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Thermal-Hydraulic and Thermo-Mechanical Behavior Under Nitrogen Inflow Condition in a Large Break Loss of Coolant Accident

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1. Introduction

This study focuses on the effect of nitrogen gas inflow on the reactor core by examining the coupled behavior of thermo-mechanic and thermal-hydraulic phenomena. Nitrogen gas inflow into the coolant system and the reactor core can change thermal hydraulic behavior and nuclear fuel deformation, leading to potential safety issues. However, there is a lack of experimental data on the thermo-mechanic and thermal-hydraulic coupled behavior under these conditions. Therefore, the main objective of this study is to produce experimental data on the heat transfer between the cladding and fluid in the subchannel of the reactor core and the mechanical deformation of the cladding when single-phase steam and steam-nitrogen mixtures are supplied. This data can inform the re-evaluation of the emergency core cooling system during such scenarios and contribute to the development of core safety enhancements for multiple failure accidents. The Korea Atomic Energy Research Institute is conducting this research using the ICARUS (Integrated and Coupled Analysis of Reflood Using fuel Simulator) test facility to verify the safety issues in response to the reinforced acceptance criteria of the emergency core cooling system and regulatory policy changes [1-5]. The results of this study can provide valuable insights into the behavior of nuclear fuel in accidents and can aid in the development of integrated safety analysis code for nuclear power plants.

Considering the confidential problem, all the data in this paper are presented with the normalized value using random numbers.

2. Descriptions for the test

ICARUS has a fuel rod simulator under an accident core environment from refill to reflood phases during a LOCA. Experimental conditions of the ICARUS facility are follows:

- Power: up to 3.0 kW/m per rod
- Cladding inner gap pressure: 2 ~ 12 MPa
- Heater temperature: up to 1050 °C
- Reflood rate: 0.2 ~ 6 cm/s
- Subchannel pressure: ambient
- Supply fluid: Water, Steam, Nitrogen, Argon, Helium

The detailed design and description for the ICARUS facility can be found in the literature [6].

2.1 ICARUS configuration

ICARUS has a fuel simulator with two guide heaters in 1×3 array bundle structure. The fuel simulator is centered and consists of the main heater inserted into a Zircaloy tube filled with helium gas to the heater-cladding gap. Guide heaters are solid-type electric heaters in the shape of intact fuel cladding. The heated length of the fuel simulator and guide heaters is 1.0 m.

Figure 1 shows a schematic drawing of test section of the ICARUS facility and locations of instruments for wall temperature (TW), heater surface temperature (TH), cladding surface temperature (TC), fluid temperature (TF), static pressure (PT), differential pressure (DP) and axial cladding strain (LVDT).

2.2 Test procedures

In this study, the ICARUS test simulates an accident core during the refill phase of an LOCA. In order to implement the realistic boundary conditions of the fuel in refill phase, the ICARUS test proceeds with the gas purge, pre-heat up, and oxidation phases as shown in Figure 2. In the pre-heat up, the cladding surface temperature is heated up to 600°C, and argon gas is injected into the test section to prevent oxidation. For external cladding pre-oxidation, 1 g/s of steam supply into the subchannel, and the cladding is maintained for 2 hours at a predefined temperature.

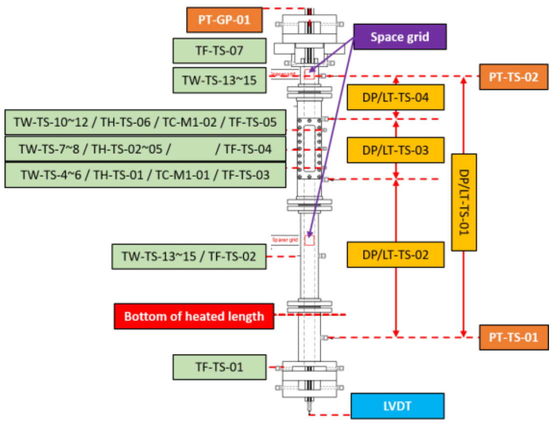

Fig. 1 Schematic drawing of the ICARUS test section with instrumentation location

