A Visual Study of Molten Metal Fuel Coolant Interactions under an Initial Phase of SFR Severe Accident using Gallium Metal vs Water or R123

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ABSTRACT

In hypothetical core disruptive accident (HCDA) of a sodium-cooled fast reactor (SFR) as a severe accident, the possibility of the severe recriticality event would increase if the molten fuel forms tight blockages within the subchannel. However, the metal fuel is known to have lower potential to reach up the HCDA compared to oxide fuel. Because of particular characteristics of the metal fuel, it can be upward dispersed without blockage even in the case of pin failures. This fuel transport introduces a substantial negative reactivity, producing a shutdown effect. Therefore, it is required to verify upward dispersion of the molten metal fuel leading to the negative reactivity feedback. There are various injection conditions of the melt with radial core positions, so it is necessary to identify whether the molten fuel is dispersed well enough with structural conditions, coolant void conditions, and the boiling conditions. In the present study, a series of experiments were conducted to clarify the fundamental behavior of the melt injected into the subchannel. Molten gallium was selected as simulant material for the metal fuel. For simulant materials of the coolant, water and R123 were used. The behavior of the molten gallium in the coolant channel was observed using a high-speed camera and visually analyzed. As a result, the driving force to move upward the melt was observed with the coolant channel conditions.

KEYWORDS

Hypothetical Core Disruptive Accident (HCDA), Metal fuel, SFR, Severe accident, Dispersion of molten metal fuel

1. INTRODUCTION

Sodium-cooled fast reactor (SFR) is one of the promising candidates for the next generation nuclear reactor because of its advantage in high thermal efficiency and large safety margin from the high boiling temperature of coolant. However, the hypothetical core disruptive accident (HCDA) of the SFR has been considered as one of the critical issues in its inherent and passive safety. During the sequence of HCDA, the fuel pin is pressurized by a fission gas at the initiating phase of the HCDA and the molten fuel is dispersed into the coolant channel due to cladding rupture. Here, in particular, if the SFR adopts the metal fuel, the melt is expected to be well dispersed and fragmented into the coolant channel compared to the oxide fuel. In addition, the melt can be levitated upward and discharged efficiently to the outside of the core leading to the negative reactivity insertion, which can lead to a mild termination of the severe accident. However, the molten metal fuel may be frozen and plugged forming tight blockages, which drives severe recriticality within the subchannel. It is called as the recriticality issue and becomes the main safety issue of the SFR design even with metal fuel. In the current Korean SFR program, early dispersion of the molten metal fuel within a subchannel is suggested as one of the inherent safety

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strategies at the initiating phase of HCDA. The safety strategy provides negative reactivity driven by the melt dispersal, therefore it can reduce the possibility of the severe recriticality event under anticipated transient without scram (ATWS) scenario for the SFR [1-2]. The behaviors of the melt dispersion are different between the inner core and the outer core in unprotected loss of flow (ULOF) accident which is one of ATWS events leading to HCDA. While the voided coolant channel region is usually developed at the inner core region, the unvoided coolant channel region is formed at the outer core region [3]. Although it is important to confirm the melt dispersion within the core region, there are not sufficient studies about the melt dispersion.

Two driving forces are considered to discharge the molten fuel from the core region: fission gas trapped within the fuel and coolant vapor pressure [3]. In the melt discharge experiments with simulant materials, the upward discharge mass rate increased with an increase of the pressure build-up under reactor conditions [4]. Kamiyama et al [5]. carried out fuel discharge tests using molten alumina and sodium. They pointed out that the massive fuel was discharged through the voided channel, where a part of sodium vaporization was entirely evacuated by heat exchange with melt and liquid sodium. In addition, Kamiyama et al [6]. conducted a series of experiments to obtain experimental knowledge of the upward discharge of molten fuel. The study showed that the flow rate of upward melt discharge was increased in accordance with the increase of the initial pressure difference between the core-simulating and upper vessels. The vapor pressure would be more built up with the increase of heat transfer rate from the molten fuel to the coolant.

