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Validation and verification of the coupled neutron kinetic/thermal hydraulic system code DYN3D/ATHLET

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A R T I C L E I N F O

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A B S T R A C T

One of the most intensively developing areas in the LWR multi-physics is a coupling of different best estimate 3-D neutron kinetic (BIPR, DYN3D, KIKO3D, NEM, PARCS, etc.) and thermal hydraulic (ATHLET, CATHARE, RELAP5, etc.) codes. Resulting coupled code systems have advanced capabilities of modeling both steady-state spatial distributions of the core power and their evolutions during different kinds of reactor transients. They are also highly useful in the analyses of possible reactor instabilities. Initial steady-state core power distributions can be disturbed by changes in the reactor loop mass flow rates and/or temperatures, by relocations of the low-temperature/diluted-boron water slugs within the primary system or by movements of control rods.

The coupled code used for LWR simulations in HZDR is DYN3D/ATHLET, which includes the 3-D core neutron kinetic and thermal hydraulic model of own development – DYN3D. The paper reports major capabilities of DYN3D as well as different ways of its coupling with the thermal hydraulic code ATHLET (external, internal and parallel), but mainly focuses on the validation and verification of the coupled code DYN3D/ATHLET. In the course of DYN3D/ATHLET validation/verification nearly 20 real plant transients and dynamic benchmarks have been simulated and analysed. The LWR types covered by these tasks are: VVER-440 (Bohunice-3, Greifswald-5 and Loviisa-1 units), VVER-1000 (Balakovo-1, Balakovo-4, Kalinin-3, Kozloduy-6, Saporozhye-6 and Temelin-2 units), B&W PWR (TMI-1) and BWR/4 MK-1 (Peach Bottom-2).

For each reactor unit a computational model was developed according with the benchmark specifications. The simulated tasks describe different scenarios of increasing complexity, including the transients initiated by the main steam header or main steam line breaks, switching off/on of main circulation pumps, turbine trip and generator load drop. Some of the transients are characterized by a strongly asymmetric behavior of the primary system (e.g. caused by a steam line break), and the processes of coolant mixing in the lower and upper reactor plenums as well as in the downcomer are important for these cases. The coupled code DYN3D/ATHLET models the primary coolant mixing in two ways – whether by an appropriate nodalization of the mixing area or by using two specific models for mixing in the lower plenum. The first of the lower plenum mixing models is a part of the coupling interface at the core inlet plane, while the second one is the analytical coolant mixing model developed for the downcomer and the lower plenum regions of VVER-440.

The results of DYN3D/ATHLET simulations were assessed both against available measured data and calculations performed with similar multi-physics codes. The paper includes an overview of the simulated problems and the most representative results of DYN3D/ATHLET validation/verification for all coupling modes. The obtained experience of code validation provides a better understanding of reactor transients with a strong interaction between neutron kinetics and thermal hydraulics, helping to improve computation models. This experience is also useful for the present and further activities in coupling of DYN3D with other best estimate codes, like CFX, TRANSURANUS, etc.

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1. Introduction

Light water reactors (LWRs) are complex technical objects, operating on the basis of multiple interacting physical principles and, thus, representing fundamentally multiphysical systems. Due to potential risks coming from nuclear reactor technologies, the top-priority task is to ensure high levels of operational reliability and safety of LWRs as competitive electrical energy sources.

The essential part of the reactor safety assessment is a comprehensive analysis of LWR's behavior under a variety of possible operational conditions, including relevant accident scenarios. In order to cope with this ambitious task, a series of best estimate (BE) system codes, such as ATHLET (Austregesilo et al., 2012), CATHARE (Lavialle, 2006) or RELAP5 (RELAP5/MOD3.3 code manual, 2001), have been developed and validated. The constitutive models of these codes cover practically all key physical phenomena, but nonetheless remain mainly focused on the thermal-hydraulic aspects of reactor behavior, whereas the core multi-physics (i.e., interacting phenomena of the core neutronics, thermal-hydraulics, thermo-mechanics, and fuel performance) is generally described in a simplified way (e.g. by using the point kinetics model or relatively simple fuel rod models). Within a deterministic approach to reactor safety analyses the uncertainties of such "low-resolution" core models are usually handled by using appropriate conservative assumptions.

