Validation analysis of the MERCURY code for Zry-4 DIMAT experiment

Dong-Hwa Lee *, ChangHwan Shin, Sung Uk Lee, Hyo Chan Kim
LWR Fuel Technology Research Division, Korea Atomic Energy Research Institute,
111 Daedeok-Daero 989 Beon-gil, Yuseong-gu, Daejeon, Korea
**Corresponding author: donghwalee@kaeri.re.kr*

Keywords : Validation, MERCURY, fuel performance, DIMAT experiment, Zry-4 cladding tube

1. Introduction

Nuclear fuel is loaded into the reactor core to generate heat and transfer the generated heat to the coolant. At the same time, it must not undergo damage or rupture under normal operating conditions, and its behavior must remain within regulatory limits under accident conditions.

To support the analysis and evaluation of nuclear fuel behavior under both normal/accident condition, various performance analysis codes based on the finite difference method (FDM) - such as FRAPCON [1], FRAPTRAN [2], and ROPER [3] - have been developed. More recently, in order to achieve more precise analysis, performance analysis codes based on the finite element method (FEM), which can simulate mesh deformation and analyze heterogeneous materials, have been developed. Representative FEM-based codes include BISON [4], developed by the Idaho National Laboratory (INL), and the MERCURY [5-7], developed by the Korea Atomic Energy Research Institute (KAERI).

MERCURY (Multi-dimensional Entire fuel Rod Code for Understanding Reaction Yield behaviors) V1.0 was developed in compliance with the Korea Atomic Energy Research Institute's software quality assurance (SQA) procedure, and its verification was completed with numerical examples [8]. As part of the validation process - intended to assess how accurately the code can reproduce physical phenomena - the MERCURY code was applied to simulate the Zry-4 DIMAT experiment.

The DIMAT (Deformation In-situ Measurement Apparatus by image-analysis Technique) experiment is designed to replicate the high-temperature expansion and rupture behavior of nuclear fuel cladding during a Loss-of-Coolant Accident (LOCA), one of the key reactor design basis accidents (DBAs). The deformation behavior of the Zry-4 cladding tube, including expansion and rupture under LOCA conditions, was measured using in-situ imaging techniques [9–10].

In this paper, the MERCURY code was used to simulate the same experiment, and its analysis results were compared against the experimental data to evaluate the code's predictive capability.

2. DIMAT experiment

As shown in Fig. 1, the DIMAT apparatus consists of an IR furnace capable of controlling the heating rate, a pressure control system for regulating the internal pressure of the specimen, and a camera for image capture. For accurate image analysis, the cladding specimen was coated in black. Argon gas (Ar) was injected inside cladding tube through the top of the specimen in order to establish internal pressure, while additional Ar gas was continuously supplied from the bottom of the furnace to maintain an inert environment around the specimen.

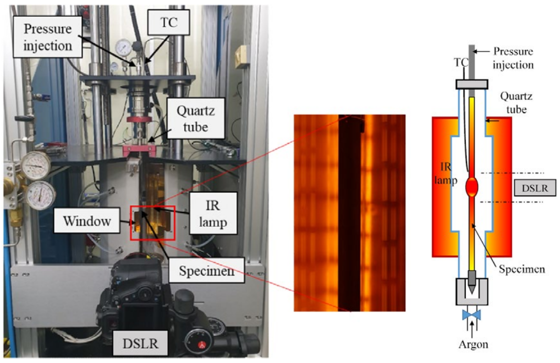

Fig. 1. DIMAT apparatus [9].

As illustrated in Fig. 2, the Zry-4 DIMAT tube burst test begins at room temperature, after which the cladding is heated at a rate of 5 °C/s up to the normal operating temperature of 300 °C. Once the target temperature is reached, the specimen is held in an isothermal condition for 300 seconds to achieve temperature stabilization. Following stabilization, argon gas is injected to pressurize the cladding, and after 60 seconds, transient heating begins and continues until burst occurs. Three heating rates (1K/s, 14K/s, and 28K/s) were selected, and three internal pressures (40 bar, 60 bar, and 80 bar) were applied, resulting in a total of 9 test cases [11-12].

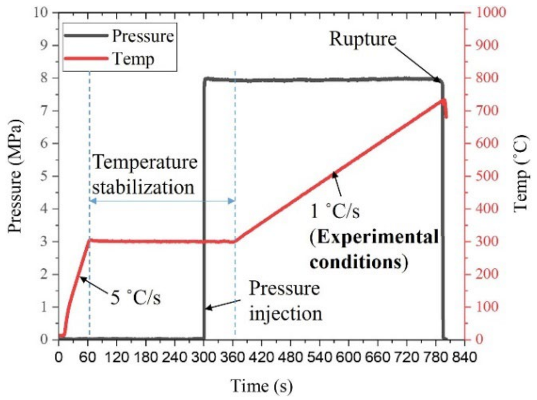

Fig. 2. Axial temperature distribution of the specimen [9].

3. Zry-4 DIMAT simulation with MERCURY

To depict the axial temperature gradient, the following fitting function, derived from experimental data, was used as axial temperature distribution:

$$y = -9.462 \times 10^{-10}x^4 + 9.089 \times 10^{-9}x^3 - 6.033 \times 10^{-6}x^2 - 5.515 \times 10^{-5}x + 1.004 \quad (1)$$

, where x is axial location in mm unit, and y is the normalized temperature. The temperatures applied as input conditions were 573K, 1573K, 14573K, and 28593K. These data were converted into a table-data input format and used as time-dependent heating boundary conditions. Since temperature boundary conditions were applied to all nodes, no separate thermal analysis was required, and only the mechanical analysis was performed.

