code initialization phase. The radial mesh generation 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, e.g., use a refined mesh for a hot spot analysis.

Two meshes are generated in CTF: a "fluid mesh" and a "thermal mesh". The fluid mesh is a representation of the thermal-hydraulics channels, while the thermal mesh is a representation of the fuel rods. After each steady-state iteration or each transient time step, the following fields can be exchanged on the generated meshes. On the fluid mesh:

- fuel Doppler temperature;
- moderator density; and
- moderator temperature.

On the thermal mesh:

- boron concentration; and
- power (mesh and integral).

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

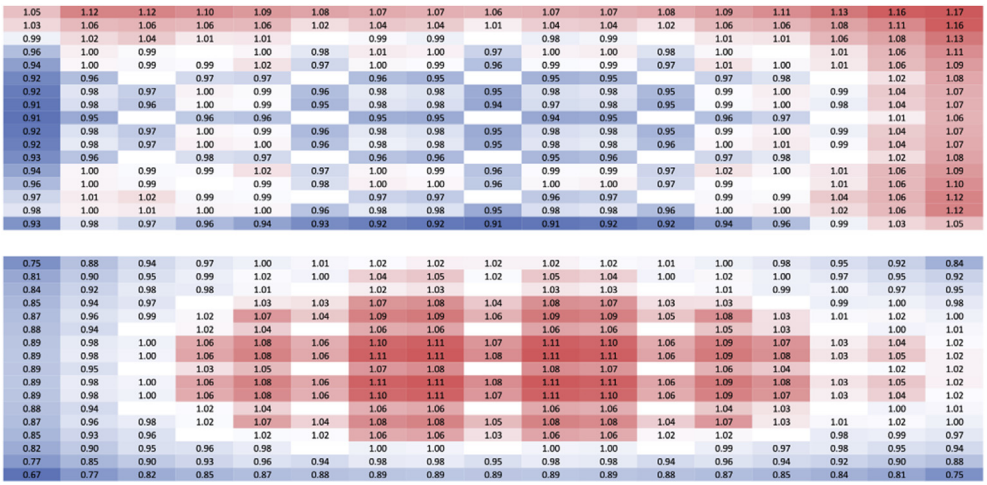

Fig. 9. Pin power distribution in the central assembly [at level 18 (top), and at level 4 (bottom)].

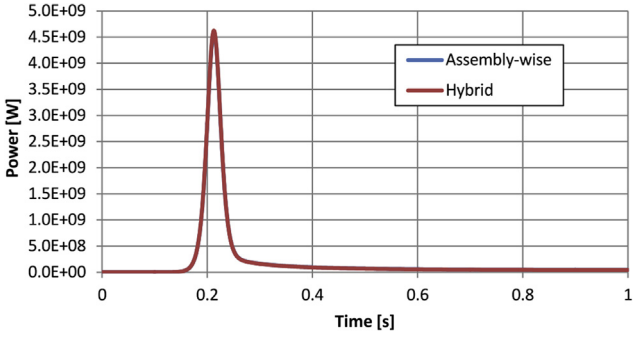

Fig. 10. Core power during transient.

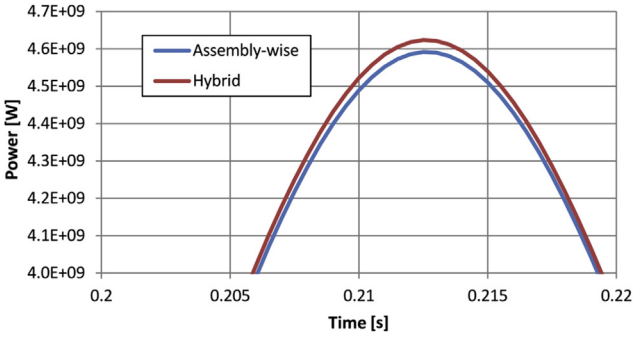

Fig. 11. Core power during transient.

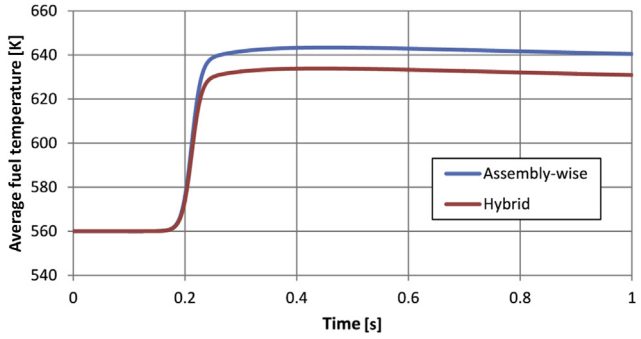

Fig. 12. Core-averaged fuel temperature during transient.

