Preliminary Tests for Fuel Clad Behavior under LOCA using Multi Physics Coupled Experimental Facility ICARUS

Jongrok Kim*, Jae Bong Lee, Hyeokjun Byeon, Kihwan Kim, Hae Seob Choi, Jong-Kuk Park, Young-Jung Youn, Sang-Ki Moon
Korea Atomic Energy Research Institute, Daedeok-Daero 989-111, Yuseong-Gu, Daejeon, Republic of Koera
**Corresponding author: jongrok@kaeri.re.kr*

1. Introduction

A safety criteria and licensing of nuclear power plant are changing because of the adaptation of the design extended condition (DEC) and high burn-up fuel safety issues. For this movement, multi-physics coupled safety analysis has been required. One of activities related to multi-physics coupled safety analysis is a development of coupled safety analysis code system for the thermal hydraulic safety analysis code and thermal mechanical safety analysis code. Currently, the experimental data to validate the coupled safety code system is not enough. Therefore, coupled experiments for thermal hydraulics and thermal mechanics are required to support this activity and to assess new safety criteria.

An experimental facility named ICARUS (Integrated and Coupled Analysis of Reflood Using fuel Simulator) was developed for multi-physics coupled phenomena during loss of coolant accident (LOCA) at KAERI (Korea Atomic Energy Research Institute) [1-2]. Fig. 1 shows picture of ICARUS. This facility can simulate deformation of fuel cladding under LOCA and reflood condition. There were several previous experimental research for this topic [3]. However, most previous facilities measured cladding geometry after end of test. So, the important design concept of ICARUS was to measure the thermal hydraulic and thermal mechanic parameters in real time during transient test. For this aim, several measuring systems to measure parameters related to thermal hydraulics and thermal mechanics were installed. These systems measure temperature, pressure and cladding geometry in real time during a transient experiment. Detail information of measurement system is described in a reference [4].

Fig. 1. Picture of ICARUS

In this paper, two preliminary experimental results for cladding ballooning and burst using ICARUS are presented and discussed.

2. Experimental Facility

Fig. 2 shows a cross section of ICARUS test section. Blue square block is a test section wall. Working fluids are deionized water, steam, argon, and helium. The maximum pressure of test section is 1.0 MPa. The maximum temperature of fluid at entrance is 180 °C. The test section has sight window to measure clad surface temperature and clad geometry using IR pyrometer and laser displacement sensor, respectively.

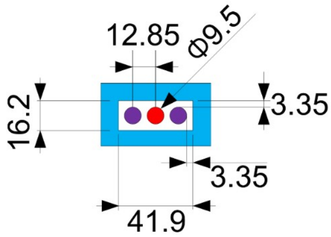


Fig. 2. Cross section of test section (unit: mm)

The test section has one main heater (red circle) and two guide heaters (violet circles). The main heater was designed to simulate cladding deformation. Two guide heaters were designed to make thermal boundary around the main heater. Each heaters has 1 m heated length and 6 thermocouples to measure heater surface temperature. The maximum temperature of main heater is 1150 °C and the maximum temperature of guide heater is 1200 °C. A prediction of a position where cladding will be deformed or burst is very difficult. So, the heaters were designed with power peak to make a deformation or burst at the sight window region because IR pyrometer and laser displacement sensor can measure through sight window. The designed power distribution is summarized on Table I.

Table I: Power distribution of main and guide heater

Step No. (-)	Starting elevation (mm)	End elevation (mm)	Power factor (-)	Grid position (mm)
1	0	500	0.892	-
2	500	600	1.094	500
3	600	800	1.231	-
4	800	900	1.094	-
5	900	1000	0.948	900

The main heater is assembled with a clad as Fig. 3. The outer diameter of main heater is 7.5 mm. The outer diameter and inner diameter of clad are 9.5 mm and 8.3 mm, respectively. So, the inner gap between heater and clad is 0.4 mm. The gap is filled with helium gas and designed maximum gap pressure is 12 MPa. If the main heater and clad are heated up, the mechanical properties of clad are changed and inner pressure is increased by thermal expansion of helium gas. When the temperatures, mechanical properties, and inner pressure become certain conditions, the clad balloons or bursts. To monitor these parameters, thermocouples, pressure transmitters, flowmeters, and IR pyrometer were installed.

Each guide heaters has 9.5 mm outer diameter, 6 thermocouples on the heater surface, and power distribution as Table I.

