Coupled Fuel Depletion/Thermal Hydraulic Analysis of a Liquid Metal Fast Reactor ANST100e

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1. Introduction

The calculation of fuel burnup and the dynamic evolution of isotopic compositions are crucial aspects to comprehend the reactor's operational characteristics and performance. In previous investigations, the RAST-F code system garnered attention for its proficiency in depletion analysis [1,2], providing valuable insights into fuel evolution. Yet, these studies predominantly focused on the verification and validation of the depletion solver in isolation, without accounting for the feedback effects from thermal-hydraulic (TH) parameters. This existing gap in knowledge necessitates a closer examination of how the inclusion of TH feedback impacts the accuracy and reliability of depletion predictions within the RAST-F framework. Therefore, the verification of the integrating between depletion solver and thermal-hydraulic solver is essential for any further development. In this study, the fuel burnup simulation with thermal-hydraulic feedback is performed using nodal diffusion code RAST-F. The ANTS-100e core [3] is chosen for a verification process. The main purpose of this study is to present the RAST-F code system capabilities for fuel burnup simulation coupled with TH feedback. Through this coupling, the RAST-F code system is primed to deliver a more accurate and realistic portrayal of fast reactor (FR) behavior under real-world operational scenarios.

2. Reactor core description

The ANTS-100e core [3] is designed to provide sustainable and clean energy over extended periods, which contributes to its exceptional efficiency and safety. The ANTS-100e core is a lead-bismuth cooled fast reactor with a maximum electric power of 100 MWe from a thermal power of 300 MW. The active consists of 138 FAs divided into two enrichment zones of 10.0 % and 13.0 %. Each FA is divided into four axial components: lower reflector, fuel, gas plenum, and upper reflector. The CR system is compartmentalized into two independent systems: the primary CR system consisting of 3 CR SAs, and the secondary CR system consisting of 9 CR SAs. The primary system is responsible for regulating the core power during normal operation, while the secondary system is primarily utilized for shutdown purposes or emergency scram, remaining fully withdrawn during normal operation. The absorber material selected for the design is B_4C, with a 90 % enrichment of the ^{10}B isotope. The reflector region uses stainless steel to improve the neutron economy in the fast reactor. The ANTS-100e is a promising nuclear reactor design that can generate clean and sustainable energy over a 10-year first cycle. Detailed descriptions of the geometry and materials can be found in Ref. 3.

3. Computational methodology

3.1 RAST-F nodal diffusion code

RAST-F is a new full-core analysis nodal code capable of k-eigenvalue, depletion, transient, and thermal-hydraulic calculations, which is under development by the CORE laboratory for FR applications [4-7]. In the framework of RAST-F code development, the micro depletion calculation is based on the CRAM module [8] to solve the Bateman equation and is optimized to take advantage of the sparsity of the burnup matrix to reduce computation time. The burnup chain encompasses a total of 221 nuclides, which includes 28 heavy nuclides and 193 fission products. This comprehensive representation allows for the accurate modeling of the evolution of the nuclear fuel and the prediction of various isotopic concentrations throughout the burnup process. The matrix solver is accelerated using the sparse Gauss-Seidel method. This method is employed to efficiently solve the system of linear equations that arise from the discretization of the governing equations. By utilizing the sparse Gauss-Seidel method, RAST-F can achieve faster convergence and improved computational efficiency for solving the system of equations. This accelerates the overall simulation time and enables the code to handle large-scale problems encountered in FR analysis. To optimize data storage in RAST-F, a binary format is employed, which offers several advantages over traditional text-based formats. By utilizing a binary format, the data is represented in a more compact and efficient manner, resulting in reduced memory requirements and improved performance. The code also supports triangular depletion schemes for multi-cycle simulations, enabling the assessment of fuel burnup and isotopic evolution over extended operation periods. Furthermore, RAST-F incorporates features such as restart and shuffling capabilities, facilitating multi-cycle analysis and optimization studies. While the TH model implemented in RAST-F employs a simplified approach to address the radial heat conduction and axial heat convection phenomena. RAST-F adopts a single-phase formulation, neglecting boiling effects. Additionally, the code assumes constant pressure, eliminating the need to solve the momentum equation. Consequently, the flow problem in RAST-F involves solving the mass continuity and energy conservation equations. Polynomial constitutive relations are utilized to satisfy the closure requirements of the field equations at a specific pressure. Under these assumptions, RAST-F considers two main processes: radial heat conduction and heat convection in the coolant. The governing equations for these processes are carefully reviewed and implemented in the code to accurately represent the thermal behavior of the reactor system.