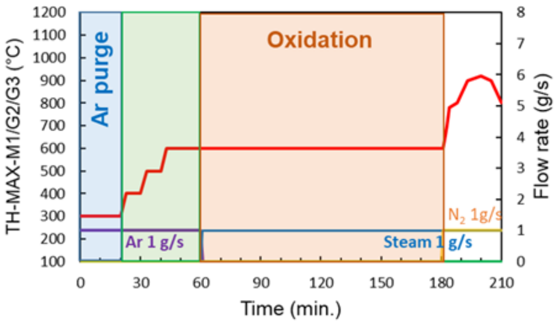

Fig. 2 Schematic drawing for the ICARUS test procedure showing time evolution of fuel simulator surface temperatures and supply steam/nitrogen flow rates

Prior to the fuel temperature excursion, the fuel simulator is pressurized with helium gas up to the target cladding inner gap pressure. Simulation of transient test during the LOCA begins at the same time as fuel simulator power increases. Test was performed until cladding rupture occurred where the cladding inner gap pressure rapidly decreased. In the ST-01 and ST-03 tests where only single-phase steam was supplied, the steam flow rate was maintained at approximately 2 g/s during the transient simulation, and only the cooling effect of steam on the cladding was taken into account. On the other hand, in the ST-02 test where nitrogen and steam mixtures were supplied, as depicted in Figure 2, both steam and nitrogen gas were supplied at approximately 1 g/s each during the transient simulation, and the cooling effect of the steam and nitrogen mixture on the cladding was simulated.

Table Ⅰ: Major Test Conditions and Test Results (Normalized Data)

Test ID	Tag ID	ST-01	ST-02	ST-03
Ambient temp. (-)	TF-CW-01	0.15	0.16	0.11
Input Power at the transient (-)	PM-MH-01	0.41	0.44	0.35
Rod fill pressure (-)	PT-GP-01	0.77	0.77	0.76
Housing wall temp. (-)	TW-TS-09	1.19	1.24	1.02
Steam flowrate (g/s)	QM-SI-02	1.91	1.46	2.11
Nitrogen flowrate (g/s)	Rotameter	-	~ 1.00	-
Max. cladding temp. (-)	TC-M1-01	4.14	4.39	4.07
Rupture pressure (-)	PT-GP-01	X	0.77	0.76
Rupture temp. (-)	TC-M1-01	X	4.33	4.03
Rupture time (-)	-	X	0.20	0.45
Termination of heater power (-)	PM-MH-01	0.24	0.24	0.46

3. Experimental results

The single-phase steam supply experiments were conducted twice in ST-01 and ST-03. In the ST-01 experiment, the test was terminated without the cladding rupture because the heater surface temperature (TH-M1-01~06) reached the interlock condition of 1,000 ℃. In the ST-03 experiment, the heater power was set lower than in the ST-01 experiment to simulate a transient state, and the test was terminated due to a decrease in the gap pressure caused by cladding rupture. The nitrogen-steam mixture gas supply experiment was conducted in ST-02, simulating a transient state with the same output conditions as ST-01, and the test operation was terminated due to cladding rupture. Table I summarizes the major boundary and initial conditions, as well as the key results of the experiments.

ST-01 and ST-02 tests were performed with similar levels of power input from 0 seconds to simulate a transient state, as seen in Fig. 3. In ST-01, the cladding rupture did not occur due to steam cooling, but the heater surface temperature reached to the protection limit, leading to the test termination. On the while, in ST-02, the cladding is not adequately cooled with the steam-nitrogen mixture fluid, resulting in a temperature increase rate difference of 4.59 in ST-01 and 5.32 degrees per second in ST-02 when compared to ST-01. he ST-03 experiment simulated a transient state with a relatively low power compared to the previous two experiments and the cladding was cooled only by steam. ST-03 exhibited similar behavior in terms of cladding surface temperature to ST-01 and did not reach rupture or heater overheat conditions until the termination point of the ST-01 and ST-02 experiments. Furthermore, the time elapsed from the transient state to cladding rupture in ST-03 was twice as long as that in ST-02, which used a steam-nitrogen mixture fluid for cladding cooling.