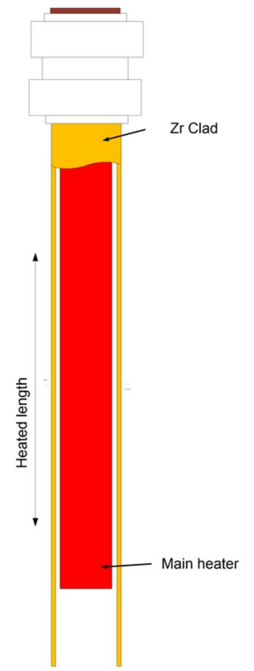


Fig. 3. Assembled heater and cladding

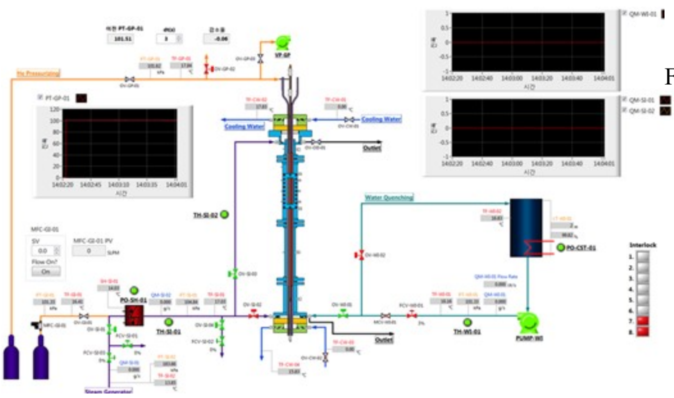


Fig. 4. Control panel for fluids supply system.

A fluids supply system was installed to supply steam, water, and gases. Thermal hydraulic parameters of fluids are controlled by this system and monitored using pressure transmitters, thermocouples, and flow meters. Fig. 4 is control panel for fluids supply system.

3. Experimental Result

A ballooning test and burst test was performed as preliminary test of ICARUS. Pressure of test section was ambient pressure for two tests.

3.1 Ballooning Test

A Ballooning test was performed to simulate LOCA. During the test, electric power was applied with 4 steps as Fig. 5 to avoid fast temperature increasing because high temperature increasing rate may occur sudden change of material property and disturb test result.

Fig. 6 shows clad surface temperatures during transient. The elevation of lower TC was 620 mm and upper TC was 780 mm from bottom of heated length. Before reflood, temperatures increased as Fig. 6. After reflood, steam that was produced at quench front cooled the clad. The temperature decreasing times for both TC were similar because steam velocity was fast and time difference was very short. And then the quench front moved up and passed TCs. When the quench front passed TC, temperature decreased sharply. In the case of quench time, there was time difference between two TCs because moving velocity of quench front was slower than steam.