For TH feedback, the depletion solver and TH solver are independent in this framework, but they exchange variables that are input parameters for each code during neutronic calculation. The coupling scheme is shown in Fig. 1. After updating the XS based on the change in number density in fuel, the neutronic calculation is performed with the TH feedback. The nodal power distribution is computed by the RAST-F nodal diffusion code and passed to the TH1D solver [9]. The data transferred from TH solver to nodal solver includes node-wise distributions of TH properties such as fuel temperature, coolant temperature, and density. RAST-F uses these TH distributions to update the node-wise MG XSs, accounting for TH reactivity feedback. The process is iteratively repeated until certain convergence criteria are satisfied. It is important to note that in this coupling system, each fuel SA is treated as a single TH channel, with RAST-F coarse meshes determining the axial mesh size in TH1D. Because most fast reactor assemblies are enclosed by ducts, 1D flow is an acceptable presumption with no channel crossflow and ideal fluid mixing within each channel.

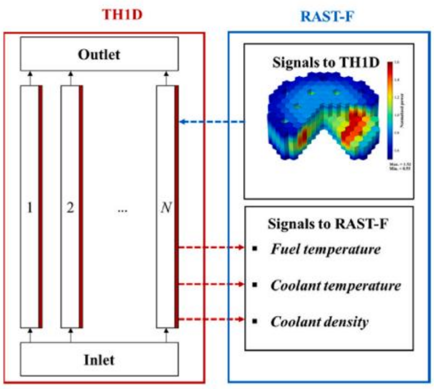

Fig. 1. RAST-F/TH1D internal coupling scheme.

3.2 XS generation

The Monte-Carlo code MCS [10] and ENDF/B-VII.0 nuclear data files are used to prepare multi-group XSs for the nodal calculation. These XSs are based on a 24-group energy structure. By employing a burnup chain that covers 221 actinide and fission products, MCS generates microscopic XSs for these 221 nuclides.

The multi-group XS library is parameterized in this study, considering the temperatures of both the fuel and coolant. The selected parameter range is designed to cover a wide spectrum of reactor conditions. For each type of fuel assembly (FA), a total of 9 separate branch calculations are conducted. Importantly, it's worth noting that this study does not factor in axial fuel rod expansion or radial diagrid expansion.

A single 2D fuel assembly (SA) model as in Fig. 2, applying reflective boundary conditions (BCs), is employed to perform fuel SA cross-section calculations. The XSs for non-multiplying zones, such as control rods and axial components situated distantly from the active core region, are computed using 2D supercell models as in Fig. 3. To accurately consider neutron leakage effects, the XSs for the radial reflector SA, along with its adjacent fuel SA, are generated through a radial reflector model as in Fig. 4. In this model, a vacuum boundary condition is applied to the right side of the system. Due to the extensive number of nuclides and the substantial quantity of histories required to attain precise microscopic XS, the computational runtime is anticipated to be longer than the standard scenario involving only macroscopic cross-sections. Non-fuel materials do not necessitate microscopic XS data or branch calculations. Additionally, considering that XSs in FRs are deemed to exhibit minimal burnup dependency, the XSs for all components are exclusively generated at the beginning-of-cycle (BOC).

Fig. 2. 2D single model for fuel region.

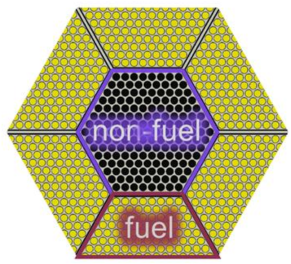

Fig. 3. 2D supercell model for non-fuel regions.

