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Best-estimate simulation of a VVER MSLB core transient using the NURESIM platform codes

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ABSTRACT

This paper summarizes the nodal level results from the VVER MSLB core simulation in the NURESAFE EU project. The main objective is to implement and verify new developments in the models and couplings of 3D core simulators for cores with hexagonal fuel assemblies. Recent versions of the COBAYA and DYN3D core physics codes, and the FLICA4 and CTF thermal-hydraulic codes were tested standalone and coupled through standardized coupling functions in the Salome platform. The MSLB core transient was analyzed in coupled code simulation of a core boundary condition problem derived from the OECD VVER MSLB benchmark. The impact of node sub-division and different core mixing models, as well as the effects of CFD computed core inlet thermal-hydraulic boundary conditions on the core dynamics were explored.

1. Introduction

The analysis of main steam line break (MSLB) reactivity transients is a challenging task because of the strongly pronounced local 3D effects in the core and the reactor pressure vessel (RPV) and correspondingly the need for detailed modeling of both the neutronics and the coolant mixing. The VVER-1000 MSLB simulation has been subject of the OECD VVER-1000 Coolant Transient Benchmark – V1000CT-2 (Kolev et al., 2006). The analysis of the benchmark results indicated the potential for improving the quality of simulation through the use of enhanced models of the flow mixing and the 3D core dynamics.

This article presents the full-core nodal-level simulation results from the VVER MSLB work package in the NURESAFE EU project. As stated in the NURESAFE description of work (Chanaron, 2012; Chanaron et al., 2015) the main objective of the work on the VVER MSLB situation target was to develop and execute simulation schemes towards higher-resolution. Specific objectives were to test new developments in the nodal and pin-by-pin models and couplings for VVER applications, as well as CFD and CFD/system code simulation of the RPV with enhanced prediction capability. This paper concentrates on the nodal core models which can be supplemented by pin-power reconstruction (PPR) and application of CFD computed core boundary conditions. The results from pin/pin models, sub-channel thermal-hydraulic analysis and coupled COBAYA4/CTF pin-cell simulation of VVER core subsets will be subject of separate publications.

For the purposes of this study a core boundary condition problem with pre-calculated boundary conditions was derived from the OECD VVER MSLB benchmark. Validated COBAYA and DYN3D core-physics models with homogenized nodes were coupled to full-core FLICA4 or CTF thermal-hydraulic models. The core transient scenario was analyzed in coupled COBAYA3/FLICA4, COBAYA4/CTF and DYN3D/CTF simulations.

Special attention was paid to the effects of different flow mixing models in the RPV and the core. Time-dependent MSLB core boundary conditions (BC) were obtained in two variants: from CATHARE coarse-mesh RPV simulation (Spasov et al., 2010), and from CFD calculations for the down-comer and the lower plenum (Vyskocil, 2015). The corresponding vessel mixing models were qualified against Kozloduy-6 data from a vessel mixing experiment conducted during the plant commissioning phase (Topalov et al., 2004; Kolev et al., 2007). The impact of CFD computed core boundary conditions on the 3D core dynamics was explored in comparative MSLB core calculations.

For multi-physics core simulation a wide-range multi-parameter VVER MSLB cross-section library for homogenized

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nodes was generated (Petrov et al., 2015) using the APOLLO2 code (Sanchez, 2010; Santandrea et al., 2008). This library is supplemented by a multi-parameter library of APOLLO2 computed pin-by-pin form functions for each node which allows DYN3D pin power reconstruction.

In the sections below a brief description of the codes and models used is given and the simulation results are discussed.

2. Codes and models description

For coupled core neutronic-thermal hydraulic (N/TH) simulation, recent versions of COBAYA, DYN3D, FLICA4 and CTF were used. The considered code couplings are COBAYA3/FLICA4, COBAYA4/CTF and DYN3D/CTF in Salome (http://www.salome-platform.org/). CATHARE2 (Geffraye et al., 2011) and FLUENT (ANSYS-Fluent, 2015) codes were used to solve the MSLB RPV boundary condition problem and to compute time-dependent MSLB core BC, as discussed in paragraphs 4.2 and 5.3 below.

These codes and couplings, except for FLUENT, make part of the European NURESIM software platform (Chauliac et al., 2011 and Chanaron et al., 2015) which is a set of state of the art software devoted to the simulation of normal operation and design basis accidents of light water reactors: BWR, PWR, VVER. This platform currently includes 12 codes covering different physics: neutronics, thermal-hydraulics, fuel thermo-mechanics and relevant scales: local (sub-channel or pin), fuel assembly, core and reactor system. Given their complementary features, the selected codes offer solutions suitable for various situations.

