Development of measurement system for thermo-mechanical behavior of cladding in LOCA-simulated experiments

Hyeokjun Byeon , Jae Bong Lee, Jongrok Kim, 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 Korea
**Corresponding author: skmoon@kaeri.re.kr*

1. Introduction

LOCA (loss of coolant accident) is one of major concerns related to safety issue of nuclear fuel. It has been investigated by numerous researchers [1-3]. From previous researches, various characteristics related to nuclear fuel and surrounding heat transfer phenomena could be revealed. However, most previous researches focused on separated effect tests on LOCA by studying either thermo-mechanical or thermo-hydraulic effect. On the other hand, because LOCA is multi-physics phenomena, it could be elucidated more deeply by conducting experiments with coupled phenomena. Therefore, an experiment for the multi-physics is required and it could be used to validate a multi-physics coupled safety analysis and to address a new LOCA acceptance criterion.

In order to understand multi-physics phenomena in LOCA, an experiment facility named ICARUS (Integrated and Coupled Analysis of Reflood Using fuel Simulator) is established at the innovative system safety research division, KAERI. This facility is designed to simulate the thermo-mechanical and thermo-hydraulic phenomena of rod and its surrounding during transient rod deformation with injection of water before severe accident occurs (under temperature of 1200K). In this study, measurement system for thermo-mechanical behavior of the cladding is described and results from test-run experiments are presented.

2. Experimental setup

2.1 ICARUS and experimental procedure

Figure 1 shows ICAUS test section and its loop briefly. The test section consists of one main heater and two guide heater with inner dimensions of 41.9 mm×16.2 mm. The main heater, which imitates fuel pellets, is surrounded by Zicaloy-4 cladding. Outer diameter of the main heater and cladding are 7.5 mm and 9.5 mm, respectively. Gap distance between heater and cladding is 0.4 mm. Two guide heaters with diameter of 9.5 mm are installed to mimic the effect of neighbor fuel rods around the main heater. Heating length of heaters is one meter. Considering that fuel rod length in nuclear reactor is about 3 m, in this way, ICARUS can simulate the fuel rod in various elevations by changing the boundary condition. Transparent quartz window is inserted to observe the thermo-mechanical behavior of the cladding. Thermocouple was attached to the main heater cladding at the location of the window bottom end. In addition, ICARUS has supporting system to input helium gas, argon gas, steam and water for various experimental conditions.

Before the experiment starts, helium gas was injected to inner space (gap) between main heater and cladding to increase the initial gap pressure. Afterwards, test-run experiment scenario with two parts began.

The first part was power step-up period. Monitoring cladding temperature, electrical power input to the heater was manipulated for step increase of cladding temperature. Due to high temperature of inner gas, gap pressure was increased continuously. Moreover, the ductility of cladding was changed. Up to 800 ℃, the ductility of zircaloy-4 is increased due to larger α-phase grain size. However, if the temperature keep increasing, phase transformation from α-phase to α/β mixture phase occurs and the ductility of cladding is decreased [4]. In order to maintain maximum ductility of the cladding, the temperature was controlled up to 800 ℃. After cladding temperature hit pre-determined value (~800℃), gap pressure was monitored to check its decreasing tendency. The second part, reflood period, started 350 s after the gap pressure started to decrease. Water was injected to the test section and quenched it. In overall process, additional steam flow was not supplied to the test section.

Other experimental conditions are listed in Table. 1.