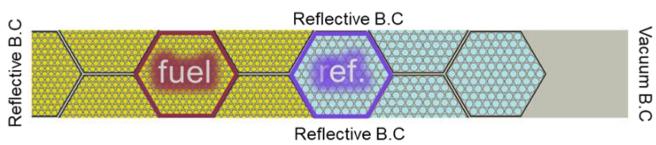

Fig. 4. 2D fuel-reflector for peripheral fuel and adjacent reflector regions.

4. Numerical results and discussion

The depletion calculation with TH feedback in the RAST-F code is compared to the calculation without TH to assess the impact of including TH effects on the accuracy and reliability of the depletion analysis. In the depletion analysis without TH feedback [1] in the RAST-F code, the fuel and coolant temperatures are set to specific values all times during calculation. In this case, the fuel temperature is set to 750 K, and the coolant temperature is set to 648 K. On the other hand, when considering TH feedback, the initial temperatures set for calculation is 623 K for both coolant and fuel temperature. The code calculates and updates the average fuel temperature and coolant temperature throughout the depletion analysis. With TH feedback, the resulting fuel average temperature is approximately 715 K, while the coolant temperature remains at approximately 648 K. Figure 5 presents the evolution of multiplication factor, fuel average temperature, and coolant average temperature with and without TH feedback. In the case with TH feedback, there is an increase in core multiplication factor of approximately 40 pcm due to the lower fuel average temperature compared to the case without TH feedback. However, there is no significant difference observed in the normalized radial and axial power between the TH1D and non-TH1D cases.

In the depletion analysis with TH1D feedback, the RAST-F results are compared with those obtained from the MCS/MARS-LBE [11] codes at the middle of cycle (MOC) and end of cycle (EOC) conditions. MARS-LBE is a specialized TH1D system code that has been developed as an extension of the MARS 3.1 release. This code is tailored to address the unique TH challenges and characteristics associated with LMFRs, providing a dedicated tool for the analysis and simulation of these advanced reactor systems. In this analysis, neutronic calculations were carried out using the MCS code with a 3D core model. Subsequently, the obtained results, including power and flux distributions, were employed in a THFB analysis conducted with the MARS-LBE code. The parameters of interest in the depletion analysis with TH1D feedback include the average values of centerline fuel temperature, cladding temperature, and coolant temperature, as well as the temperature of the hottest SA in the core. These parameters are compared with the corresponding values obtained from the MARS-LBE code and shown in Figs. 6 and 7. The difference between the depletion results obtained with TH1D feedback and those from the MARS-LBE code is found to be less than 1 % for all cases and at all points along the axial direction. This indicates a good agreement between the two codes in terms of the evaluated temperatures.

5. Conclusions

In this study, the depletion of the ANTS-100e core, coupled with TH feedback, was simulated using the RAST-F diffusion code. For the comprehensive 3D core simulation, homogenized XS were generated utilizing the MCS Monte Carlo code. Throughout the depletion analysis, key parameters such as the multiplication factor, as well as axial and radial power distribution, exhibited insignificant change between solutions with and without the inclusion of TH feedback. The RAST-F solutions are compared with those obtained from the MARS-LBE code at the MOC and EOC conditions. Notably, the incorporation of thermal-hydraulic feedback led to an enhanced alignment between the RAST-F and MARS-LBE systems. The RAST-F code exhibited remarkable accuracy in predicting variables such as fuel temperature feedback, coolant density, and overall thermal-hydraulic dynamics. This precision substantiated the code's capability in ensuring secure operational conditions. As future enhancements, it is eligible to consider refining the system by developing a cross-section library that adapts to burnup-dependent variations. Additionally, the implementation of a feedback mechanism to update the XSs during the simulation could contribute to a more robust and accurate predictive capability of the code.