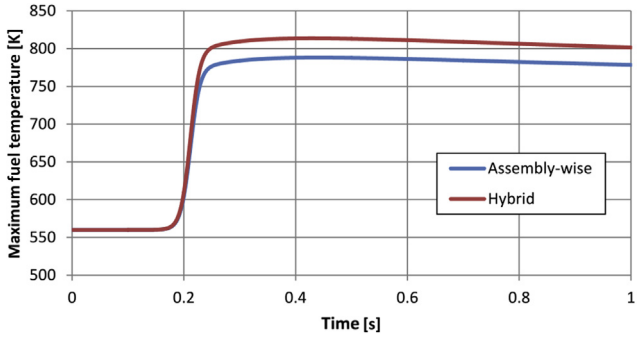

Fig. 13. Maximum fuel temperature during transient.

rod guiding tubes are located). The algorithm can select the correct model by checking the fuel pin object multiplication coefficient. When the multiplication coefficient is larger than one, an assembly-wise mesh is automatically assumed. At the pin scale, it is possible to model the thermal-hydraulics with the rod-centered or coolant-centered models (see Fig. 3).

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 model 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.

An example of a hybrid mesh (assembly-wise + pin-by-pin) is provided in Fig. 4.

4. Model description

A control rod ejection in a PWR minicore at HZP is simulated. The minicore is based on the MOX/UO2 Core Transient Benchmark [18]. The minicore consists of a 3×3 fuel assembly arrangement surrounded by the reflector (see Fig. 5). The central assembly where the control rod is inserted is UOX with a 4.5% enrichment. It is surrounded by six UOX assemblies with a 4.2% enrichment and two MOX assemblies with a 4.3% enrichment. All fuel assemblies are fresh (no burnup). The MOX assemblies are placed to get an asymmetric core. The objective is to maximize the peaking factor within the assembly modeled pin-by-pin.

4.1. 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 cross-section libraries for DYN3D were generated jointly at IRSN and UPM during the NURESAFE project using the lattice code APPOLO2 [19]. They 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/m^3), fuel temperature (473.15, 973.15, 1,373.15, and 1,773.15 K) and boron concentration (fixed at critical conditions). The support points for moderator density and fuel temperature were chosen to allow the simulation of a broad spectrum of transients while keeping the library (and spectral calculations) within a reasonable size.

The form functions, presented in Fig. 6, were generated at the same time as the macroscopic cross-sections. Form functions depend 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.

4.2. Thermal-hydraulics model

Two thermal-hydraulics models of the minicore are built in CTF. The first CTF model describes the minicore using an assembly-wise resolution. The reflector "assemblies" are 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). In total, the CTF hybrid model features 313 channels ($24 + 289$). When coupled with DYN3D, the thermal-hydraulics feedbacks from the pin-by-pin part of the model are automatically averaged/merged by the interpolation tool.

5. Results and analysis

5.1. Steady-state

The control rod is initially inserted 170 cm from the top of the active core (total core length = 365 cm). The corresponding radial and axial power profiles are presented respectively in Figs. 7 and 8. In the radial plane, the asymmetry introduced by the MOX assemblies can be clearly seen. The axial power profile is strongly bottom-peaked (peaking factor > 2.5), which is caused by both the partial rod insertion and the absence of thermal-hydraulic feedback (HZP state).

The pin power distribution in the central assembly is shown for two axial levels in Fig. 9. At the top of the figure, the distribution at axial level 18 (where the control rod is inserted) is displayed. At the bottom of the figure, the distribution at axial level 4 (without the control rod) is displayed. The asymmetry introduced by the MOX assemblies can be seen at the pin level. The influence of the uncontrolled/controlled form functions presented in Fig. 6 is also obvious.

5.2. Transient

The simulation starts from the HZP critical state. At $t = 0$ s, the control rod is ejected within 0.1 s. The maximum reactivity insertion is 1.4$.

The power responses of the assembly-wise model and the hybrid model are compared in Fig. 10. Clearly the modeling has little influence on the maximum power.

However, the difference between the two models is more apparent in Fig. 11. The hybrid model reaches a slightly higher power than the assembly-wise model (+0.7%). At the end of the transient, however, the power is higher in the assembly-wise model (+6.7%). This shows that the volume averaged fuel temperature in the pin-by-pin model differs from the direct calculation of the assembly-wise model. This is due to the heterogeneous power profile and the non-linear behavior of the fuel temperature.

The fuel temperature responses of the assembly-wise model and the hybrid model are compared in Figs. 12 and 13. A higher maximum fuel temperature is reached in the hybrid model than the assembly-wise model (+35 K or 3.1%). The difference is larger than for the core power because of the larger peaking factor introduced by the pin-by-pin modeling (especially the form function). With higher maximum power and temperature, the hybrid model is thus conservative compared to the assembly-wise model.

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 (+10 K or +1.5%). The DNB ratio and cladding temperature are not shown because their behavior is not relevant with regards to safety.

6. Conclusions

The subchannel code CTF and the neutronics code DYN3D were successfully integrated and coupled on the NURESIM platform. In order to test this coupling, a PWR rod ejection transient was simulated on a MOX/UOX minicore. Two different coupled models were 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 the hybrid model, an assembly-wise resolution is used, except for 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.

This study shows the capability of the NURESIM platform for hybrid coupled simulations. The analysis shows the influence of the different models on the minicore power, core average fuel temperature, but also on the maximum fuel temperature. Hybrid simulations are interesting because they offer direct access to local parameters at the pin level, which can be conservative compared to assembly-wise simulations.

Conflicts of interest

The authors have no conflicts of interest to declare.

Acknowledgments

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