The Validation of the Coupled CUPID/FRAPTRAN Code Using HALDEN and ICARUS Experiments

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1. Introduction

After Fukusima, the needs for fuel performance and thermal-hydraulics coupled analysis are increasing due to the change of safety criteria such as the design extension condition (DEC) and high burn-up fuel safety. Thus, the coupled codes that can simulate the nuclear fuel behavior by coupling thermo-mechanical and thermal-hydraulic phenomena have been developed based on one-dimensional system analysis code and they includes MARS/FRAPTRAN[1] and SPACE/FRAPTRAN [2].

Recently, KAERI has been developed the multi-scale and multi-physics coupled MASTER/CUPID/MARS code which aims at the rod-scale full core safety analyses [3]. The PWR MSLB application of the coupled code indicates that the rod-scale full core safety analyses can be realized in the current state of the art. Thereafter, the FRAPTRAN was adopted as a member of the coupled code to simulate the fuel performance during the safety analyses. In this study, the validation calculations of the coupled CUPID/FRAPTRAN code [4] were conducted using the OECD-Halden IFA-650.5 test[5] and the ICARUS-RT-20-02 test[6].

2. Methods and Results

2.1 OECD-Halden IFA-650.5 test

OECD-Halden IFA-650.5 test is for a high burnup(83 MWD/kgU and 65 μ m oxidation layer) nuclear fuel rod (48.0 cm long and 1.075 cm in diameter) in the pressure vessel (97.1 cm long and 4 cm in diameter). He and Ar gases were filled in the fuel rod at 40 bar. A cylindrical electrical heater (51.8 cm long and 2.62 cm in diameter) was equipped between the fuel rod and the vessel to simulate the role of the neighboring fuel rod. The powers of the fuel rod and the heater were 24 W/cm with 1.05 peaking and the 17 W/cm, respectively.

Initially, the coolant water of 6.6 MPa, 511 K was injected with 0.23 m/s, and the test section being closed, the coolant is blew down into discharge tank of 0.2 MPa. The two powers were decreased at 1.1 W/cm and 0 W/cm at 366 s after the blowdown. The water spray was injected to provide the oxidation environment for the fuel cladding with the interval of 20 s and duration of 0.5 s from 138 s and 418.15 s after the blowdown. The cladding and the heater temperature at 10 cm from the bottom were measured during this test.

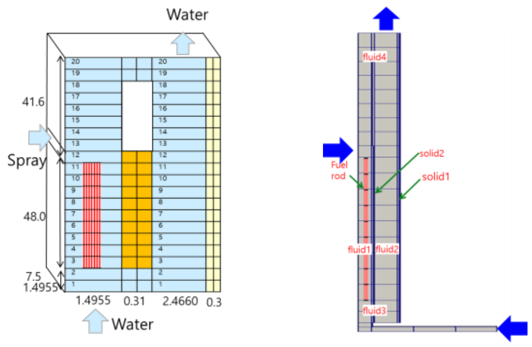
2.2 ICARUS-RT-20-02 test.

ICARUS-RT-20-02 test is for an artificial fresh (0 MWd/kgU and 0 μ m oxidation layer) nuclear fuel rod (1.0225 m long and 9.5 mm in diameter), in the rectangular channel (1.0225 m long and 41.9x16.2 mm). The artificial fuel rod consisted of Zr-4 cladding and the NCH1 electrical heater. Two neighboring heater (1.0225 m long and 7.5 mm in diameter) consisted of only NCH1 electrical heater.

The powers of the main heater and the two heaters were 346 W/m and 510 W/m. The coolant mixture gas (steam 50% and Ar 50%) of 0.121 MPa and 373.15 K was injected with 3.961 m/s. At first the power and the coolant flow were at the given level and then, the two powers were increased up to 5.7 times of initial powers. The coolant gas temperatures at 63 cm, 71 cm, and 79 cm from the bottom and the cladding temperatures at 63 cm and 79 cm were measured during the test.

2.3 Calculation of OECD-Halden IFA-650.5 test

The one-dimensional mesh concept and the calculation mesh for OECD-Halden IFA-650.5 test are presented in the Fig. 1. The cylindrical heater, the pressure vessel, and the two flow path are modelled by 111 1-dimensional cells (51 fluid cell and 60 solid cells). The fuel rod was modelled 9 porous media cells duplicated with 9 fluid cells as shown in Fig.1. With this mesh, OECD-Halden IFA-650.5 test was simulated by the condition given in the Section 2.1.



(1) Mesh concept (2) Calculation mesh
Fig. 1. Mesh concept and calculation mesh for OECD-Halden IFA-650.5 test.

The calculated cladding and electrical heater temperatures are compared to the measured ones in Fig.2, where TCC1 and TCH1 indicate cladding and heater, and CUPID, exp, CUPID/FRAPTRAN indicate

CUPID standalone calculations, experiments, and CUPID/FRAPTRAN coupled calculations. The overall temperature behaviors of the cladding and the heater including the temperature increase due to the blowdown at 100 s and the temperature decrease due to the power loss at 466 s are well predicted by the two calculations.

