Development of NEST experimental setup for large deformation test of cladding with neighboring rod effect using DIC techniques

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1. Introduction

The ballooning and rupture phenomena on the fuel cladding occurs during early stages of loss of coolant accident (LOCA) due to the difference of pressure between inner and outer, and they induce channel blockage and fuel relocation/dispersal. As a consequence of that, core coolability would be impaired. To investigate the fuel rod behavior during LOCA, most of previous studies focused on the behavior of single rod and applied to code development [1,2]. However, it is difficult that single rod tests represent the practical fuel rod behaviors with the consideration of the mechanical restriction effect of neighboring rods and the changes of thermal gradient.

From this reason, some of multi rod or bundle tests have been performed. Nevertheless, there is limitations on the previous test program except COCAGNE program in progress (IRSN). The cladding does not deform with a fixed geometry in the bundle test programs such as FEBA/SEFLEX (KfK), THETIS (UKAEA) and COAL (IRSN) to investigate the effects of deformed cladding on the coolability. And the measurement of deformation in cold-state, not real-time, was performed in multi-rod dynamic ballooning test programs such as such as REBEKA (KfK), MRBT (ORNL), JAERI, MT (NRU), PHEBUS-LOCA (CEA), and QUENCH-LOCA (KIT). In addition, test database including multi-dimensional measurement data is essential for the validation of multi-dimensional code. In this regards, **N**eighboring rods **E**ffect **S**imulation **T**ester (NEST) using real-time DIC (Digital Image Correlation), which are experimental setups for the large deformation of fuel cladding considering neighboring rods, has been developed to validate multi-rod analysis model. The performance tests were also performed.

2. Experimental setup and procedure

To simulate the fuel behavior in bundle during LOCA, two kinds of experimental setup are constructed, NEST-1 and 2. **Fig. 1** shows a configuration of NEST-1, 2. NEST-1 was designed to acquire real-time data on multi-dimensional deformation in inert environment by introducing the DIC and laser telemeters. And NEST-2 was designed to validate the deformation and oxidation models in steam environment by introducing the linear variable differential transformers (LVDTs). The chamber of NEST-1 is made of stainless steel with four flat quartz glass with the intention of measurement. The chamber material of NEST-2 is quartz glass to prevent the oxidation of chamber in steam environment and chamber is connected to steam supply system and quenching line.

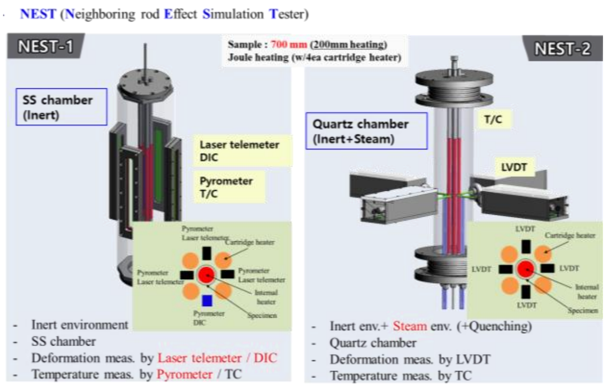
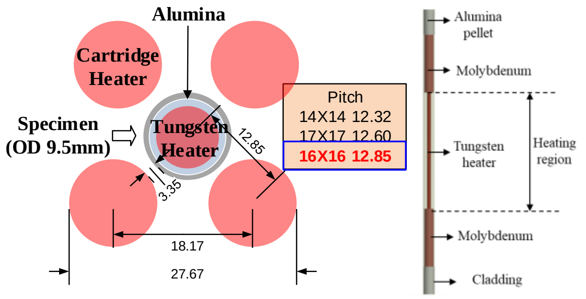


Fig. 1. Configuration of NEST-1, 2

A cladding specimen with an outer diameter of 9.5 mm was placed concentrically inside a chamber. This was arranged in a cruciform shape and surrounded by cartridge heaters (heated guard rods) which did not deform. The guard rods were spaced at the standard pitch of the pressurized rods, as shown in **Fig. 2 (a)**. For internal heating, a tungsten heater with axial length of 200 mm was connected to upper and lower molybdenum rods that were insulated from the annular alumina pellets, and then the cladding tube was mounted concentrically onto the heater, as described in previous study [3,4] (**Fig. 2 (b)**). A tungsten heater is electrically heated by resistance (Joule heating) and a maximum current of 250 A was applied.

