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Development of Measurement System of an Experimental Facility for Thermo-Mechanical and Hydraulic Behavior during LOCA

Jongrok Kim [a*], Jae Bong Lee [a], Kihwan Kim [a], Seunghyun Hong [a], Jong-Kuk Park [a], Sang-Ki Moon [a]
[a]*Korea Atomic Energy Research Institute, , 111,Daedeok-daero, 989beon-gil, Yuseong-gu, Daejeon, Korea 34057*
[*]*Corresponding author: jongrok@kaeri.re.kr*

1. Introduction

New directions on LOCA related a licensing approach and safety criteria of nuclear fuel are significantly raised, internationally. It is due to the adaptation of design extension conditions, and of the safety issue on a high burn-up nuclear fuel. In addition, the assessment issue of the nuclear safety is extended to the severe accident. Therefore, the new integrated assessment system on a nuclear fuel should be based on a multi-physics coupled safety analysis. Most of previous research investigates the separated effects on LOCA, for a better understanding on a mechanical behavior of the fuel and a thermo-hydraulic behavior during LOCA, individually. However, a LOCA has coupled phenomena associated with the thermo-mechanical and the thermo-hydraulic dynamics. Therefore, the multi-physics experiment is required in order to validate for a multi-physics coupled safety code and assess a new LOCA acceptance criterion.

An experimental facility for the multi-physics phenomena during reflood phase is being prepared at the thermo hydraulic and severe accident safety research division, KAERI. In order to understand and investigate multi-physics phenomena on LOCA, the information of cladding deformation and thermo-hydraulic variables (cladding temperature, fluid temperature, pressure, and etc.) are required.

Generally, a fuel core experiences a rapid increase during the reflood phase. In this phase, the high temperature and the rise in inner pressure of the cladding cause a ballooning of the cladding. The ballooned cladding affects to the subchannel flow area, heat transfer area between fluid and cladding, flow re-distribution, and flow pattern at near of the ballooned cladding. Therefore, real-time measurement for the cladding deformation is one of important experimental techniques for experiments to analyze the multi-physics. For in-situ real-time measurement of a cladding deformation in LOCA condition, a laser displacement sensor and a conductivity sensor were developed for a new experimental facility.

The temperature of cladding surface is a fundamental value to understand the multi-physics phenomena In the case of an experiments only for the thermo-hydraulic dynamics, attached thermocouple is common way to measure the temperature of cladding surface. However, the attached thermocouple can make a distortion of mechanical stress on the cladding during deformation. Additionally, it is difficult to install a thermocouple on the oxidation layer of the cladding surface. For this reason, contactless measuring methods were developed, and optimized installation method of thermocouple was also developed.

In the present paper, the developed measurement techniques for multi-physics phenomena and validation results for the measurement techniques are described.

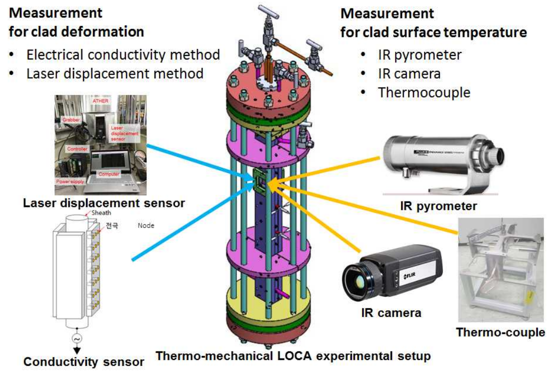

Fig. 1. Measuring techniques of new experimental facility for multi-physics

2. In-situ real-time measurement for cladding deformation

2.1 Electrical conductivity sensing technique

The ballooning is limited in the core bundle because the ballooned cladding contacts the neighbor ballooned cladding as Fig. 2. Therefore, ballooning shape is forced from circle to square after cladding contact. To analyze cladding deformation characteristics with a restricting by a neighbor, an electrical conductivity sensing method was suggested to measure the cladding deformation with contact in real-time.

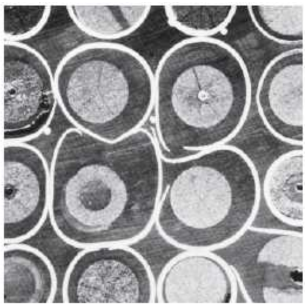

Fig. 2. Cladding deformation in a core bundle [1]

To simulate the limitation of ballooning, guide plate are installed as Fig. 3. The ballooned cladding cannot expend after contacts these plates. These plates have electrode array on their surface and the conductivity between the cladding and each electrode is monitored during the experiment. The contact point and pattern are measured in real-time by monitored conductivity. To validate this method, a preliminary test was performed with a 3x3 electrode array and an aluminum balloon as shown in Fig. 4. This technique detected contact point well in the real-time.

