Melt Fragmentation Characteristics of Metal Fuel with Melt Injection Mass during Initiating Phase of SFR Severe Accidents

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1. Introduction

Sodium-cooled fast reactors (SFRs) are proposed by one of next-generation nuclear reactors due to its sustainability compared to light water reactors (LWRs) [1]. Recently, the disposal of spent nuclear fuel was a serious issue in South Korea. To solve this issue using the SFR fuel cycle, they have been developing the SFR called a Prototype Generation-IV Sodium-cooled Fast Reactor (PGSFR). The PGSFR has adopted the metal fuel for its inherent safety under severe accident conditions. However, this fuel type is not demonstrated clearly yet under the such severe accident conditions. Additional experiments for examining these issues should be performed to support its licensing activities.

Under initiating phase of hypothetic core disruptive accident (HCDA) conditions, the molten metal could be better dispersed and fragmented into the coolant channel than in the case of using oxide fuel. This safety strategy provides negative reactivity driven by a good dispersion of melt. If the coolant channel does not sufficient coolability, the severe recriticality would occur within the core region. Thus, it is important to examine the extent of melt fragmentation. The fragmentation behaviors of melt are closely related to a formation of debris shape. Once the debris shape is formed through the fragmentation process, its coolability is determined by the porosity or thermal conductivity of the melt.

There were very limited studies for transient irradiation experiments of the metal fuel. These studies were performed by Transient Reactor Test Facility (TREAT) M series tests in U.S. The TREAT M series tests provided basic information of metal fuel performance under transient conditions [2]. However, these experimental data did not examine the melt behavior after the cladding bleach in detail. In Argonne National Laboratory (ANL), they thought that the debris size and shape were determined by hydrodynamic breakup of the melt jet. To improve their breakup theory, they conducted vertically melt injection experiments [3].

The melt injection experiments using actual metal fuel and sodium coolant are meaningful to obtain the validation data. However, most previous works were conducted using simulant materials due to limited use of actual metal fuel. As one of the melt discharge mechanisms, coolant vapor pressure was proposed. Kamiyama et al. [4] performed molten fuel injection tests by using molten alumina and sodium. The massive amount of melt was discharged through the voided channel, where the sodium vapor was generated by heat exchange between the melt and liquid sodium. In addition, Heo et al. [5] visualized that built-up vapor pressure of the coolant caused discharge of the melt. To acquire more experimental knowledge for the upward discharge of the melt, Kamiyama et al. [6] conducted a series of melt injection experiments. The upward discharge rate of the melt increased with the increase of initial pressure difference between a core-simulating vessel and an upper vessel. Though some of the previous works were for the SFR with oxide fuel, its results provided the experimental backgrounds and basic knowledges for melt dispersion and fragmentation.

The fragmentation behavior of the melt is affected by key factors; melt injection mass, Froude number of melt, Weber number of ambient fluid, and initial temperature difference between melt and coolant etc. There is no study explicitly examining the effect of the melt injection mass on the extent of the melt fragmentation. The purpose of the present study is to understand the nature of metal fuel fragmentation behavior with melt injection mass. This paper describes the visual results obtained from given lab-scaled experiments. It would help to the melt fragmentation.

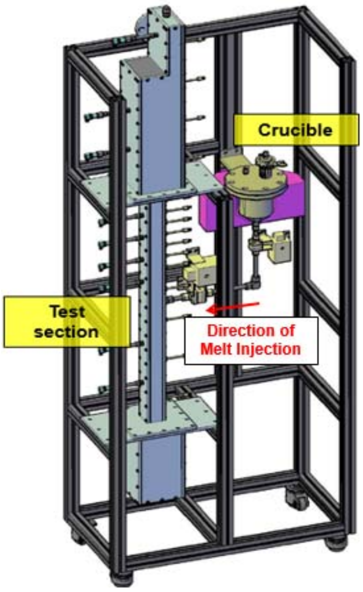

Fig. 1. Schematic of UNICORN test facility.

Table I: Properties of molten materials and coolants

	Actual materials		Simulant materials	
	Metal fuel (U-10Zr)	Sodium	Wood's metal	Water
Density (kg/m^3)	15849	840	9383	998
Surface tension (N/m)	N/A	0.20	~ 1.00	0.07
Melting /boiling point (°C)	1160/-	98/883	72/-	0/100

2. Experimental methods

Figure 1 shows a schematic of the UNICORN test facility. The test facility was composed of the crucible and coolant channel. In this experiment, two test sections were used; hexagonal channel to simulate actual PGSFR subchannel structure and rectangular channel to visualize the fragmentation behavior of the melt. They had little difference in equivalent diameter so that the difference did not give noticeable effect on the experimental result. The length between the top and the bottom end of the coolant channel is 2230 mm. The diameter of the melt injection nozzle is 12.7 mm. The melt injection system was pressurized with nitrogen gas, which controlled the initial pressure in the injection system. The fragmentation behavior of the melt in the coolant channel was observed using a high-speed video camera (1000 fps).

Table 1 lists the physical properties of molten materials and coolants which were used in the experiments. Molten wood's metal was selected as the simulant material of the molten metal fuel due to the low melting point of wood's metal. As the simulant material of the coolant, the water was used instead of the sodium. The present study focused on what the fundamental physical phenomena in terms of melt fragmentation was. Since melt-coolant chemical interaction was not considered in this study, it was appropriate to use these simulant materials.

