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STATUS OF FUEL AND THERMAL HYDRAULIC COUPLED ANALYSIS IN KOREA

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INTRODUCTION: The behavior of fuel and thermal-hydraulics is strongly interdependent during transient conditions. In particular, during a Loss of Coolant Accident (LOCA), the cladding temperature and internal rod pressure increase significantly due to the loss of effective heat removal by the coolant. This can lead to severe cladding deformation. If the cladding undergoes large deformation or rupture, it may obstruct the coolant flow, thereby degrading the reactor's coolability and potentially leading to a severe accident. Accordingly, it is critical to evaluate and quantify the consequences of design basis accidents such as LOCA with respect to established safety criteria. To address the complex interactions between fuel and thermal-hydraulic behavior in such scenarios, various multiphysics coupling studies have been conducted in Korea. Notably, integrated analysis systems such as MARS-KS/FRAPTRAN, CUPID/FRAPTRAN, CUPID/MERCURY, and MARS-KS/CUPID have been developed to simulate these coupled phenomena. This study provides an overview of the current status of multiphysics-coupled analysis research in Korea. Coupled analysis approaches have proven to be valuable tools for improving the understanding of fuel behavior under accident conditions. Since fuel behavior is highly sensitive to the prevailing thermal-hydraulic environment—and conversely, thermal-hydraulic behavior is influenced by fuel deformation (e.g., through changes in flow channel geometry and local heat generation)—a coupled analysis framework enables more accurate prediction by providing realistic boundary conditions for both domains.

1. IMPORTANCE OF FUEL/THERMAL HYDRAULIC COUPLED ANALYSIS

In the view of safety analysis, the study of fuel behavior under accidental conditions is a major concern. During a loss of coolant accident (LOCA), the temperature of the cladding and the rod internal pressure are increased due to a lack of heat removal by the coolant, which can eventually result in a large deformation of cladding. When the cladding ruptures, radioactive material stored in the fuel rod can be released into the primary circuit of the reactor. During a Loss of Coolant Accident (LOCA), significant deformation and rupture of the cladding can obstruct coolant flow, thereby degrading the reactor's coolability and potentially leading to a severe accident. It is therefore essential to evaluate and quantify the consequences of design basis accidents such as LOCA in accordance with safety criteria (e.g., Peak Cladding Temperature [PCT] and Equivalent Cladding Reacted [ECR]). To incorporate fuel behavior into safety analysis, previous studies have employed coupled simulations between thermal-hydraulic codes and fuel performance codes. The left image in Fig. 1 shows experimental results from the Multi-Rod Burst Test (MRBT) conducted at Oak Ridge National Laboratory (ORNL). In this experiment, a LOCA scenario was deliberately created to investigate the response of the fuel and flow channel. A significant blockage of the flow channel occurred due to severe fuel deformation, which consequently reduced the coolant's heat removal capability. The right graph in Fig. 1 presents simulation results obtained using the MARS-KS/FRAPTRAN coupled code system, based on different fuel deformation and flow blockage models. The results indicate that the inclusion of volume change and contact models significantly affects fuel safety parameters such as PCT and ECR.

Because fuel behavior is highly sensitive to the surrounding thermal-hydraulic environment—and vice versa, as thermal-hydraulic conditions are influenced by changes in the flow channel geometry and local heat generation caused by fuel deformation—a coupled analysis framework enables more accurate and realistic predictions by providing consistent boundary conditions for both domains.

