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Extension of the reactor dynamics code DYN3D to SFR applications – Part III: Validation against the initial phase of the Phenix EOL natural convection test

E. Nikitin [a,b,*], E. Fridman [a]

[a] Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany
[b] Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

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ABSTRACT

The reactor dynamics code DYN3D, initially developed for LWR applications, is being extended for steady state and transient analyses of Sodium cooled Fast Reactor (SFR) cores. The extension includes the development of the few-group cross section generation methodology, updating of the thermal-hydraulic database with thermal-physical properties of sodium, and development of the thermal-mechanical model to account for thermal expansion effects of the core components.

Part I of the paper provided a detailed description of the recently implemented thermal expansion models able to treat axial expansion of fuel rod and radial expansion of diagrid. The results of the initial verification tests were also presented in Part I of the paper.

The capability of the extended version of DYN3D to perform steady state and transient analyses of SFR cores was validated using selected tests from the end-of-life experiments conducted at the Phenix reactor. Steady state analysis of the control rod withdrawal tests is covered in Part II of the paper.

Part III of the paper reports on the results of the transient analysis of the initial stage of the natural circulation test from the Phenix end-of-life experiments.

1. Introduction

The reactor dynamics code DYN3D (Rohde et al., 2016), initially developed for LWR applications, is being extended for steady-state and transient analyses of Sodium cooled Fast Reactor (SFR) cores. The extension includes the development of the few-group cross section (XS) generation methodology (Fridman and Shwageraus, 2013; Rachamin et al., 2013; Nikitin et al., 2015a, 2015b), the updating of the thermal-hydraulic (TH) database with thermal-physical properties of sodium, and the development of the thermal-mechanical (TM) model to account for thermal expansion effects of the core components.

Part I of the paper (Nikitin et al., 2018a) provided a detailed description of the thermal expansion models that have recently been implemented in DYN3D. The models enable the treatment of important thermal expansion effects occurring within the SFR core, in particular axial expansion of fuel rod and radial expansion of diagrid. The axial expansion model is capable of modeling non-uniform core expansions by using the spatial temperature distribution of the fuel rods. The radial diagrid expansion model utilizes the average inlet sodium temperature to uniformly expand the core in the radial direction. The initial verification study, summarized in Part I of the paper, demonstrated an adequate performance of the newly implemented models.

Part II of the paper (Nikitin et al., 2018b) presented the verification and validation of the extended version of DYN3D against the IAEA benchmark on the control rod (CR) withdrawal tests from the end-of-life (EOL) experiments conducted at the Phenix reactor (IAEA, 2014). The benchmark results, summarized in Part II of the paper, were used to validate the few-group XS generation methodology and the neutronic performance of DYN3D in steady state analyses.

Part III of the paper focuses on validation of DYN3D against a transient scenario taken from the IAEA benchmark on the Phenix EOL natural circulation test (IAEA, 2013). Initially, the benchmark targeted sodium capable TH system codes utilizing point kinetics models for validation. However, by combining this benchmark with the detailed core description of the CR withdrawal benchmark, the point kinetics model can be exchanged with a spatial neutron kinetics code for a more detailed evaluation of the test,

* Corresponding author at: Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany.
E-mail address: e.nikitin@hzdr.de (E. Nikitin).

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as it was also done in (Chenu et al., 2012). Similarly, the initial stage of the natural convection test was calculated with DYN3D using the 3D nodal diffusion solver together with the intrinsic TH model and the new TM models. This study provides an assessment of DYN3D for coupled neutron kinetics thermal-hydraulics (NK/TH) transient analyses of SFR cores in general, and presents the impact of using uniform axial expansion profiles instead of simulating a more realistic non-uniform core expansion for this particular test.

The following section provides a brief overview on the initial phase of the natural circulation test. The computational methodology and the modeling assumptions are presented in Section 3. The numerical results obtained with the DYN3D are compared to the experimental data in Section 4. Section 5 summarizes the paper and presents possible directions for the future work.

2. Description of the initial phase of the natural convection test

The natural circulation test (IAEA, 2013) was dedicated to investigate the onset and development of natural circulation in pool-type SFR systems. In the framework of the benchmark, the experimental data were made available for qualification and validation of thermal-hydraulic system codes that are aimed for modeling liquid sodium systems.

The test was initiated by manual dry out of the two steam generators at the reduced power of 120 MWth. This caused a loss of heat removal from the secondary, and consequently, from the primary side. After the initial phase, which lasted 458 s, the reactor was manually scramed. Eight seconds later, the primary pumps were tripped and the characteristics of natural circulation were measured in the primary system.