To improve the core models of BE system codes, these codes are integrated with advanced 3D models of neutron kinetics, like DYN3D (Grundmann et al., 2000a; Duerigen et al., 2013), NEM (Beam et al., 1999), PARCS (Downar et al., 2002), etc. The resulting coupled codes are not only the tools to increase the quality of reactor safety assessments and to predict more realistic values of reactor design margins, but they also provide the basis for further modelling improvements, e.g. by adding BE fuel performance codes like TRANSURANUS (Lassmann, 1992) and/or increasing a space resolution of thermal-hydraulic models in the core and other reactor components (multi-scale approach). To be a reliable tool for LWR safety analyses, the coupled neutronic/thermal-hydraulic codes must be validated and verified against relevant plant transients and benchmark solutions. Moreover, a validation of all constitutive models and correlations in integrated codes is a precondition for using coupled codes for reactor safety analyses (Safety standards, 2012).

The presented paper describes coupled code DYN3D/ATHLET (Grundmann et al., 1995; Kozmenkov et al., 2007) developed at Helmholtz-Zentrum Dresden-Rossendorf (HZDR) for modelling steady-state and transient behavior of LWRs, concentrating mainly on the efforts spent to validate/verify this code. The paper contains an overview of the simulated test problems as well as selected results of DYN3D/ATHLET validation/verification.

2. DYN3D core model and its integration with the system code ATHLET

DYN3D is a three-dimensional (3D) code for steady-state and transient simulations of LWR cores with hexagonal or quadratic geometry of fuel assemblies (FAs). It includes the models of 3D neutron kinetics, two-phase core thermal-hydraulics, and fuel rod behavior. In combination these models allow to perform standalone transient simulations with predefined time-dependent conditions at the core inlet and outlet boundaries.

DYN3D is able to perform:

- core burn-up calculations,
- core criticality calculations,
- reduction of homogenization errors by using assembly discontinuity factors (ADFs),
- decay heat calculations,
- calculations of equilibrium Xe and Sm concentrations in the core,
- pin-wise power reconstruction in selected FAs.

The neutron kinetics model of DYN3D is based on the solution of the 3-D neutron diffusion equation by nodal expansion methods. The transversal integration method is used to solve the neutron diffusion equation within the nodes, while an implicit difference scheme with exponential transformation is used for time integration. In recent years the treatment of the neutron energy dependence in the code was extended from two to multi groups, and SP3 neutron transport model was implemented to improve the accuracy of diffusion approximation (Duerigen et al., 2011, in press). Different formats of macroscopic cross-section libraries are supported by the code (Grundmann et al., 2010).

The thermal-hydraulic model of DYN3D is represented by parallel core channels with fuel rods inside (Manera et al., 2005; Rohde, 2001). One- or two-phase coolant flows in the core channels are described by four differential equations of the mass, energy and momentum balances. Cross flow connections for coolant exchange between parallel core channels are not modelled in DYN3D. The number of parallel flow channels in a core model can be either equal or less than the number of modelled FAs. All fuel rods within a single FA are assumed to have the same (node-averaged) fuel and cladding temperatures. Additionally, one hot fuel rod can be connected to any of modelled FAs, taking into account possible deviations of fuel rod parameters from their average values. Hot fuel rods have no impact on the neutronic part of DYN3D. The radial heat conduction equation is solved in each axial layer of modelled fuel rods. The mechanism of heat transfer in the fuel rod gap includes both heat conduction and heat radiation. Dynamic change of the gap size in transients is taken into account. Heat transfer coefficients at the outer surfaces of claddings are determined for the whole range of possible flow regimes in the core channels – from single-phase liquid flow to superheated steam flow (Rohde, 2001).

Internal, external and parallel coupling techniques were used to integrate DYN3D with the standard system code ATHLET, originally containing 0D (point) and 1D (one-dimensional) models of neutron kinetics. Each of these techniques has its own advantages and disadvantages, depending on the task to be solved. In the case of internal coupling, only the neutron kinetics model of DYN3D is integrated with the system code, while the core thermal-hydraulics (as well as the thermal-hydraulics of all other reactor components) is calculated by ATHLET. The fuel rod model of ATHLET includes all capabilities of the above mentioned fuel rod model of DYN3D. The internal coupling technique is the most consistent approach which, however, requires significant modifications of the coupled codes. Besides this, the system code might either become too slow or even have numerical problems being applied to simulations of the cores with a large number of parallel flow channels.

Within external coupling approach all physical phenomena in the core, including its thermal-hydraulics, are completely modelled by DYN3D, while ATHLET simulates the rest of reactor systems. This technique requires exchange of the core inlet and outlet boundary conditions between thermal-hydraulic models of DYN3D and ATHLET, which is relatively easy to implement. It helps to reduce the cost of simulations in the cases with multiple core channels, but under conditions of a strong feedback between thermal-hydraulics and neutronics (e.g. in boiling water reactors) can lead to numerical instabilities.