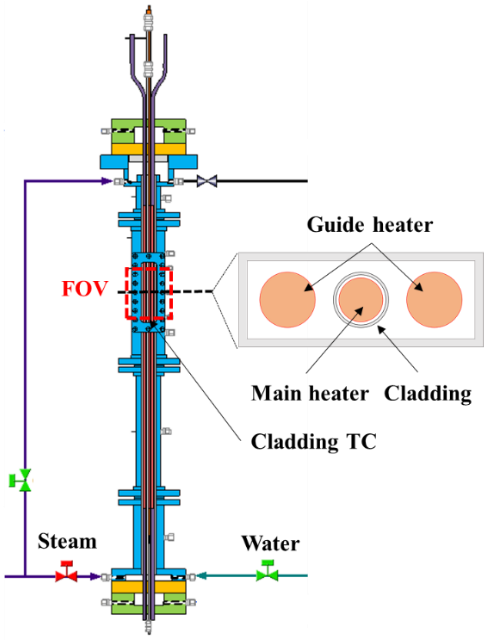

Fig. 1. Schematic diagram of ICARUS test section and loop

Table I: Experimental conditions

Parameter	Range
Heater Power	1.1 kW/m
Maximum heater temperature	~800 ℃
Sub-channel pressure	Ambient
Initial gap pressure	~32 bar
Water velocity	3.98 cm/s
Coolant temperature	~42 ℃

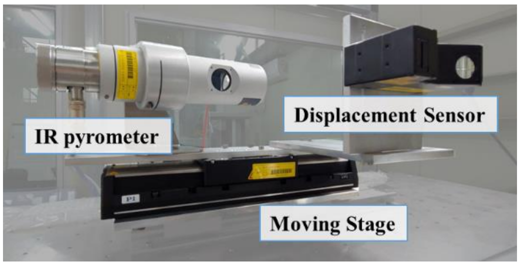

Fig. 2. Measurement system configuration

2.2 Measurement system for the thermo-mechanical behavior of cladding

Figure 2 presents the measurement system used in this study, major point of this system is measuring thermo-mechanical behavior of cladding by simultaneous measurement of both 3D shape of cladding and its surface temperature in non-invasive way. The system consists of two different instruments on linear translation stage (V-412, Physik Instrumente, Germany). For shape measurement, laser displacement sensor (LJ-V7200, Keyence, Japan) on translation stage was adapted to contactless measuring. The repeatability of the sensor is 20 μm in vertical and 1 μm in depth-wise direction, respectively. By moving the line scanning sensor horizontally, shapes of all three heaters could be measured [5]. Because the location of translation stage was recorded, the location of shape measurement could be easily found. The spatial resolution of this scanning system was 0.12 mm×0.30 mm and 1 μm in depth-wise direction. Because laser sensor detects reflected light from the surface, measured surface is limited by its curvature. For the case of circular rod, the surface corresponded to 120° could be measured.

For temperature measurement, IR-pyrometer (Endurance Series E2RL, Fluke, USA) was utilized. The pyrometer has temperature range from 250 ℃ to 1200 ℃ with spatial resolution of 7 mm. The measurement uncertainty of the pyrometer is ±0.5% of measured temperature. By combining it with line-scanning accessory and loading on the translation stage, pseudo-2D temperature field could be obtainable. In addition, because line-scanning accessory does not provide its location, reference temperature bar was installed in front of visualization window. By finding reference temperature in temperature data, the location of temperature measuring could be determined.

The measurement system have field of view of 100 mm×62 mm with required scanning time of about 8 seconds. This scanning time can be modified by adjusting the speed of translation stage and the field of view. All devices were connected and controlled by DAS programmed with LabView. Measured shape and temperature were displayed for real-time monitoring. Afterwards, shape and temperature data were handled to plot temperature map on 3D cladding shape. House-build MATLAB code was used to represent the temperature field on the measured cladding surface.

3. Results

Figure 3 illustrates strain of middle part of cladding with temperature and gap pressure. Deformation and burst of the cladding could be confirmed by strain calculation. Strain was calculated by comparing the length of cross-sectional curve of the cladding with that of intact one. Before the cladding ruptured, it is clear that strain increased after the cladding temperature was over 700 °C. The measurement was stopped because of water droplet coming from quench front.