The cladding tube analyzed had a length of 200mm, an outer diameter of 8.36mm, and a thickness of 0.57mm. The mesh dependency study was performed using 4 elements through the thickness and 50, 100, and 200 elements along the axial-direction, each consisting of 8-node elements.

4. Analysis result

Here we present one analysis result among 9 test cases. Fig. 3 shows the results of the experiment under 40bar internal pressure and 1K/s heat rate (P40_HR01). It was confirmed that increasing mesh density did not change the results, indicating no mesh dependency issue. The analysis graph exhibits a discontinuity (marked by a vertical dashed line), which corresponds to the transition temperature of 1085.15K, where the creep coefficient of Zry-4 shifts from the α phase to the α+β phase. This confirms that the observed discontinuity originates from the material property transition.

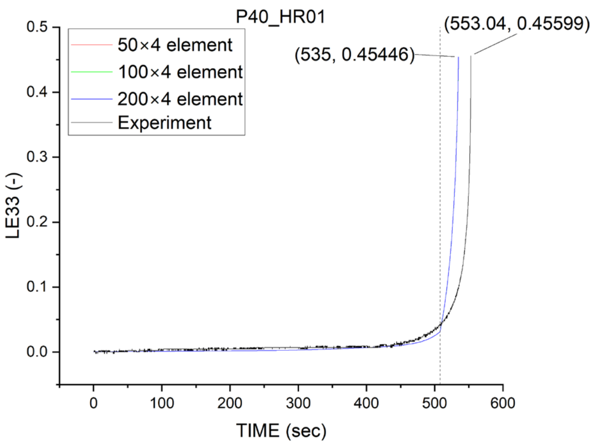

Fig. 3. Analysis and experimental results of P40_HR01.

5. Conclusions

The MERCURY, a finite element–based fuel performance code, was applied to analyze the Zry-4 DIMAT experiments for code validation. In this study, the heating experiments were modeled, and the cladding deformation and burst time were selected as figure of merit (FOM).

Mesh sensitivity was examined using 50, 100, and 200 axial elements, and the results showed negligible dependence on mesh size. Burst was defined as the point where cladding strain reached the failure criterion. The analyses reproduced experimental trends well, with burst consistently occurring at the tube center due to the imposed axial temperature gradient.

Discontinuities observed in strain–time curves corresponded to the 1085.15K transition, where Zry-4 creep properties change from the α phase to the α+β phase. These discontinuities were attributed to sudden property changes, suggesting that a continuous temperature-dependent creep model for Zircaloy would improve future simulations.

REFERENCES

[1] Geelhood, K. J., et al. FRAPCON-4.0: A Computer Code for the Calculation of Steady-State, Thermal-Mechanical Behavior of Oxide Fuel Rods for High Burnup, PNNL-19418, Vol.1 Rev.2, 2015.
[2] Geelhood, K. J., et al. FRAPTRAN-2.0: A Computer Code for the Transient Analysis of Oxide Fuel Rods, PNNL-19400, Vol.1 Rev2, 2016.
[3] Choi, J. M., et al. A Fuel Rod Performance Analysis and Design Code–ROPER. In: Korean Nuclear Society Spring Meeting. 2009.
[4] J. D. Hales et al. BISON Theory Manual The Equations Behind Nuclear Fuel Analysis. Idaho National Laboratory. Idaho Falls, Idaho, Oct. 2014.
[5] Kim, Hyochan, et al. Development of MERCURY for simulation of multidimensional fuel behavior for LOCA condition. Nuclear Engineering and Design, 2020, 369: 110853.
[6] Lee, Sung-Uk, et al. Validation of MERCURY code under LOCA condition with Out-of-pile and In-pile tests. Nuclear Engineering and Design, 2022, 392: 111775.
[7] 김효찬 외, MERCURY V1.0 이론 매뉴얼 (MERCURY V1.0 Theory Manual), KAERI/TR-10442/2024, 2024.
[8] 이동화, 이성욱, 김효찬, 신창환, 핵연료 열기계 유한요소해석 솔버 검증 방법 및 결과 (Verification of FEM based thermo-mechanical solving system for fuel performance code and its results), KAERI/TR-9835, 2023.
[9] 최경하, 김동현, 박동준, 신창환, 피복관 고온 변형의 이미지 분석을 통한 변형률 측정방법 개발 (Development of Strain Measurement Method by Image Analysis for Cladding Deformation), KAERI/TR-7930, 2019.
[10] 최경하, 신창환, 박동준, 김재용, 이미지 분석 기법을 활용한 피복관 고온변형 측정 및 평가 (Measurement and Evaluation of High-temperature Deformation of Fuel Cladding using image analysis technique), KAERI/TR-8338, 2020.
[11] G. Choi, D. Kim, C. Shin, J. Kim, B. Kim, In-situ deformation measurement of Zircaloy-4 cladding tube under various transient heating conditions using optical image analysis, Nuclear Engineering and Design, vol. 370, 110859, 2020.
[12] G. Choi, C. Shin, J. Kim, B. Kim, Circumferential Steady-state creep test and analysis of Zircaloy-4 fuel cladding, Nuclear Engineering and Technology, vol. 53, pp. 2312-2322, 2021.