In the unprotected phase, while the total mass flow rate remained constant, the core inlet temperature has increased by around 40 °C. As a result, the total power has dropped from 120 MWth to 50 MWth, and the inner core outlet temperature by around 10 °C, as shown in Fig. 1. The power reduction driven by the core reactivity was initiated by the thermal expansion of the core diagrid. The further development of the total reactivity (Fig. 1) was mainly influenced by the thermal expansion of the diagrid and fuel rods, the Doppler effect, and the relative CR movement caused by the simultaneous expansion of the core, CR drivelines and vessel. The measured core characteristics, shown in Fig. 1, include time-dependent inlet and outlet coolant temperatures, reactivity, and total power.

The temperature increase of the core inlet is mainly driven by the loss of heatsink in the steam generators. The small and slow change of the outlet coolant temperature has only a minor influence on the core inlet during the unprotected phase. Therefore, to a certain extent, the core TH behavior may be considered decoupled from the primary circuit, and can be modeled with a core simulator by using the inlet temperature curve as time-dependent boundary condition (Fig. 1, top). In this study, the unprotected stage of the test was calculated in such way with DYN3D, and the numerical results were compared with the experimental data provided by the benchmark specification (IAEA, 2013).

3. Computational methodology

The calculations were done in a two-step approach using the Serpent-DYN3D codes sequence. In the first step, the homogenized few-group cross sections (XS) were generated on lattice level with Serpent, and in the second step, the full core nodal calculations were performed with DYN3D.

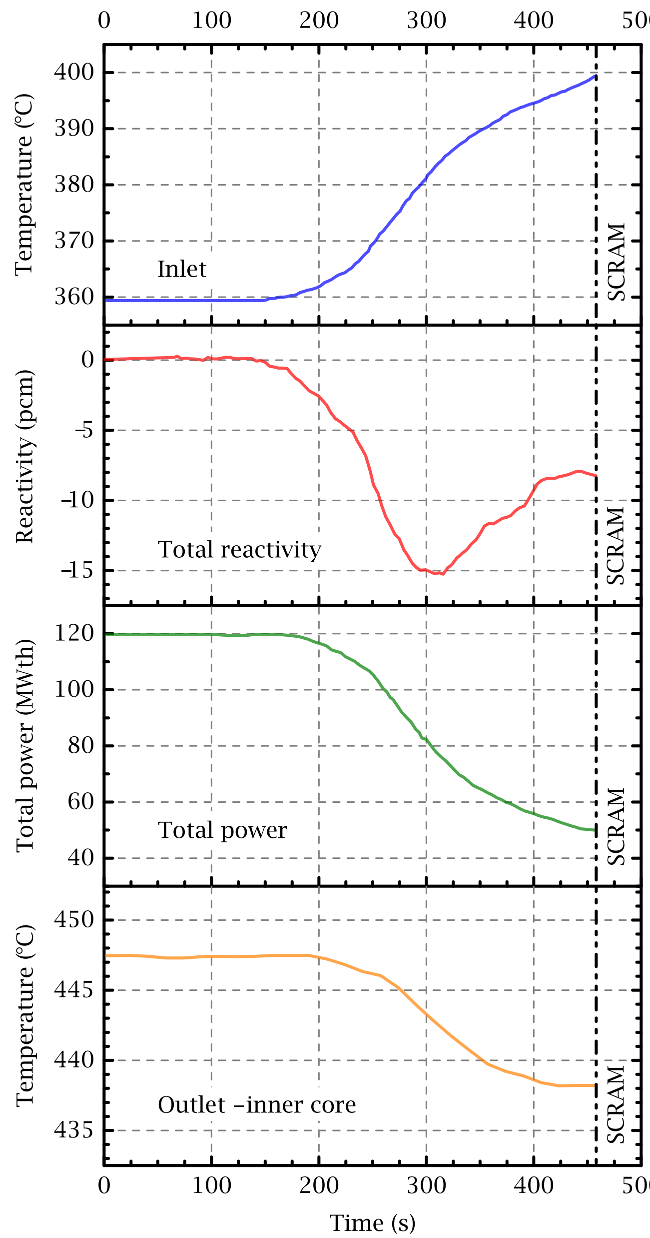

Fig. 1. Measurements in the initial phase of the natural convection test. *Top* to *bottom*: inlet coolant temperature, reactivity, total thermal power, outlet coolant temperature of the inner core. Data are extracted from the benchmark report.

3.1. Generation of parametrized cross section libraries

A parametrized cross section library was generated for DYN3D that covers the full range of reactor conditions of the CR shift tests and the natural circulation test. In this way, the same library was utilized in all calculations presented in Part II and III of the paper.

The XS were calculated with Serpent at different fuel temperatures, coolant temperatures, axial expansion and radial diagrid expansion states. Table 1 presents the selected states that span the parameter space of the XS-library. In Table 1, the temperature-dependent expansion coefficients are defined as

$$\varepsilon(T) = \frac{L(T)}{L(T_0)} = 1 + \alpha(T)\ (T - T_0), \tag{1}$$

where L is the linear dimension and α is the linear expansion coefficient corresponding to the temperature T, and T_0 is the reference