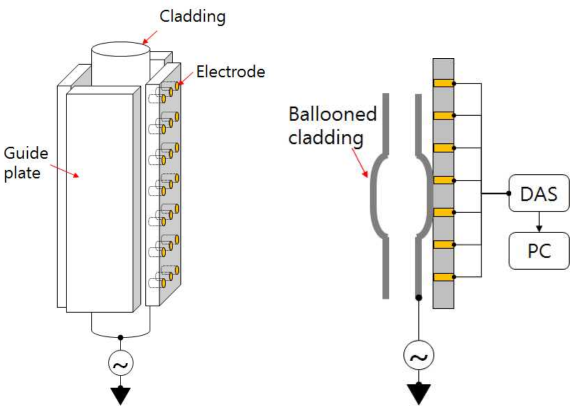

Fig. 3. Schematic diagram of conductivity sensor

Fig. 4. Preliminary test result of conductivity sensor

2.2 Laser displacement sensing (LDS) technique

The conductivity sensor gives a geometry information of the ballooned cladding after contact occurs. However, the deformation behavior before contact is also required to analyze the mechanical dynamics. The LDS technique was applied to measure the cladding deformation before contact. LDS technique is contactless method using the laser.

Several validations were performed to investigate distortions by a sight glass and a distance between sensor and target, a laser incident angle, a medium temperature, and a steam flow. Fig. 5 shows a configuration of validation test for a distance effect among the sensor, sight glass and target. The LDS and sight glass was fixed and target was moved. Fig. 6 shows the original measured data. Sight glass made a shifting of measured value, and the distortion by the distance was negligible. To calibrate for the distortion by the sight glass, a correction factor was applied, and the results are plotted on Fig. 7. The accuracy of the LDS with correction was acceptable for a new experimental system.

The LDS was applied to the ATHER that is an experimental facility for the thermal-hydraulics under reflood phase in KAERI. The ATHER has 5x5 heater bundle, steam flow system, measuring instruments. Pre-tests were preformed to verify the cladding surface temperature effect and steam flow effect. Fig. 8 is schematic diagram of bundle test. The LDS can access to measure the front row heater rods. Heater rods were heated up and the rod shape was measured at 203 ℃ and 343 ℃ in heater rod temperature. The rod profile was well measured for different rod temperature conditions (Fig. 9 left). The LDS measured the rod with steam flow in subchannels. The 300 ℃ steam flows with 0.16 mm/s and 0.23 mm/s velocities (Fig. 9 right). There was no distortion with the steam flow conditions.

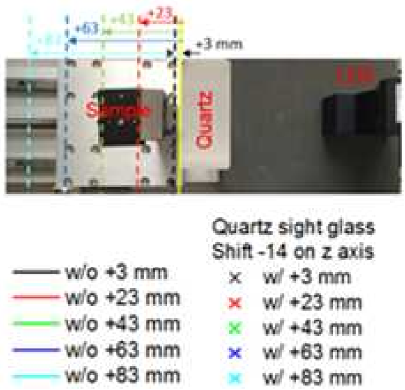

Fig. 5. Sight glass (Quartz) and distance effect test

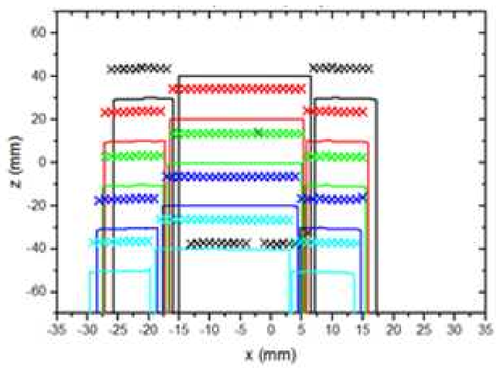

Fig. 6. Original measured data. Lines are real value, cross symbols are measured valued.

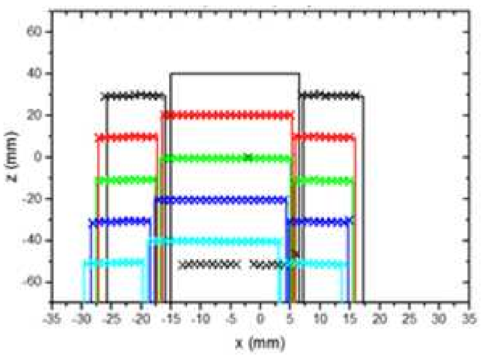

Fig. 7. Measured data with developed correction method. Lines are real value, cross symbols are measured valued.