From the previous studies [7-9], the coolant vapor pressure was considered as one of the driving force to move the melt towards outside of the core. There was complexity of the phenomena during intermixing of the melt with the coolant after melt injections. It is too difficult to understand the several combined mechanisms related to the melt dispersion and the fragmentation. Thus, it is worthwhile to study the melt injections into the coolant channel at lower temperature, which helps to observe the dispersion phenomena. In that sense, it is required to clarify whether the coolant vapor pressure is the driving force for the melt dispersion with the core region.

In the present study, some experiments were conducted to observe the fundamental dispersion behavior of the melt, which was into the coolant channel. For the parametric study, the tests were performed according to the structural conditions, the coolant void conditions, and the boiling conditions. Molten gallium was selected as a simulant material for the metal fuel (U-20TRU-10Zr) because it is easy to conduct the experiment due to low melting point of the gallium. The molten material was injected into water or R123, which were used as simulants for the coolant. Since the R123 has low boiling point of 28 ℃ at sea level, the R123 was used to simulate a coolant boiling condition. The physical properties of molten materials and coolants are listed in Table I, respectively. The materials were selected to reflect a relationship between melting point of melt and boiling point of coolant.

2. Experimental apparatus and conditions

Fig. 1 shows a schematic diagram of the experimental apparatus. The experimental apparatus is composed of a coolant channel to simulate the subchannel structure and a melt injection system. A length between the top end of the coolant channel and the melt injection point is 260 mm. An equivalent inner diameter of the coolant channel is 15 mm, and the inner diameter of the melt injection nozzle is 3.7 mm. One valve is installed in the melt injection tube to control the amount of the melt mass. In the experiment, the melt injection into the coolant channel was started by opening the valve and terminated by closing the valve. The melt injection mass was measured with a calculation of mass flow rate. Initial temperature and pressure were measured with thermocouples and pressure gauges before the melt injection.

Table I. Physical properties of molten materials and coolants

	Actual materials		Simulant materials		
	Metal fuel	**Gallium**	**Sodium**	**Water**	**R123**
Density (kg/m^3)	14100	6095	966	998	1460
Surface tension (N/m)	0.573	0.735	0.200	0.073	0.015
Viscosity (mPa·s)	$5 \cdot 10^{-3}$	$1.889 \cdot 10^{-3}$	1.125	1.002	0.449
Melting / Boiling point (℃)	1077 / -	30 / -	- / 881	- / 100	- / 28

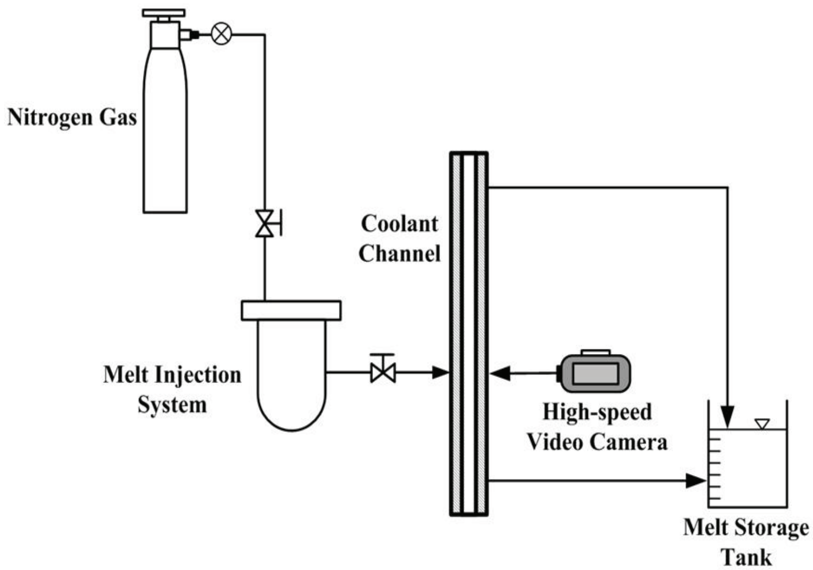

Figure 1. Schematic of experimental apparatus.