The test matrix for this experiments are listed in Table 2. To conduct the melt injection experiment using the simulants, the Froude and the Weber number are key dimensionless number for the similarity analysis. The Froude number represents the ratio of the inertial forces to the gravity forces, and the Weber number represents the ratio of the disruptive hydrodynamic forces to the stabilizing surface tension force [7]. The Froude number and Weber number are defined as follows, respectively.

$$Fr = \frac{V_m^2}{gD_m} \tag{1}$$

$$We = \frac{\rho_c \left\| \overrightarrow{V_m} - \overrightarrow{V_c} \right\|^2 D_m}{\sigma_m} \tag{2}$$

where V_m and V_c are the melt and coolant velocities, respectively; g is the gravitational acceleration; D_m is the diameter of the melt injection nozzle; σ_m is the surface tension of the melt; and ρ_m and ρ_c are the melt and coolant densities, respectively.

These dimensionless numbers indicate which forces are dominant for the behavior of melt fragmentation. This approach enabled the experiment to satisfy hydraulic similarity compared to actual severe accident the condition.

Table II: Test matrix of the melt injection experiment

	1	2	3	4
Melt/coolant material (-)	Wood's metal /Water	Wood's metal /Water	Wood's metal /Water	Wood's metal /Water
Melt injection mass (kg)	0.18 (single pin failure)	0.18 (single pin failure)	1.40 (multi-pins failure)	1.40 (multi-pins failure)
Melt/coolant temperature (°C)	250/22	250/20	252/21	250/21
Initial melt injection pressure (MPa)	0.1	0.1	0.1	0.1
Coolant flow velocity (m/s)	0	0	0	0
Froude/Weber number (-)	229/323	229/323	229/323	229/323
Shape of test section	Hexagonal channel	Rectangular channel (for visualization)	Hexagonal channel	Rectangular channel (for visualization)

3. Results and discussion

3.1 Single pin failure

Figure 2 shows the visual observation of melt fragmentation behavior with 0.18 kg of melt injection mass. This melt mass was applied to consider single pin failure condition. The early behavior of the melt injection was dominated by air mushroom. The air was supplied from the intermediate pipe tubes between the crucible and the test section. After the air injection, the melt was injected into the coolant channel and collided to the channel wall. During the melt injection process, the melt fragmentation behavior was determined from several combined physical phenomena. Firstly, the melt fragmentation occurred in interfacial surface between melt and coolant. The melt with 150°C superheat was instantly quenched in the interfacial surface and fragmented from the melt jet. The remaining melt jet, which was not quenched, was collided to the coolant channel wall in the liquid phase. This collision made impact force to fragment remaining melt jet. As shown in Fig. 2, the local vorticity was generated in the area near the melt jet. This vorticity stirred and collapsed the lower end of air-occupied region. Due to the collapse of voided region, coolant inflow was accelerated from relatively high position to melt-coolant interaction zone. This physical phenomenon activated the extent of melt fragmentation. The debris was formed after the melt fragmentation and moved downward owing to its high density.

Fig. 2. Fragmentation behavior of melt with 0.18 kg of melt injection mass.

Fig. 3. Agglomerated debris after melt injection with 0.18 kg of melt injection mass.

Figure 3 shows debris in the hexagonal channel using X-ray measurement. The debris formation stood for the coolability of core region. With continuous melt injection, the melt agglomeration was formed and its area was expanded. This agglomerated area increased up to 15% of inner cross section of the channel. This means that the melt agglomeration partially blocked the coolant channel. In this experimental condition, there was the coolable geometry in the coolant channel.

2.2 Multi-pins failure

As shown in Fig. 4, the fragmentation behavior of melt under multi-pins failure condition was different compared to that of single pin failure. In this case, the melt mass of 1.40 kg was used, which was equal to the weight of eight fuel pins based on the design criteria of

Fig. 4. Fragmentation behavior of melt with 1.40 kg of melt injection mass.

Fig. 5. Agglomerated debris after melt injection with 1.40 kg of melt injection mass.

the PGSFR fuel. Like a previous case, the air was injected into the coolant channel in early phase of the melt injection. The melt was injected to coolant channel after the air injection. The melt fragmentation occurred at the interfacial surface between the melt and the coolant. This fragmentation behavior was explained by hydrodynamic instability theory. Also, the inertia force of melt jet kept its collision with the channel wall. From this series of process, the melt fragmentation was accelerated. A part of the melt moved upward in the air-occupied region, but most of it moved downward generating vorticity. The vorticity collapsed air-occupied region and activated the melt fragmentation procedure.

In case of 1.40 kg melt injection mass, the debris was significantly agglomerated compared to the case of single pin failure. Since the melt injection mass increased, the melt was able to be more agglomerated as shown in Fig. 5. The increased melt mass extended the reaction time for the formation of the melt agglomeration. The area agglomerated by the melt was 65% of inner cross section of the hexagonal channel. This means that this agglomeration blocked most of the coolant channel. The results indicated that the coolability of coolant channel was not ensured under multi-pins failure condition.

4. Conclusions

The effect of melt injection mass was evaluated in terms of the fragmentation behaviors of melt. These behaviors seemed to be similar between single-pin and multi-pins failure condition. However, the more melt was agglomerated in case of multi-pins failure. This means that there would be a critical amount of melt agglomeration forming the flow blockage. Therefore, more experimental database should be established as a further works.

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