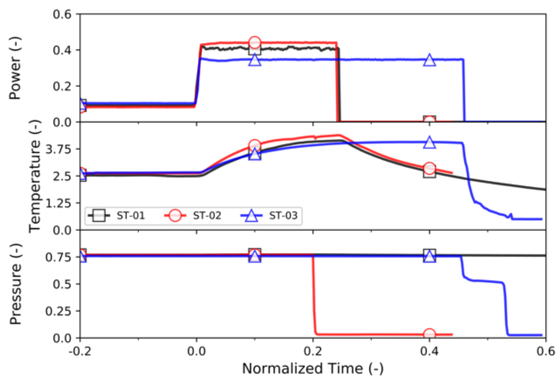

Fig. 3 Comparison of heater power, cladding surface temperature, and gap pressure behavior in transients for cases with single-phase steam and steam-nitrogen mixture supply

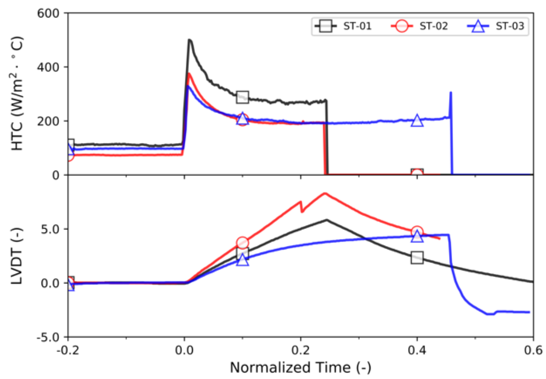

Fig. 4 Comparison of heat transfer coefficients from the cladding to the fluid in the subchannel and axial deformation measured by a Linear Variable Displacement Transducer (LVDT) in transient cases with single-phase steam and steam-nitrogen mixture supply

Fig. 4 shows the heat transfer coefficient from the cladding to the subchannel fluid, expressed as $h=Q/(\pi DH(T_c-T_f))$, where Q is the total heat output of the fuel rod, H is the heated length of the fuel rod (1 m), h is the heat transfer coefficient (HTC), D is the diameter of the cladding (9.5 mm), T_c is the surface temperature of the cladding surface, and T_f is the temperature of the coolant. The temperature difference between the fuel rod surface and the coolant in ST-02, where a nitrogen-steam mixture was supplied, was much larger than that in ST-01, where only steam was supplied, despite the similar power in the transient state. The ST-03 experiment had a relatively low power but the cladding heat transfer coefficient was similar to that of ST-02. In addition, Fig. 4 shows the axial deformation of the cladding during each experiment. The axial strain was higher in the ST-02 experiment where a nitrogen-steam mixture was supplied, compared to the single-phase steam supplied in the previous ST-01 experiment. Through this study, it was found that the material deformation of the cladding was accelerated by a decrease in the heat transfer coefficient due to changes in the thermal-hydraulic boundary conditions caused by the injection of nitrogen into the coolant flow, leading to cladding failure.

4. Conclusions

In conclusion, this study investigated the impact of nitrogen injection on the behavior of the reactor core and provided valuable experimental data on the coupled thermo-mechanical and thermal-hydraulic phenomena. The results indicated that nitrogen injection into the coolant flow could significantly affect the heat transfer coefficient and thermal-hydraulic boundary conditions, leading to accelerated cladding deformation and potential fuel rod failure. Specifically, the heat transfer coefficient and axial deformation of the cladding were found to be much higher in the case of steam-nitrogen mixtures compared to single-phase steam. These findings can be used in the development of integrated safety analysis codes and emergency core cooling systems for nuclear power plants. This can contribute to enhancing the overall safety and reliability of the nuclear energy industry.

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