Investigation of metallic fuel relocation in a 19-pins bundle structure of a sodium-cooled fast reactor using Wood's metal

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1. Introduction

Metal-fueled sodium-cooled fast reactors (SFRs) are originally designed to prevent severe accident. However, it is still crucial to provide consequence and safety assessment of the severe accident. Hypothetical core disruptive accidents (HCDAs) are generally considered as unrealistic accidents, but they could be an initiating event where cladding failure occurs in metal-fueled SFRs. Since there are different fuel relocation behaviors between the metallic and oxide fuel, the metal-fueled SFRs have advantages rather than that of oxide fuel for safety issues. Gabor et al. [1,2] investigated fragmentation experiments using the metallic fuel in an open sodium pool. They found highly porous debris bed which would be able to form coolable geometry. It has been also known that the molten metallic fuel would be swept out above of the core after cladding failure. Flow blockages would not also be formed due to chemical compatibility between the metallic fuel and sodium coolant [3]. However other phenomena might occur depending on accident scenarios. Unprotected loss of flow (ULOF) accident is one of HCDA. In the accident condition, there might not be sufficient driving force to discharge the fuel. Kim et al. [4,5] performed metallic fuel relocation experiments in a single-pin core structure using the metallic uranium fuel uranium and sodium. They were conducted in no coolant flow condition. As a result, eutectic mixtures between the fuel and HT-9M cladding were formed, but they were frozen in a channel.

Previous studies have conducted the fuel relocation experiments. They focused on understanding of the fuel behavior and assessment of safety characteristics for the metallic fuel [6-8]. Most of fuel relocation experiments were conducted in an open pool or a single-pin structure. They were useful to provide fundamental knowledge. However, it is necessary conduct fuel relocation tests in actual fuel assembly geometry and transient condition to provide experimental database for validation of in-house code. In the present study, the fuel relocation experiments were conducted in 19-pins bundle geometry. The objective of the study is to setup the experimental methods and understand thermal-hydraulic phenomena of fuel relocation. The Wood's metal was used as simulant for the metal fuel. Radiographic images were taken to observe frozen Wood's metal without any disturbance. Numerical simulation for investigation of the fuel relocation was also performed using Flow-3D.

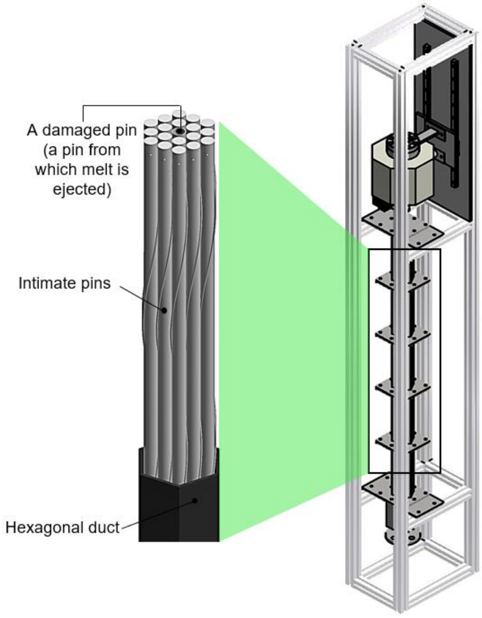

Fig. 1. Schematic diagram of UNICORN.

The numerical simulation result was compared with the experimental result.

2. Experimental procedure and conditions

A schematic diagram of UNIST test facility for molten fuel and coolant interaction (UNICORN) is shown in Figure 1. The test facility was improved and developed from previous one. The UNICORN facility consisted of a crucible and 19-pins bundle geometry. In the crucible, most of melt ejection conditions like an initial melt mass, temperature, and pressure were determined. The 19-pins bundle geometry was designed considering design parameters for 150 MWe-class SFR. Wire-wrapped stainless steel rods were used for pin structures. The rod was fabricated from 8 mm outside diameter. Pitch to diameter (P/D) and lead to diameter (L/D) for the UNICORN facility is 1.14 and 29.88, respectively. The center rod was assumed as a damaged pin which the cladding failure occurred. To eject melt from the crucible to narrow coolant channel, the center rod was directly connected to the crucible. The melt was ejected through a hole at surface of the center rod. The failure shape of the cladding was assumed to be a circle. There was a pneumatic valve in a connection line to control the melt ejection. Post-test was performed to take radiographic

Table I: Physical properties of molten materials

	Reactor materials	Simulants
Material	Metallic fuel (U-10Zr)	Wood's metal
Density [kg/m^3]	17400	9383
Thermal conductivity [W/m/K]	26	12.8
Specific heat [J/Kg/K]	201.3	172
Thermal diffusivity [m^2/s]	$7.42{\cdot}10^{-6}$	$7.93{\cdot}10^{-6}$
Surface tension [N/m]	0.57	1.00
Melting point [K]	1350	345

image to observe melt relocation behavior.

Physical properties of reactor material and simulant are listed in Table I. The melt relocation behavior is determined when the melt loses its momentum as it freezes. Since cooling time of melt depends on its thermal diffusivity, the Wood's metal was chosen as a simulant for the metallic fuel. The initiating event for the present study was assumed as simultaneous occurrence of unprotected transient over power (UTOP) and ULOF with conservative assumption. A severe accident code SAS4A was used to calculate melt ejection conditions in the event. The initial melt mass, temperature, and pressure were 15.26 g, 360 K, and 4.4 MPa, respectively. The channel was under air-occupied condition because the sodium was rapidly vaporized when the cladding was failed.

