Transactions of the Korean Nuclear Society Autumn Meeting
Yeosu, Korea, October 25-26, 2018

Validation of SPACE-FRAPTRAN Coupled Code using IFA-650.5 Experiment

Seung Wook Lee*, Hyo Chan Kim and Kyung-Doo Kim
Korea Atomic Energy Research Institute, 111 Daedeok-Daero 989 Beon-gil, Yuseong-gu, Daejeon, Korea
**Corresponding author: nuclist@kaeri.re.kr*

1. Introduction

In the previous study [1], a system analysis code, SPACE [2] was coupled with a fuel transient analysis code, FRAPTRAN [3] using a dynamic link library (DLL) scheme. In this coupling scheme, FRAPTRAN handles the heat conduction model including fuel deformation of single fuel rod and, SPACE deals with the calculation of all hydraulic cells and heat structures except for the fuel rod coupled with FRAPTRAN. This coupled code has been developed for coping with the change of auditing requirements for the emergency core cooling system (ECCS). In order to validate the SPACE-FRAPTRAN coupled code, several OECD-Halden IFA-650 experiments [4] have been simulated by using coupled code and present study will introduce the simulation results for IFA-650.5 experiment [5] which was a LOCA (loss of coolant accident) test using a high burnup fuel.

2. Overview of IFA-650.5 Experiment

A high burnup fuel rod was used in the OECD-Halden IFA-650.5 and located in a standard high-pressure flask in the test rig, which was connected to a high-pressure heavy water loop and a blowdown system of Halden reactor. The fuel rod was surrounded by an electrical heater inside the flask. The heater is a kind of a flow separator, which divides the flow channel into a central channel surrounding the fuel rod, and an outer annulus. In addition, the heater also has a function of a simulator of adjacent fuel rods in the reactor core, so that cladding temperature of fuel rod is affected by both rod and heater powers. An overall layout of the IFA-650 test loop is shown in Fig. 1.

In prior to the LOCA test, the outer loop was isolated from test rig, and after a few minutes with natural circulation in the rig, the LOCA was initiated by opening the valves in the pipe connected to a blowdown tank. The initial system pressure was about 70 bar and the pressure in the blowdown tank was about 2 bar. Rod power was about 24 W/cm including decay heat and the axial power shape was nearly flat with a peaking factor of 1.05. The initial heater power was about 17 W/cm and controlled to make the peak cladding temperature close to target of 1100 ℃ during the test. Detailed information of the fuel rod of IFA-650.5 are presented in Table 1.

3. SPACE and FRAPTRAN Modeling

3.1 SPACE Modeling

An overall layout of SPACE modeling for IFA-650.5 is presented in Fig. 2. As for the fluid system, the inlet flow from TFBC (Temporal Face Boundary Condition) of C100 enters lower plenum (C110) and is spilt into two channels for fuel rod and heater through cross flow (C115). Both channels are mixed at the top of upper plenum (C160) and finally exit to the outlet TFBC (C300) via the outlet pipeline (C200). Active fuel region and heater region are divided into 9 axial nodes. Flow and pressure boundary condition are applied to inlet and outlet TFBC, respectively. Blowdown valve to simulate the LOCA and spray injection are modeled as TFBC-999 and TFBC-555, respectively. For the heat structures, there are three heat structure components to simulate a fuel rod (H130), electric heater (H140) and pressure flask (H150), respectively. It was pointed out that the radiation heat transfer played a very important role in behavior of the cladding temperature in IFA-650 test [6,7], therefore, a radiation enclosure model is applied into the facing surface of the fuel rod, heater and flask. A convective heat transfer condition is applied to the outer surface of the flask and, the heat transfer coefficient and bulk fluid temperature are assumed to be 3000 W/m^2-K and 235 ℃ which is the coolant temperature of heavy water in Halden reactor. A schematic diagram of the test rig for SPACE is presented in Fig. 2.

3.2 FRAPTRAN Modeling

As mentioned earlier, high burnup fuel was used in the test, so that FRAPCON [8] calculation is required to achieve the initial condition of FRAPTRAN input. Burnup calculation using FRAPCON was performed according to the power and burnup history as shown in Fig. 3. In addition, default option for plenum temperature, ‘balon2’ option for fuel deformation and Cathcart-Pawel model for high temperature oxidation were applied for FRAPTRAN simulation.

4. Simulation Results

4.1 Clad and Heater Temperature

Comparison of clad and heater temperature between coupled code and experiment are shown in Fig. 4. As shown in the figure, clad and heater temperature show a very good agreement with the experimental results. This good agreement resulted from not the fuel deformation model but the radiation enclosure model. Fig. 5 is a simulation results of SPACE standalone calculation in which the fuel deformation model was not used but the same radiation enclosure model as that of coupled calculation was applied. Comparing Fig. 4 and Fig. 5, it is found that there is little difference between the simulation results. Therefore, it can be induced that the fuel deformation model has little effect on the clad temperature in IFA-650 tests.