The four deformation measurement locations were placed between two cartridge heater. For NEST-1, laser telemeters on three sides and DIC apparatus on one side were circumferentially equipped at same elevation. And four LVDTs were circumferentially mounted at same elevation on the NEST-2 chamber with inert gas purging system. Temperature is measured by thermocouple (T/C, max. 20 ea) and four infrared pyrometers are installed for NEST-1. The gap between alumina pellet and cladding is filled with He in the pressure range of 20-50 bar. The ramp rate is targeted to 5-10 K/s based on the typical reflooding condition used in the previous study [1,2]. The ramp rate and internal pressure could be changed to serve a test purpose. The typical experimental conditions are summarized as shown in **Table I**.



(a) (b)

Fig. 2. Configuration of assembly of test section
(a) cross-section of NEST-1, 2, (b) inner-heater

Table I: Experimental conditions

	Description
Environment	Inert (Ar) : NEST-1,2 Steam : NEST-2
Rod array	cruciform shape (surrounded by heated guard rods)
Ramp rate	5-10 K/s
Internal pressure	20-50 bar (He)

3. Performance tests

To confirm the functions of experimental setup with target ramp rate (5-10 K/s), the performance tests of NEST-1 and NEST-2 were performed, respectively. **Fig. 3** shows the photo of NEST-1 and its configuration for performance test. In this test, only inner heated only by inner heater (ramp rate ~ 3.8 K/s) and 50 bar of inner pressure were maintained.

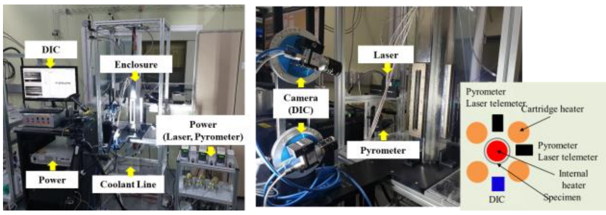
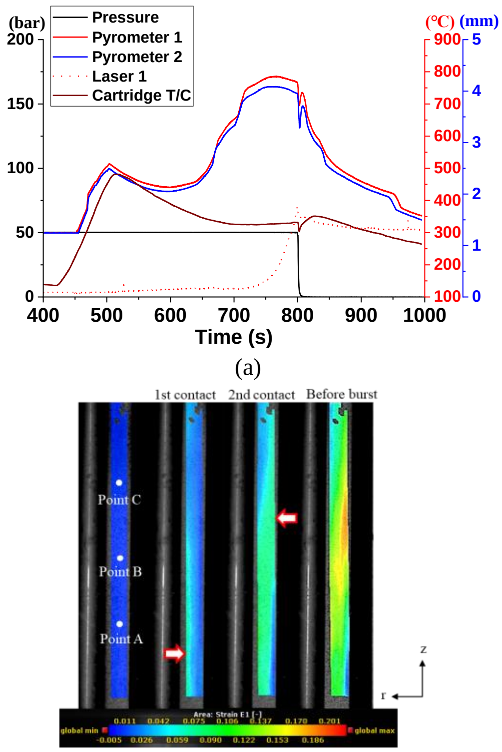