2.1. COBAYA code

COBAYA is a multi-scale 3D core simulator code developed by the Universidad Politecnica de Madrid (Cobaya team, 2015; Ahnert, 2015). It uses transport-corrected multi-group (MG) diffusion approximation and performs steady-state and transient calculations of light water reactors (LWR) for both Cartesian rectangular and hexagonal geometries. At the nodal level, the flux solver, called ANDES (Analytic Nodal Diffusion Equation Solver) (Lozano et al., 2008) uses the ACMFD (Analytic Coarse-Mesh Finite-Difference) method (Aragones et al., 2007; Garcia-Herranz et al., 2002). ANDES can be used stand-alone to perform nodal full-core calculations, or as an accelerating module for the pin-by-pin solver. It has been numerically validated for a number of numerical benchmarks (Lozano et al., 2010). In hexagonal geometry, the code is capable of node sub-division to 6 or 24 triangles per hexagon. In the present study, 6 triangles per hexagon (6 N) and 30 axial nodes in the heated core were assumed. At the pin level, the multi-group diffusion equation is solved using a FMFD (fine-mesh finite-difference) method (Herrero et al., 2009).

The COBAYA nodal core physics solver has been extensively benchmarked in the frame of EU projects. Recently a new version of the code, COBAYA4 has been released (Ahnert, 2015) which features a fully renovated code architecture and improved capability of parallelization on multi-core systems and graphical processing units (GPU). The code has been coupled with core thermal-hydraulic codes in the Salome platform (see the paragraph on coupling below).

2.2. DYN3D code

DYN3D is a 3D core simulator developed by the Helmholtz-Zentrum Dresden-Rossendorf. It solves the 2G diffusion equation with a nodal expansion method and performs steady-state and transient core calculations of LWR with hexagonal and square fuel assemblies (Rohde et al., 2016). Recently a multi-group nodal solver for hexagonal geometry and a multi-group SP3 pin-by-pin solver for square lattices have been added. The code has been coupled with core TH codes in the Salome platform (see the paragraph on coupling below). In this study at the nodal level the VVER model assumes one node per hexagon and 30 axial nodes in the heated part of the core.

DYN3D is capable of nodal calculations with pin power reconstruction in hexagonal geometry (Hádek et al., 2009; Hádek, 2012; Gomez et al., 2014). In the frame of NURESAFE a recent version of the nodal/PPR calculation scheme using an APOLLO2 generated multi-parameter library of pin-by-pin node power shapes (form-functions) has been numerically validated vs. transport reference solutions for VVER mini-cores (Hádek, 2016).

2.3. Full-core FLICA4 model

FLICA4 (Toumi et al., 2000; Fillion et al., 2011a,b) is a 3D core thermal-hydraulic code of CEA with sub-channel capabilities. It is based on a fully 3D, four-equation mixture model with a correlation for the interphase slip.

The FLICA4 full-core coarse-mesh VVER model used in the present study and its validation are described in (Spasov and Kolev, 2013). The core model assumes one channel per fuel assembly and 30 axial nodes in the heated core. The fuel heat conduction model used 9 radial meshes in the fuel pellet, 1 for the gas gap and 1 for the cladding, and fitted nonlinear approximations of the fuel thermal properties from the specifications.

2.4. Full-core CTF model

COBRA-TF thermal-hydraulic code with sub-channel capabilities was originally developed by the Pacific Northwest Laboratory in 1980 and since then has been modified by several institutions. COBRA-TF also found use at the Pennsylvania State University (PSU) and subsequently at the North Carolina State University (NCSU) where it has been improved, updated, and subsequently re-branded as CTF (Avramova et al., 2006; Avramova, 2007; Avramova and Cuervo, 2013). The CTF code uses a nine-equation three-field flow model (Avramova, 2007). The user can opt between 3D TH model and multi-channel with cross flow.

The CTF coarse-mesh core model for VVER used in this simulation is described in (Jimenez and Sanchez, 2013). The TH model assumes one channel per fuel assembly and 30 axial nodes in the heated core. The fuel heat conduction model used 9 radial meshes in the fuel pellet, 1 for the gas gap and 1 in the cladding.

For the discussion and comparison of results, it is important to mention the modeling options that are common with the FLICA4 model and those that are code-specific. The coarse-mesh spatial discretization of the core is the same in both thermal-hydraulic models. The fuel pin discretization in the heat conduction models is also unified and the gas gap conductance coefficient for burnt fuel is assumed to be a given constant. The CTF model differs from that of FLICA4 by the basic flow equations, the flow mixing modeling and the heat transfer models. For details see the references and the discussion of results in the sequel. There is also a small difference in the approximations of the fuel thermal properties as a function of temperature. In this simulation CTF used linear interpolation in a table while the FLICA4 model used fitted non-linear functional approximations based on the same table.

2.5. Code couplings

The DYN3D/CTF coupling at the nodal level is based on previous neutron kinetics – thermal-hydraulic coupling implementations within the NURESIM platform (Jimenez et al., 2015). Both codes have an Application Programing Interface (API) which was used