4.2 Rod Internal Pressure

Fig. 6 shows a comparison of predicted and experimental rod internal pressure. Fuel clad was ruptured at 155 s in the simulation and at 178 s in the experiment. After the rupture, the rod internal pressure decreased very slowly in the experiment, whereas predicted one drastically fell off to the level of coolant pressure. This discrepancy is caused by high content of hydrogen in the clad. Due to the high content of hydrogen, the clad became brittle and the rupture area was very small. Finally, the rod internal pressure decreased slowly due to a small rupture area. On the other hand, FRPATRAN doesn't consider the rupture size and determines whether rupture occurs or not. In FRAPTRAN, rod internal pressure is assumed to be the same as fluid pressure when clad rupture occurs.

4.3 Circumferential Strain

Circumferential strain cannot not be compared with experimental data because there is no experimental data for it. Fig. 7 shows the predicted circumferential strains along the axial nodes. The maximum strain occurs at the rupture location and its value is about 17%.

5. Conclusions

From the simulation results of SPACE-FRAPTRAN coupled system against Halden IFA-650.5 test, the cladding and heater temperatures predicted by code agreed well with experimental data. In addition, it was revealed that the most important factor for the cladding and heater temperature in the IFA-650 test is the surface-to-surface radiation heat flux and the fuel model had little effects on them. Therefore, it is required that surface-to-surface radiation enclosure model should be simulated appropriately for the Halden IFA-650 test to predict the proper behavior of the cladding temperature.

Acknowledgement

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning(KETEP) and the Ministry of Trade, Industry & Energy(MOTIE) of the Republic of Korea. (No. 20161510101840)

REFERENCES

[1] Seung Wook Lee et al., Coupled Calculation of SPACE and FRAPTRAN, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 17-18, 2018.

[2] Sang Jun Ha et al., Development of the SPACE Code for Nuclear Power Plants, Nuclear Engineering and Technology, Vol. 43, No. 1, pp. 45-62, Feb. 2011.

[3] K. J. Geelhood et al., FRAPTRAN-2.0: A Computer Code for the Transient Analysis of Oxide Fuel Rods, PNNL-19400, Vol.1, Rev.2, May 2016.

[4] V. Lestinen et al., LOCA testing at Halden, Trial runs in IFA-650, Nuclear Safety Research Conference, Oct. 20-22, 2003, Washington.

[5] Laura Kekkonen, LOCA TESTING AT HALDEN, THE PWR EXPERIMENT IFA-650.5, HWR-839, OECD HALDEN REACTOR PROJECT, Jan. 2007.

[6] Tong Soo Choi, Code Assessment against IFA-650 LOCA Tests, S06NX08-F-1-TR-041 Rev.0, KEPCO-NF, July 2016.

[7] Won Ho Kim et al., Simulation of IFA-650.10 Test Using a Modified Version of RELAP5/MOD3.1, Transactions of the Korean Nuclear Society Autumn Meeting Gyeongju, Korea, October 27-28, 2016.

[8] K. J. Geelhood 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-19148, Vol.1, Rev.2, Sep. 2015.

Table I: Fuel Rod Information of IFA-650.5

Item	Value
Active Length (mm)	480
Rod Diameter (mm)	10.73
Pellet Diameter (mm)	9.144
Pellet height (mm)	11.0
Pellet dish depth (mm)	0.28
Pellet surface roughness (mm)	0.002
Cladding Type	Zr-4
Cladding surface roughness (mm)	0.0005
Cladding thickness (mm)	0.721
Average ZrO_2 thickness (μm)	65
Total plenum volume (m^3)	1.5E-5
Fill pressure (bar at RT)	40
Gas composition	He 10%, Ar 90%
Average burnup (MWd/kgU)	83