Fig. 3. Photo of NEST-1 and the configuration for performance test

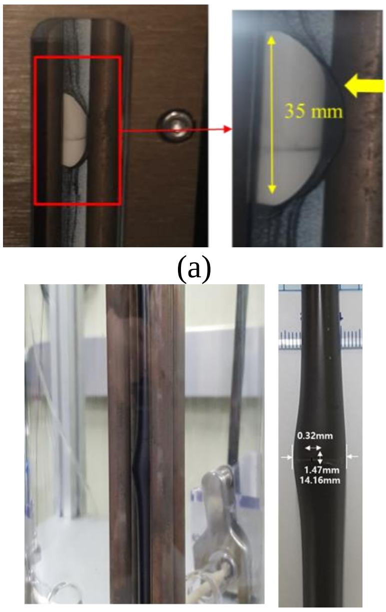
As shown in **Fig. 4**, temperature ramped from 450 ℃ to 785 ℃ and cooled after burst. During the test, all of data were successfully measured including multi-dimensional / in-situ deformation data using DIC and laser telemeter. The performance test of NEST-2 was also successfully performed. As shown in **Fig. 5**, the large deformation and burst phenomenon of cladding were observed, respectively.



(a)

(b)

Fig. 4. Measured data of NEST-1 performance test
(a) temperature, pressure and deformation by laser telemeter, (b) deformation by DIC



(a)

(b)

Fig. 5. Burst specimen during performance test
(a) NEST-1, (b) NEST-2

To apply the test results into validation data of multi-rod analysis model, temperature distribution of specimen and cartridge heater were measured during experiments. K-type T/Cs with the sheath of 0.5mm diameter were spot-welded on the surface of specimen and cartridge heaters as shown in **Fig. 6**. The multiple tests were performed with various combination of power and gas flow. The temperature distribution of specimen and cartridge heaters in one of temperature distribution test of NEST-2 are shown in **Fig. 7**. The target ramp rate (5-10 K/s) was accomplished with 7.6 K/s and the maximum cladding temperature reached to 818.9 ℃. The maximum differences in the axial 80 mm area were 34 K on a cladding and 37 K on cartridge heaters, respectively. The maximum differences in the azimuthal direction 10 K on a cladding and 20 K on cartridge heaters, respectively.

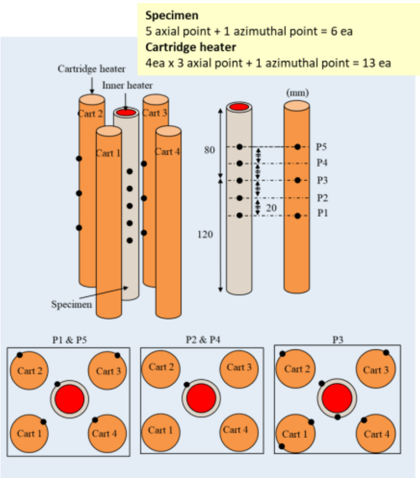


Fig. 6. T/C welding locations for temperature distribution test of NEST-2

The optimization of ramp rate and the temperature difference between cartridge heater and specimen would be controlled by additional tests.

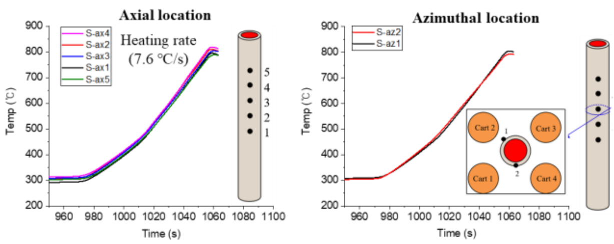


Fig. 7. Temperature distribution of the specimen in NEST-2

4. Conclusion

Neighboring rods Effect Simulation Tester (NEST), which are experimental setups for large deformation of cladding considering neighboring rods, has been developed to validate multi-rod analysis model. NEST-1 was designed to acquire real-time data on multi-dimensional deformation in inert environment, and NEST-2 was designed to validate the deformation and oxidation models in steam environment. The performance tests were performed to confirm the functions of experimental setup with target ramp rate and the temperature distributions for further code analysis. According to the results of performance tests, the test matrix would be determined. From the further tests, the studies are planned to investigate the differences in the ballooning/burst behavior in multi-rods with that in single rod such as long ballooning and resulting the increase in flow blockage area.

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