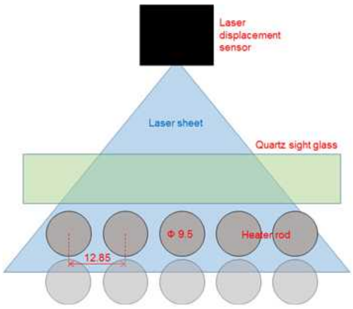

Fig. 8. Schematic diagram for bundle test using LDS

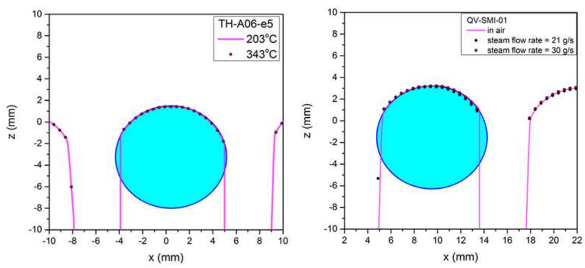

Fig. 9. Temperature effect and steam flow effect on LDS

3. Measurement technique for cladding surface temperature

IR-pyrometer (point measuring) and IR-camera (2D temperature profile) was applied to measure the cladding surface temperature. These techniques are contactless method. And thermocouple attaching method also developed and validated.

3.1 IR-Pyrometer

Temperature measurement using IR is affected by a surface material of target and a temperature of a medium between IR sensor and target. For validation, IR-Pyrometer was also applied to the ATHER to verify the temperature effect and flow condition effect (air flow, steam flow, reflood condition). Measured temperature by using the IR-Pyrometer was compared with the temperature measured by a thermocouple (TC) on the heater surface.

Figure 10 shows a comparison between two measurement results. Assuming the temperature measured by the TC is true, the accuracy of IR-Pyrometer is within 10 % for 300 to 600 °C in temperature and different flow conditions.

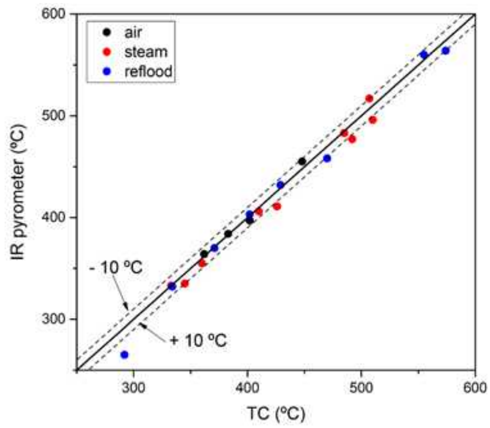

Fig. 10. Measured data under various temperature and flow conditions

3.2 IR-camera

Principle of IR-camera is same with IR-Pyrometer. However, applied IR-camera could not measure the temperature of heaters because it uses different the wave length of IR-pyrometer. The conclusion was that the new experimental system have to install special window to use IR-camera.

Fig. 11. IR-camera pre-test at ATHER

3.3 Temperature measurement with attached thermocouple

A K-type thermocouple was installed on a zircaloy tube with a zircaloy strap. It is hard to attach the thermocouple on the surface of zircaoly tube if the tube has oxidation layer. So, a zircaloy strap was used to fix the thermocouple. The pre-test was required before installation for the experimental facility because the zircaloy strap increases the heat transfer from cladding surface to ambient like a fin of heat exchanger. For pre-test, a simple heater was installed in a tube that has K-type thermocouple with strap as Fig. 12. The surface temperature was measured using IR-pyrometer, and thermocouple data was compared with the data of the IR-pyrometer. For the pre-test, the temperature measured by the thermocouple was 600 ℃ while the IR-pyrometer indicated 551 ℃, since the IR-Pyrometer detected the temperature on the outer surface of zircaloy strap.

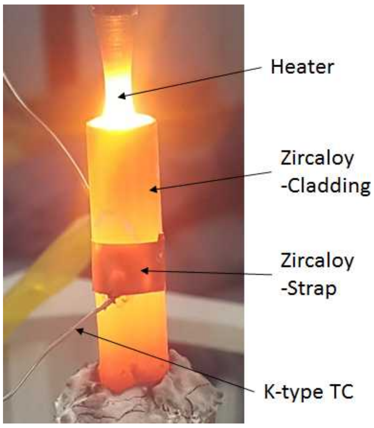

Fig. 12. Pre-test for attached thermocouple on cladding

4. Conclusions

The measurement techniques for main factors on a thermo-mechanical and hydraulic LOCA experiment were developed and validated. The main factors are deformation (strain) and outer surface temperature of a cladding, and fluid temperature and pressure at a channel of fuels. It is described the newly developed measurement techniques measuring the main factors in real time and in-situ within LOCA condition. In addition, the preliminary results with the new techniques are presented. These techniques will be applied to a new thermo-mechanical and hydraulic LOCA experimental facility.

Acknowledgement

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