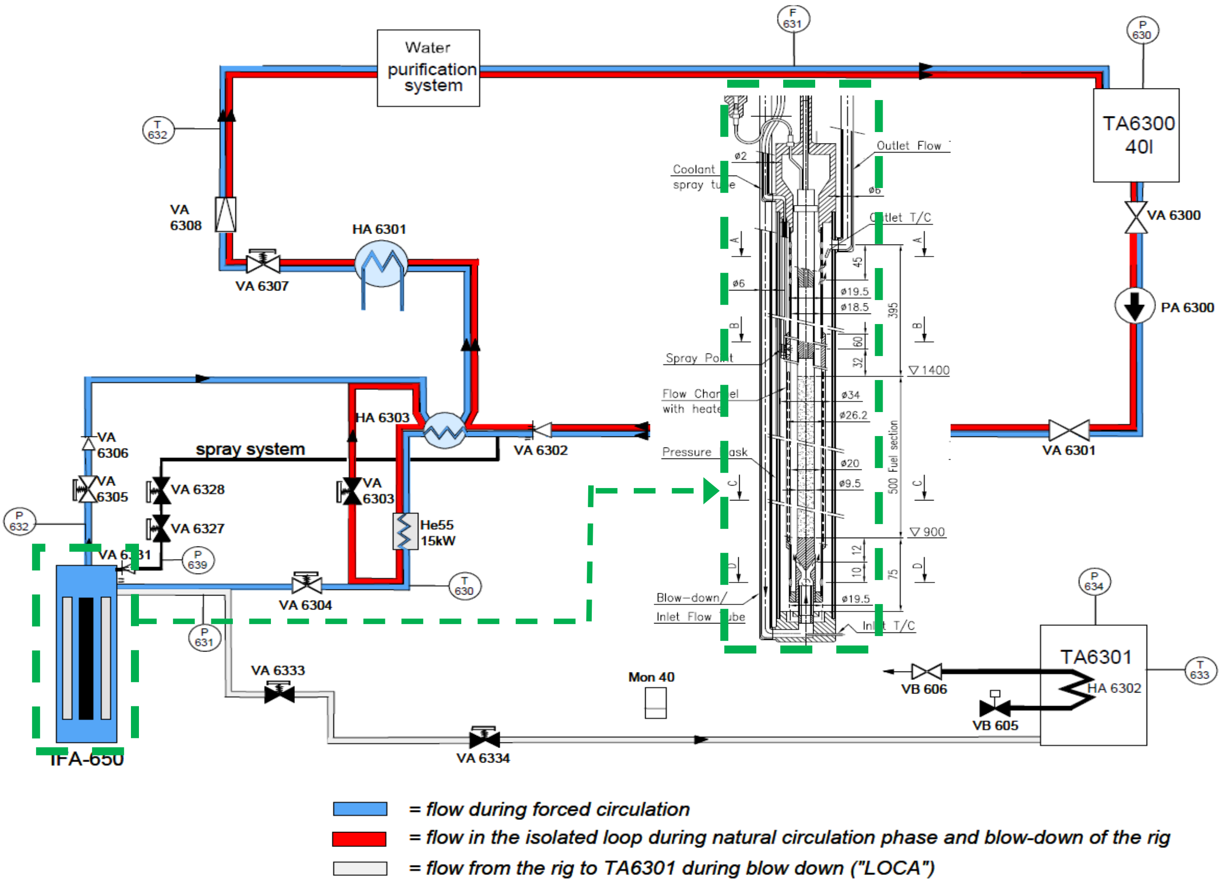

Fig. 1. Overall layout of the loop for IFA-650.5

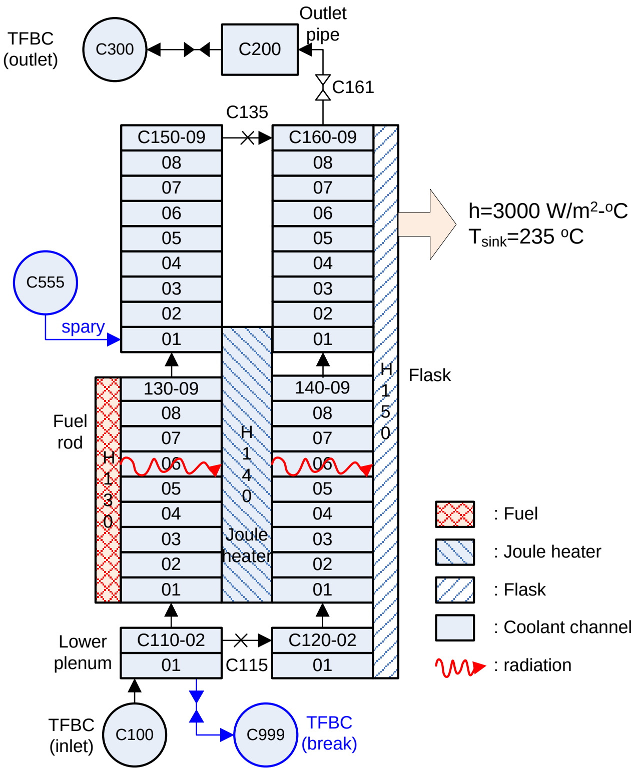

Fig. 2. SPACE nodalization for test rig

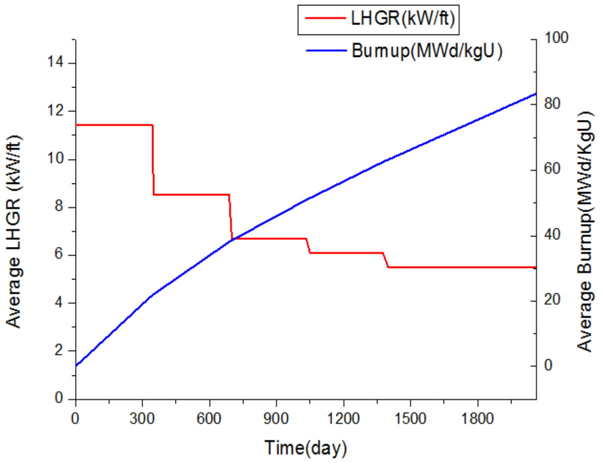

Fig. 3. Power and burnup history of fuel rod

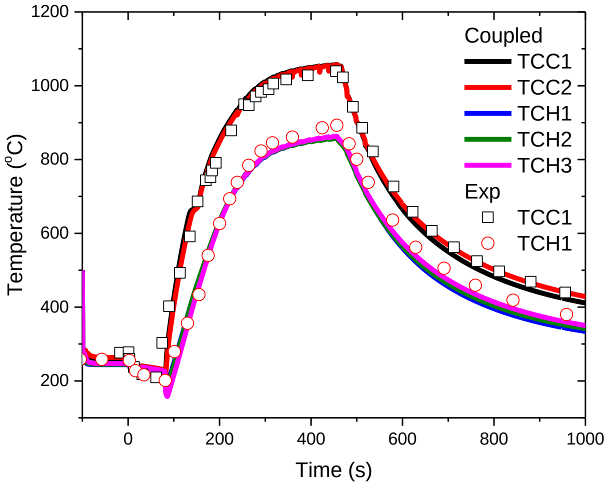