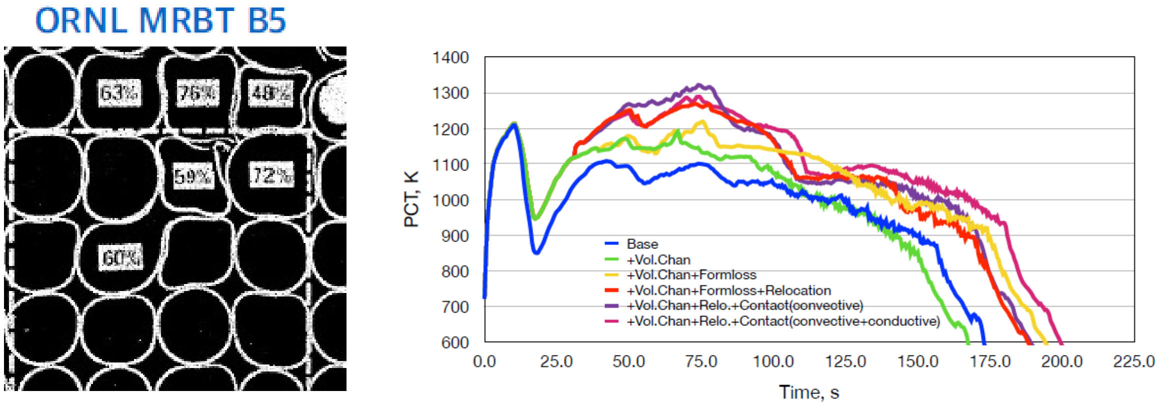

FIG. 1. Experimental results illustrating fuel behavior under accident conditions (left) [1], and simulation results based on different fuel/thermal-hydraulic coupled models (right) [2].

2. RESEARCH STATUS OF FUEL/THERMAL HYDRAULIC COUPLED ANALYSIS IN KOREA

2.1. MARS-KS/FRAPTRAN coupled analysis

In the context of fuel safety research, previous sensitivity studies exhibited limitations, as they were conducted under fixed thermal-hydraulic boundary conditions. This constraint stemmed from the FRAPTRAN code's inability to dynamically reflect changing thermal-hydraulic conditions during LOCA simulations. To overcome this limitation, the Korea Institute of Nuclear Safety (KINS) has developed the FAMILY code (FRAPTRAN and MARS-KS Integrated for Safety Analysis), which couples the MARS-KS thermal-hydraulic system code with the FRAPTRAN transient fuel performance code. MARS-KS is KINS's regulatory-grade audit tool for analyzing the thermal-hydraulic behavior of nuclear systems [3], while FRAPTRAN is the U.S. NRC's audit code for fuel performance under transient conditions [4]. Figure 2 (left) presents a schematic of the code integration structure. In the FAMILY framework, MARS-KS and FRAPTRAN exchange key coupling variables at every time step, enabling the consideration of fuel behavior in thermal-hydraulic analyses. Figure 2 (right) shows the evolution of cladding temperatures along the axial nodes, calculated using FAMILY with fuel relocation enabled. The analysis was performed for fuel with a burnup of 30 MWd/kgU. When fuel relocation was not considered, the Peak Cladding Temperatures (PCTs) during the blowdown and reflood phases were 1177.8 K and 1086.1 K, respectively. With fuel relocation activated, the blowdown PCT remained unchanged; however, the reflood PCT increased to 1133.7 K—approximately 48 K higher than the non-relocation case. This increase occurred approximately 63 seconds after the initiation of the LOCA and is clearly attributable to the effect of fuel relocation.

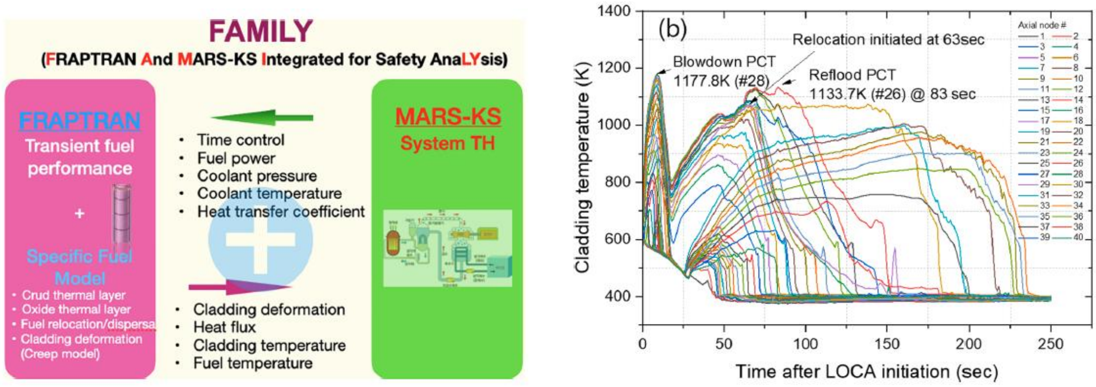

FIG. 2. Coupling variables in MARS-KS/FRAPTRAN (left) and cladding temperature during LBLOCA with fuel relocation modeled using FAMILY (right) [5]