3. Results and discussion

3.1 Melt relocation in 19-pins bundle geometry

Figure 2 shows radiographic images of frozen Wood's metal. The damaged spot was position where the molten

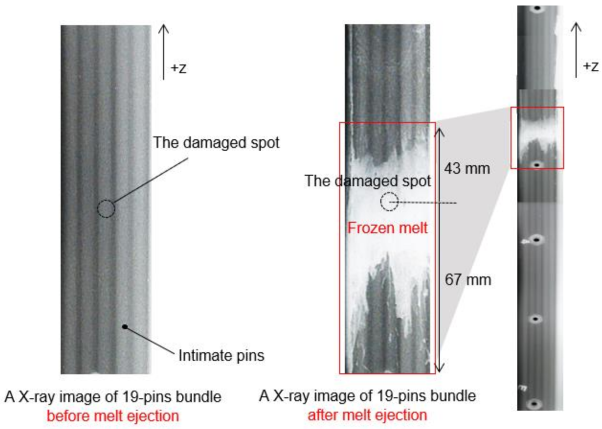

Fig. 2. Radiographic images of frozen Wood's metal before and after melt ejection.

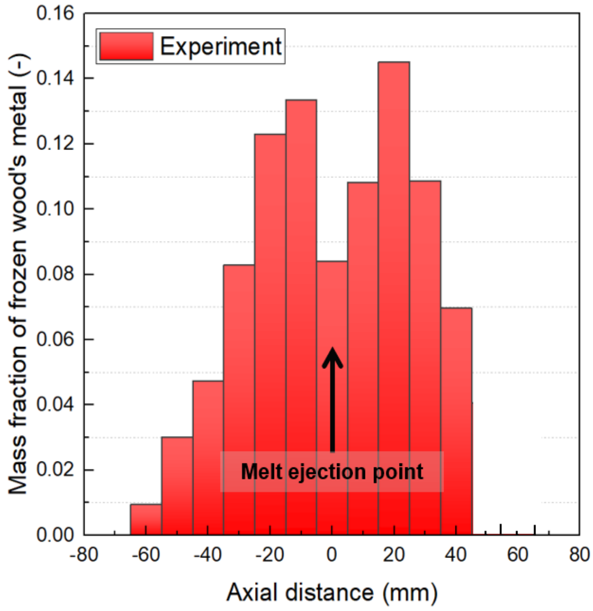

Fig. 3. Mass fraction of frozen Wood's metal along axial distance.

Wood's metal was ejected from the crucible. The pressurized molten Wood's metal in the crucible was discharged and dispersed in the multi-pins geometry. The melt dispersal occurred simultaneously in the radial and axial directions. The Wood's metal was ejected up to 43 mm and 67 mm through upper and lower part, respectively. It showed the Wood's metal was fell to the bottom side when it was frozen. Since the melt has lost its driving force, it moved downward due to its high density. When the melt dispersal occurred, the melt was collided with surrounding structures in the narrow channel where the gap between the pins was about 1 mm. These collisions induced to lose driving force for the melt discharge.

The mass fraction of frozen Wood's metal along axial distance is shown in Figure 3. To qualify the mass fraction with axial distance, it was measured in 10 mm increments. The most of melt was relocated at 14 mm and -21 mm in the upper and lower region, respectively. In the study, the upper and lower region were based on the melt ejection point. The most of melt was relocated at a distance from the ejected height. It means that these debris bed might cause a partial flow blockage. Whether the core could be under coolable state or not was highly dependent on a debris bed porosity.

3.2 Numerical analysis

Figure 4 shows a comparison between experimental and numerical simulation result. The numerical simulation was performed using Flow-3D. The physical geometry of the channel was the same as the corresponding test section of the test facility. The number of structured meshes was 100,000. From the simulation results, the melt dispersal was tended to be over-predicted due to a friction factor model in Flow-3D.

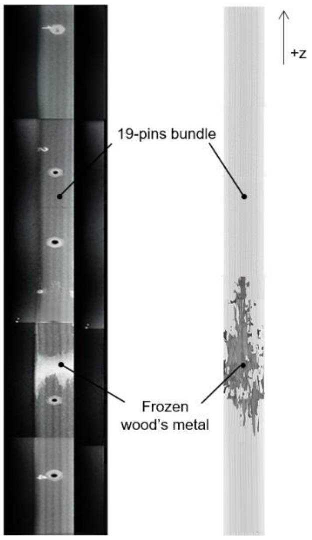

Fig. 4. Experimental and numerical simulation result for frozen Wood's metal distribution in 19-pins bundle.

4. Conclusions

The fuel relocation experiment was conducted using the simulant in 19-pins bundle geometry. In the accident of simultaneous occurrence of UTOP and ULOF, the melt relocation behavior was investigated with both the experimental and the numerical method. Although there are a few errors in the relocation behavior due to friction model in Flow-3D code, the experimental result was in a good agreement with the CFD results. In a future study, debris bed porosity would be investigated to evaluate the core coolability.

ACKNOWLEDGEMENTS

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