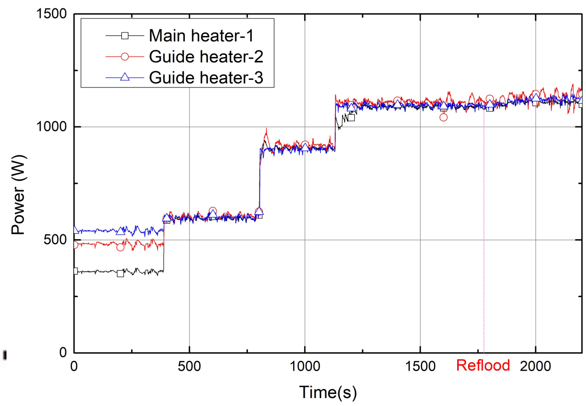


Fig. 5. Applied electric power during reflood test

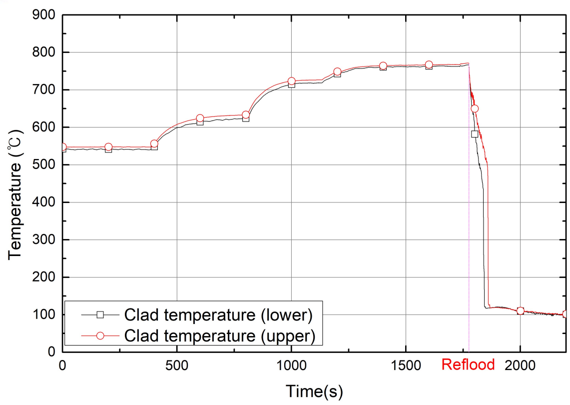


Fig. 6. Clad temperature during reflood test

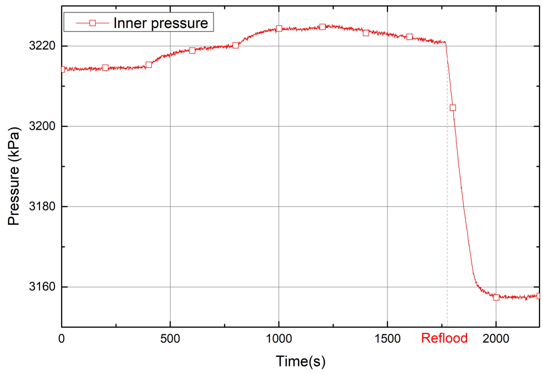
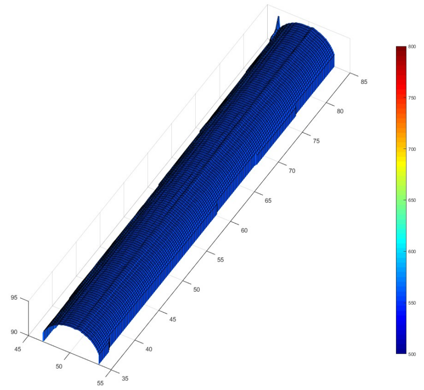
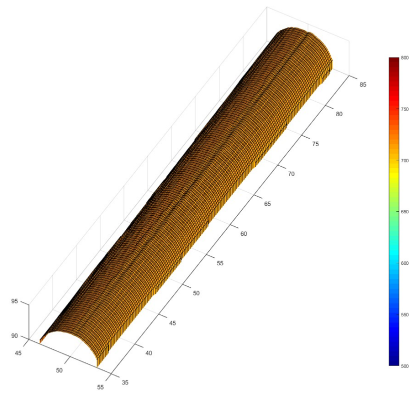


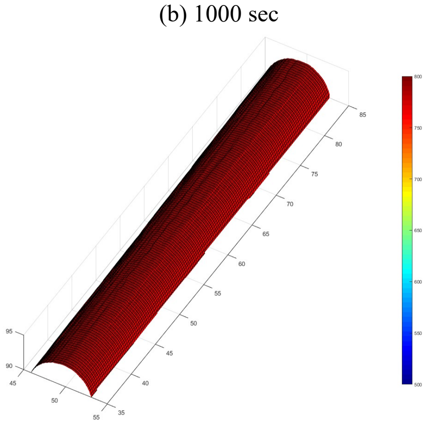
Fig. 7. Inner pressure during reflood test



(a) 200 sec



(b) 1000 sec



(c) 1700 sec

Fig. 8. Clad geometry and surface temperature during reflood test

Fig. 7 shows clad inner pressure and Fig. 8 shows clad geometry and surface temperature distribution. Around 1000 sec, the clad temperature was about 700 ℃ and clad deformation begun. Before 1000 sec, inner pressure increased because of the thermal expansion of inner gas. After ballooning of clad, however, inner volume of clad was increased and expanded inner volume reduced inner gas pressure. Thermal expansion of inner gas and volume expansion of clad competed after ballooning for inner pressure. The inner pressure decreased when the volume expansion was more dominant for pressure behavior. After reflood, inner pressure dropped sharply because inner gas was cooled down and shrunk. In this experiment, cladding was not burst. So, inner pressure kept high pressure.

3.2 Burst Test

A burst test was performed with similar process of the ballooning test. Fig. 9 ~ Fig. 11 show applied power, clad temperature, and inner pressure during burst test, respectively. For this test, clad was burst before reflood. The temperature and inner pressure behaviors had similar trend with ballooning test. When the clad was burst, however, pressure was sharply decreased to ambient pressure because inner gas vented out to sub-channel where pressure was ambient pressure. After burst, coolant was injected for reflood and power was turned off to protect facilities. Temperatures of clad surface were decreased after reflood as same manner of ballooning result.

The shape of burst clad is one of important result for this study. So, the burst clad geometry was measured using 3D scanner after end of test and the result is shown in Fig. 12.