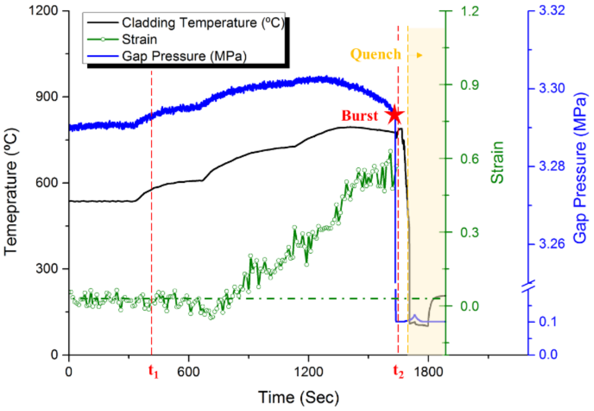

Fig. 3. Surface temperature, strain, and gap pressure plot of middle part of the cladding

Figure 4 shows shape and temperature measurement result corresponding to time. On the left column of Fig.3, the deformation of cladding could be clearly observed. Lateral and radial expansion of cladding was easily captured by displaying with coloring. On the right column, surface temperature of cladding was shown. This indicated that as temperature increase to some level (in this study, around 700 ℃), cladding starts to be deformed. This multi-physics measurement was available until water reached to measurement field because water droplet blocks scanning laser and the view of pyrometer.

Figure 5 shows the cross-sectional views of cladding at selected times compared to that of intact one. As temperature increased, gap pressure also increased. Moreover, as described before, the ductility changes as temperature increases. Combined effect from increased gap pressure and the ductility change resulted the deformation and burst of cladding. These process can be displayed with the developed system.

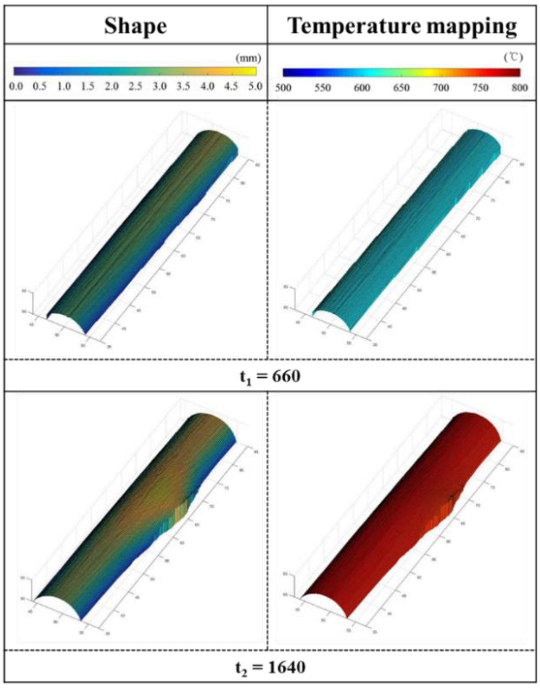

Fig. 4. Shape and shape with temperature map of claddings at different times

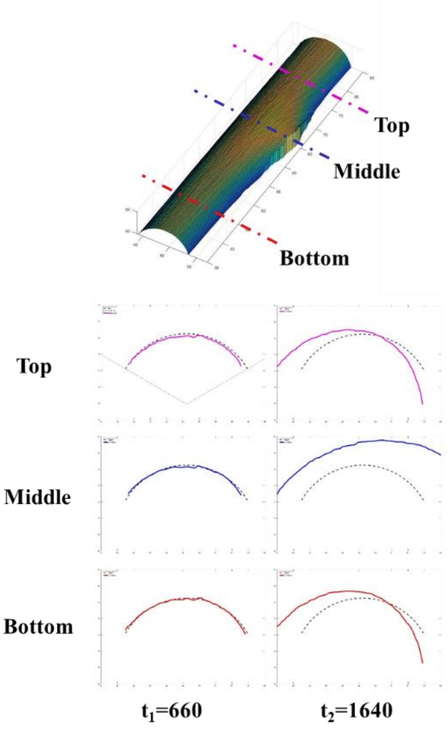

Fig. 5. Cross-sectional view of cladding with respect to time and location

4. Conclusion

Non-invasive measurement system for real-time shape and temperature of cladding in LOCA-simulated facility were introduced. Combining two different measuring devices was suggested and its results were presented. The spatial resolutions are 0.12 mm×0.30 mm and 1 μm in depth-wise direction for 3D shape measurement and 7 mm for temperature measurement. The temporal resolution is 8 seconds in this study. The system could successfully measure the thermo-mechanical behavior of cladding with shape and its surface temperature. These system will be utilized in LOCA experimental facility for better understanding of multi-physics phenomena of LOCA.

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