2.2. CUPID/FRAPTRAN coupled analysis

KAERI has developed a reactor vessel thermal-hydraulics analysis module called CUPID-RV [6]. The primary purpose of CUPID-RV is to conduct reactor safety analyses and quantitatively evaluate safety margins under hypothetical accident scenarios. To obtain transient power distributions within the reactor core, CUPID-RV is coupled with the three-dimensional neutron kinetics code MASTER. For multiple fuel rod simulations, a mapping between the computational cells of CUPID-RV and FRAPTRAN is required. Since CUPID-RV includes its own heat structure model, coupling between the two codes is relatively straightforward. Although the CUPID-RV heat structure model was originally developed to simulate multiple fuel rods, it organizes its data in a one-dimensional array where the total number of elements equals the number of axial cells per rod multiplied by the number of rods. In contrast, FRAPTRAN was originally designed for single-rod analysis and therefore uses a one-dimensional array containing only the axial cells for a single rod. To enable coupling between CUPID-RV and FRAPTRAN for multiple rods, a two-dimensional array (e.g., a(1:nz, 1:Nrod)) must be implemented—where nz is the number of axial cells per rod, and Nrod is the number of rods, as illustrated in Fig. 3 (left). Additionally, the FRAPTRAN source code must be modified to accommodate multiple fuel rods. Instead of invoking CUPID-RV's internal heat structure model, CUPID-RV now calls the FRAPTRAN code repeatedly—once for each fuel rod to be analyzed.

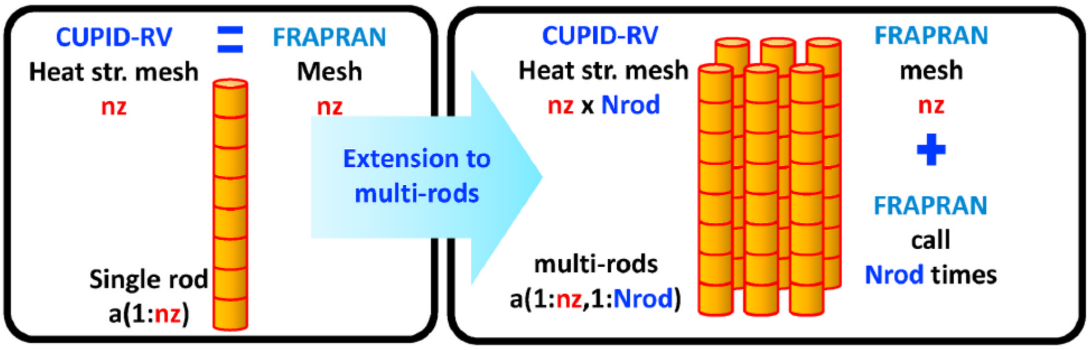

FIG. 3. Concept of multiple rods simulation in CUPID/FRAPTRAN [7]

2.3. CUPID/MERCURY coupled analysis

The CUPID/MERCURY coupling methodology is based on the existing CUPID/FRAPTRAN coupling framework. In addition, the fully coupled FRAPTRAN/MARS-KS system for evaluating fuel behavior during LOCA, and the MERCURY code, which already includes an interface compatible with MARS-KS using a similar methodology, provide the foundation for advanced multiphysics simulations. The CUPID/MERCURY code has been validated against experimental data. To investigate coupled thermo-mechanical and thermal-hydraulic phenomena under LBLOCA, the ICARUS (Integrated and Coupled Analysis of Reflood Using Fuel Simulator) test facility [8] was constructed at KAERI, as shown in Fig. 4 (left). This facility is designed to simulate cladding deformation under LBLOCA scenarios, including single-phase gas flow and reflooding phases. It is equipped with multiple measurement systems that enable real-time monitoring of cladding deformation and surface temperature distributions. A set of experimental data was acquired from the ICARUS facility under various reflooding conditions to characterize the coupled thermo-mechanical and thermal-hydraulic responses during LOCA. Given the importance of multiphysics coupling capability for accurate analysis of such phenomena, the CUPID/MERCURY code must be validated against this LOCA test dataset. Figure 4 (right) compares the simulation results with experimental data for upper cladding surface temperatures, using MARS-

KS, CUPID (stand-alone), CUPID/FRAPTRAN, and CUPID/MERCURY codes. For the test case, cladding rupture of the main heater rod was predicted to occur at 57 s, 69 s, and 95 s after power input by the MARS-KS, CUPID/FRAPTRAN, and CUPID/MERCURY simulations, respectively. All simulations predicted earlier rupture than the experimental observation at 167 s.