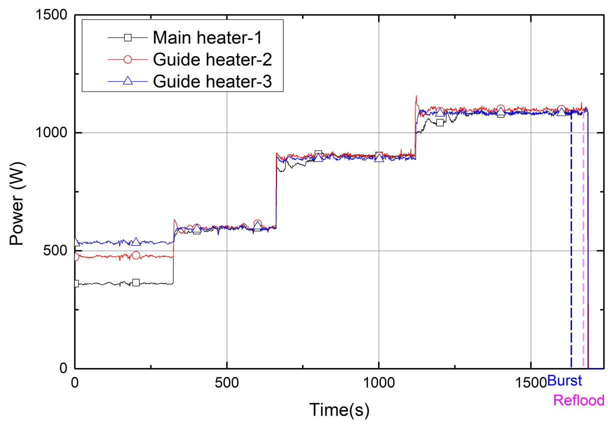


Fig. 9. Applied electric power during burst test

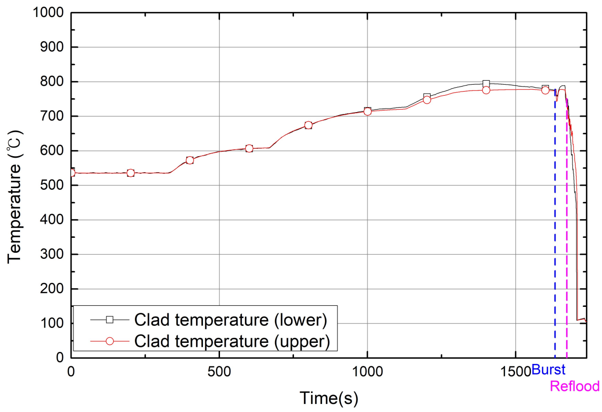


Fig. 10. Clad temperature during burst test

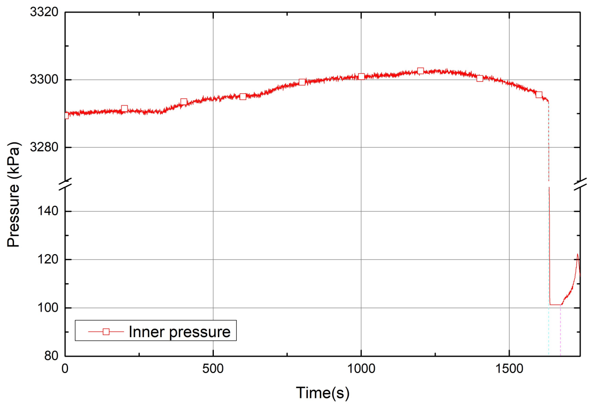


Fig. 11. Inner pressure during burst test

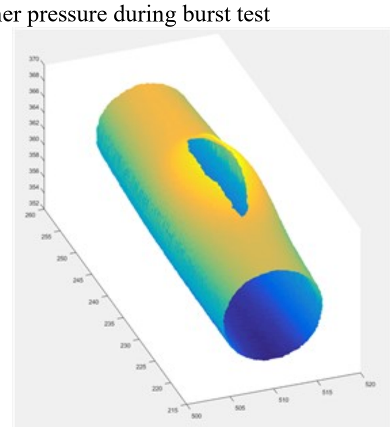


Fig. 12. 3D scan result of burst clad

4. Conclusions

An experimental facility ICARUS was developed at KAERI for multi-physics coupled phenomena during LOCA and reflood condition. Two preliminary experimental results for cladding ballooning and burst were presented. The relation among the temperature, inner pressure and deformation of clad during transient test was discussed.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2017M2A8A4015026).

REFERENCES

[1] J. Kim, J.B. Lee, K. Kim, et al., Development of Measurement System of an Experimental Facility for Thermo-Mechanical and Hydraulic Behavior during LOCA, Transactions of the Korean Nuclear Society Autumn Meeting, Jeju, Korea, May 17-18, 2018

[2] J. Kim, J.B. Lee, K. Kim, H. Byeon, J.-K. Park, Y.-J. Youn, H.S. Choi, and S.-K. Moon, Preliminary Analysis for Thermo-mechanical and Thermal-hydraulic Coupled Experiments Using DRACCAR Code Calculation, Transactions of the Korean Nuclear Society Autumn Meeting Goyang, Korea, October 24-25, 2019

[3] J. Kim, K. Kim, S.H. Hong, J.B. Lee, S. Cho, S.-K. Moon, "State-of-the Art Report on Thermo-Mechanically Coupled Experiments in a Loss-of-Coolant Accident", Kaeri technical report, KAERI/TR-7026/2017, 2017

[4] H. Byeon , J.B. Lee, J. Kim, K. Kim, H.S. Choi, J.-K. Park, Y.-J. Youn, and S.-K. Moon, Development of measurement system for thermo-mechanical behavior of cladding in LOCA-simulated experiments, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 21-22, 2020