Fig. 4. Clad and heater temperature (coupled)

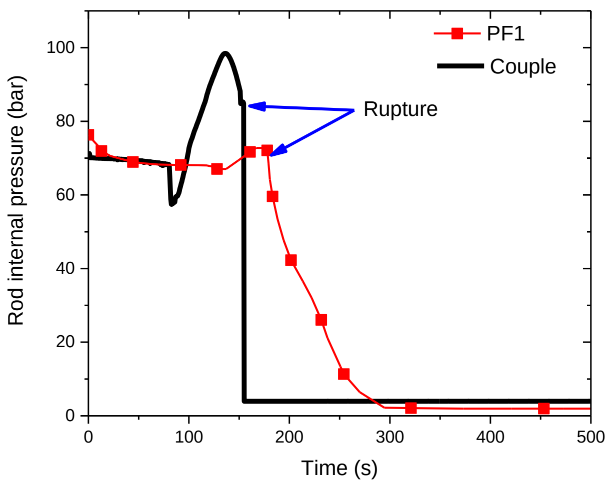

Fig. 6. Rod internal pressure

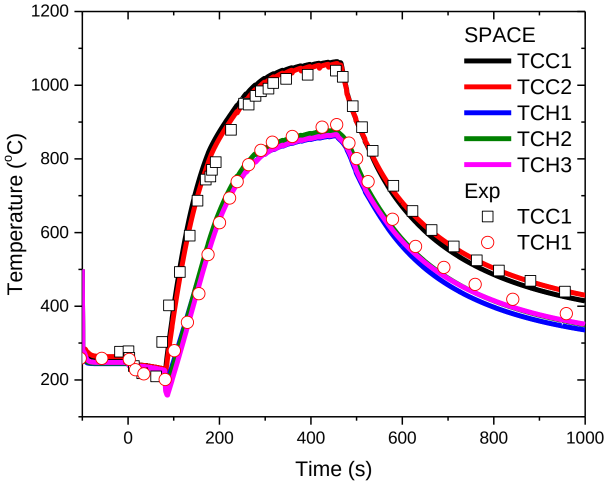

Fig. 5. Clad and heater temperature (standalone)

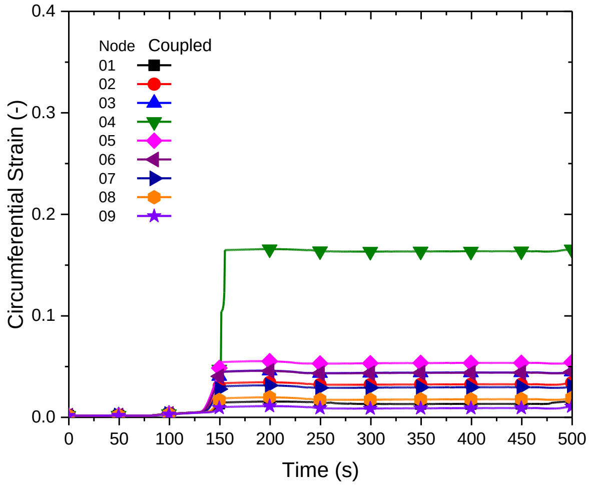

Fig. 7. Circumferential strain