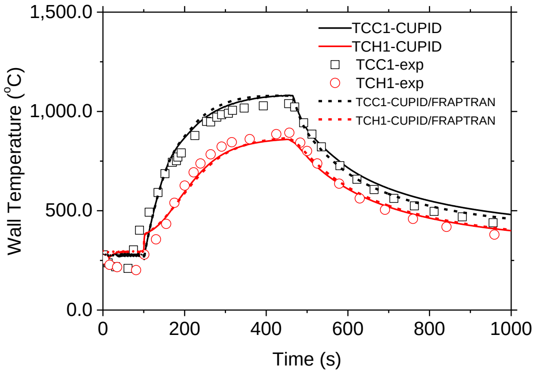
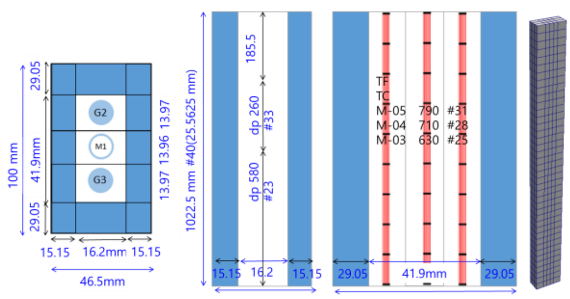


Fig. 2. Comparison of the cladding and the electrical heater temperatures.

2.4 Calculation of ICARUS-RT-20-02 test

The mesh concept and the calculation mesh for ICARUS-RT-20-02 test are presented in the Fig. 3. The fluid flow path and the solid channel wall are by 15x40 cells (120 fluid cell and 480 solid cells). The three heater rods were modelled 120 porous media cells duplicated with 120 fluid cells. With this mesh, ICARUS-RT-20-02 test was simulated by the condition given in the Section 2.2. To impose loading condition of fuel rod in FRAPTRAN, measured rod internal pressure was applied into loading condition to minimize uncertainty of multi-physic calculation. FRAPTRAN input file includes pressure history along experimental time.



(1) Ground plan (2) Side view (3) Calculation mesh

Fig. 3. Mesh concept and calculation mesh for ICARUS-RT-20-02 test.

The calculated main heater rod heater temperatures at two measuring points are compared to the measured ones in Fig.4, where 03 and 05 indicate the measuring points, and CUPID, exp, CUPID/FRAPTRAN indicate CUPID standalone calculations, experiments, and CUPID/FRAPTRAN coupled calculations. The overall temperature behaviors of the cladding and the heater including the steady state temperature at 0 s and the temperature increase due to the power increase up to 5.7 times at 150 s are well predicted by the two calculations. In CUPID/FRAPTRAN calculation, the wiggles of the main heater temperatures at 96 s indicates that the heat rod was deformed and burst at 96 s. The burst at 96 s occurred at 50s earlier than the experimental result, in which the burst occurred at 150 s. We must note that the deformation and burst model of FRAPTRAN was designed considering the conservation as a nuclear safety analysis code.

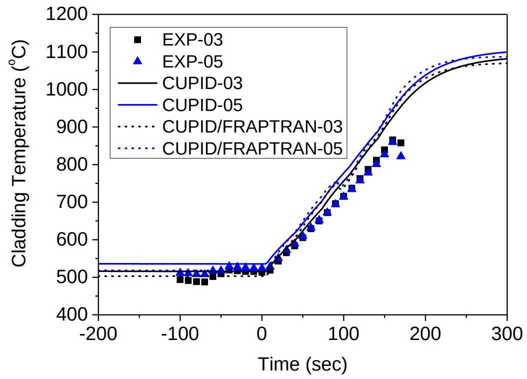


Fig. 4. Comparison of the main heater temperatures at two measuring points.

Figure 5 shows comparison amount of fuel deformation between simulation data by the coupled code and experimental data.

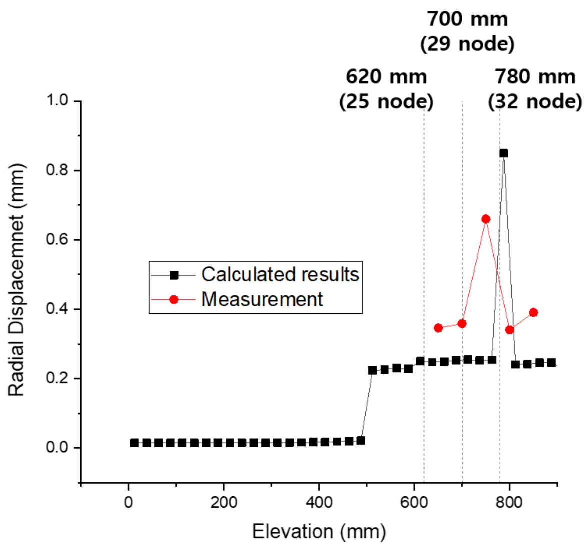


Fig. 5. Comparison of radial displacement of calculated results and experimental results

In terms of burst elevation, prediction by CUPID/FRAPTRAN is very close to experimental result. Typically, burst location is strongly related to temperature profile along axial direction during experiment. Therefore, calculated results shows a good agreement against experimental in terms of temperature profile that CUPUD standalone cannot describe. As well as, amount of deformation in experiment is slightly smaller than that of calculation. Due to limitation of ballooning model in FRAPTRAN, amount of deformation is smaller and burst time is earlier compared to single effect experimental data.

3. Conclusions

In this paper, the validation calculations of the coupled CUPID/FRAPTRAN are discussed. Two international and domestic LBLOCA tests of the OECD-Halden IFA-650.5 and the ICARUS-RT-20-02 were simulated using CUPID and CUPID/FRAPTRAN. The calculations indicate that the coupled CUPID/FRAPTRAN code as well as CUPID standalone code has a capability to simulate the thermal-hydraulic behaviors of the nuclear fuel rod during the LBLOCA. In addition, the coupled CUPID/FRAPTRAN code can provide the thermo-mechanical information on the deformation and the burst of the nuclear fuel rod during the LBLOCA. Thus, the FRAPTRAN can be adopted a member of the multi-scale and multi-physics coupled MASTER/CUPID/MARS and the highly reliable safety analysis can be evaluated using the coupled FRAPTRAN/MASTER/CUPID/MARS code.

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