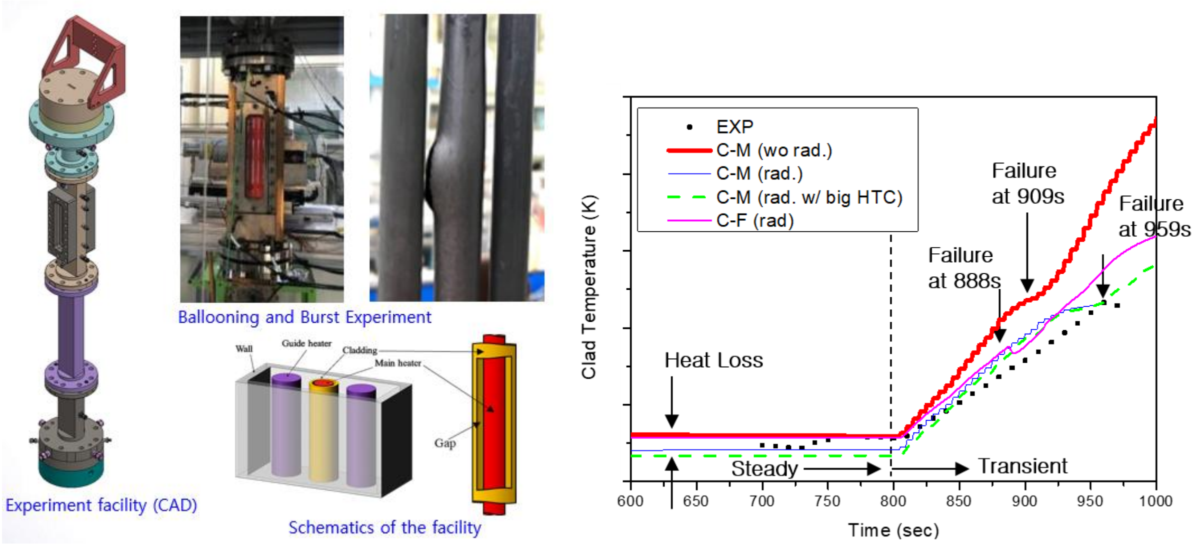

FIG. 4. Experimental result of ICARUS and Validation result of CUPID/MERCURY against ICARUS [9]

2.4. MARS-KS/MERCURY coupled analysis

The MARS-KS/MERCURY inline coupled code system has been developed to incorporate high-fidelity fuel models—such as Accident Tolerant Fuel (ATF)—into reactor safety analyses. ATF typically consists of complex, heterogeneous materials, including base cladding (e.g., Zircaloy), surface coatings, microcellular structures, and UO_2 fuel. To enable inline coupling between MARS-KS and MERCURY [10], a new coupling methodology was required due to differences in nodalization and time step size between the two codes—an issue not addressed in previous studies. To resolve the spatial mismatch, the elevation of MERCURY nodes was mapped onto the corresponding MARS-KS nodes. When MERCURY receives boundary conditions, a subroutine identifies the appropriate MARS-KS node based on elevation. Conversely, when MARS-KS obtains variables from MERCURY, these values are interpolated as a function of elevation to ensure consistency. To verify the proposed coupling methodology, a simplified benchmark problem—comprising a single heat structure and a single flow channel—was constructed. A comparative benchmark was performed among MARS-KS stand-alone, MARS-KS/FRAPTRAN, and MARS-KS/MERCURY for this problem. The verification results confirm that the proposed mapping approach functions correctly and enables accurate data exchange between codes [11]. As future work, conducting code-to-code benchmarks against other multiphysics simulation platforms will further support the validation of the coupled MARS-KS/MERCURY framework.

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