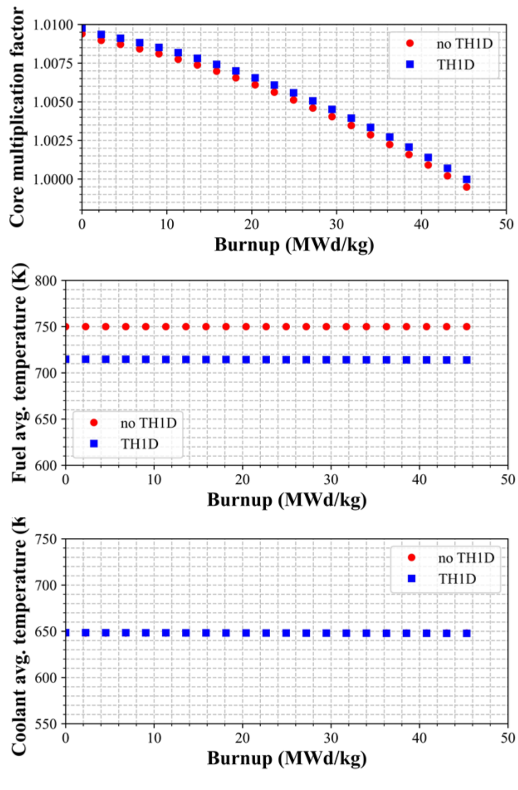

Fig. 5. Comparison of multiplication factor, fuel average temperature, and coolant average temperature with and without TH feedback in RAST-F.

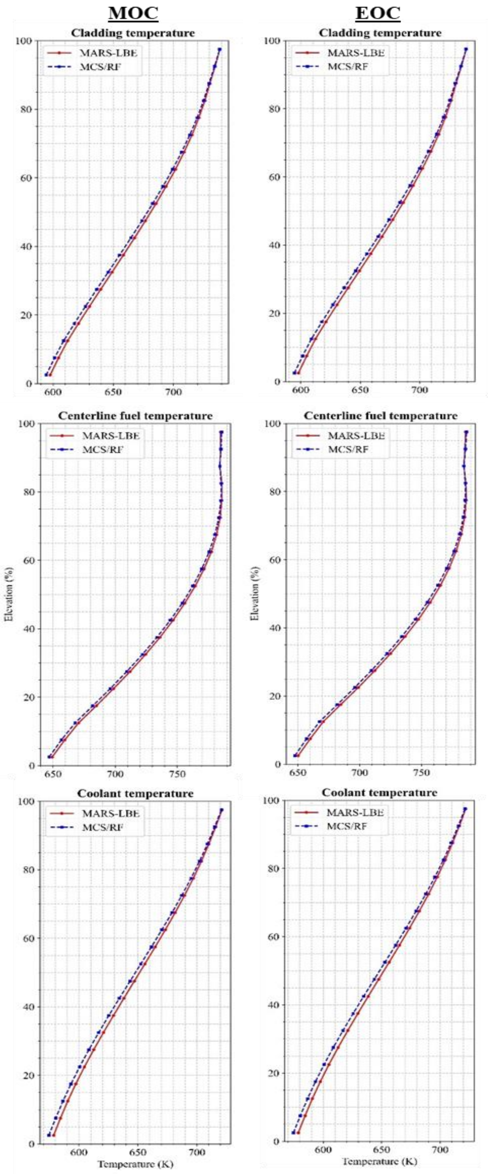

Fig. 6. Axial temperature distribution at MOC and EOC.

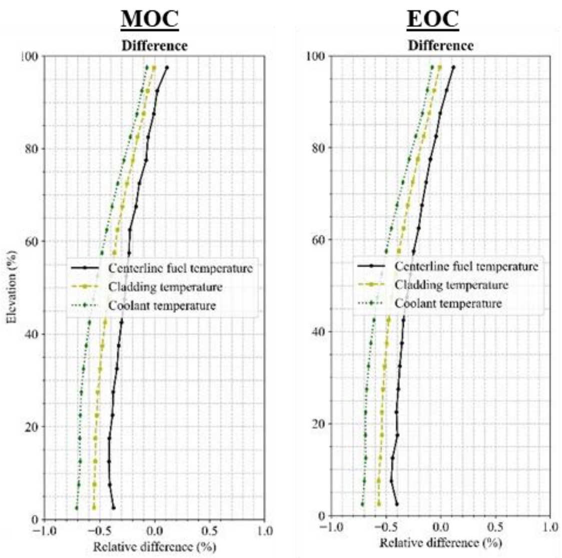

Fig. 7. Axial temperature comparison at MOC and EOC.

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