The melt injection system was pressurized with the nitrogen gas, which determined the initial pressure in the injection system. Visual observation of upward melt dispersion was made through transparent windows of the coolant channel. The dispersion behavior of the molten gallium in the coolant channel was observed, using a high-speed video camera (Phantom, v9.1, 800 frames per second). The time resolution of the images was 0.02 s.

Table II shows experimental conditions. In all cases, the initial melt injection pressure was kept at around 0.1 MPa. The test 1 and 2 were intended to confirm the structural effect on the behavior of melt dispersion. In these cases, coolant flow rate was applied to identify structural effect during melt discharge. The other tests were conducted under zero flow condition in order to simulate ULOF accident scenario. The effect of the build-up vapor pressure in the unvoided coolant channel was investigated in test 3 and 4. Test 5 was intended to simulate melt discharge in the voided coolant channel, so the experiment was conducted in the voided region. Unlike test 5, the coolant boiling was considered in test 6 maintaining other conditions. Froude number and Weber number are defined as

$$Fr = \frac{\rho_m U^2}{g D_m \left| \rho_m - \rho_c \right|} \qquad (1)$$

$$We = \frac{\rho_c U^2 D_m}{\sigma_m} \qquad (2)$$

where U is the velocity difference between jet and coolant, g is the gravitational acceleration, D_m is the injection nozzle diameter of the melt, σ_m is the surface tension of the melt, ρ_m and ρ_c are the melt and coolant density. Froude number represents the ratio of inertial forces to gravity forces and Weber number represents the ratio of the inertial forces to surface tension. In the present study, the effects of gravity and surface tension can be neglected because there are high Froude number and Weber number. It refers that inertia force is dominant compared to gravity and surface tension.

Table II. Experimental conditions

Test no.	**1**	**2**	**3**	**4**	**5**	**6**
Melt / Coolant material (-)	Gallium / Water	Gallium / Water	Gallium / Water	Gallium / R123	Gallium / Water	Gallium / R123
Melt temperature (℃)	50	50	50	50	50	50
Coolant temperature (℃)	22	22	22	22	22	22
Melt injection mass (kg)	1.17 (6 fuel pins)	1.31 (6 fuel pins)	1.22 (6 fuel pins)	1.61 (8 fuel pins)	1.24 (6 fuel pins)	1.36 (7 fuel pins)
Initial melt injection pressure (MPa)	0.1	0.1	0.1	0.1	0.1	0.1
Coolant flow velocity (m/s)	0.5	0.5	0	0	0	0
Coolant channel region (-)	Unvoid (coolant-filled)	Unvoid (coolant-filled)	Unvoid (coolant-filled)	Unvoid (coolant-filled)	Void (air-occupied)	Void (air-occupied)
Froude number (-)	1123.8	1123.8	1116.14	1230.34	1116.14	1230.34
Weber number (-)	174.3	174.3	173.08	254.93	173.08	254.93

3. Results and Discussion

3.1.1. Structural effect on behavior of melt dispersion

In order to investigate structural effect on the behavior of melt dispersion within coolant subchannel, the melt was injected into the coolant channel, where the obstacles simulating fuel pins were inserted. In the present study, the structural effect with regard to the melt dispersion was divided into two parts: influence of wire wrap and gap between the pins in multi-pin structure. The former case was investigated using single pin with wire wrap. In the latter case, three pins were used to investigate the gap effect only between pins without the wire wrap. Fig. 2 shows the melt behavior within the coolant channel under the structural conditions. The single pin structure was composed of a pipe and wire wrap of pipe of each

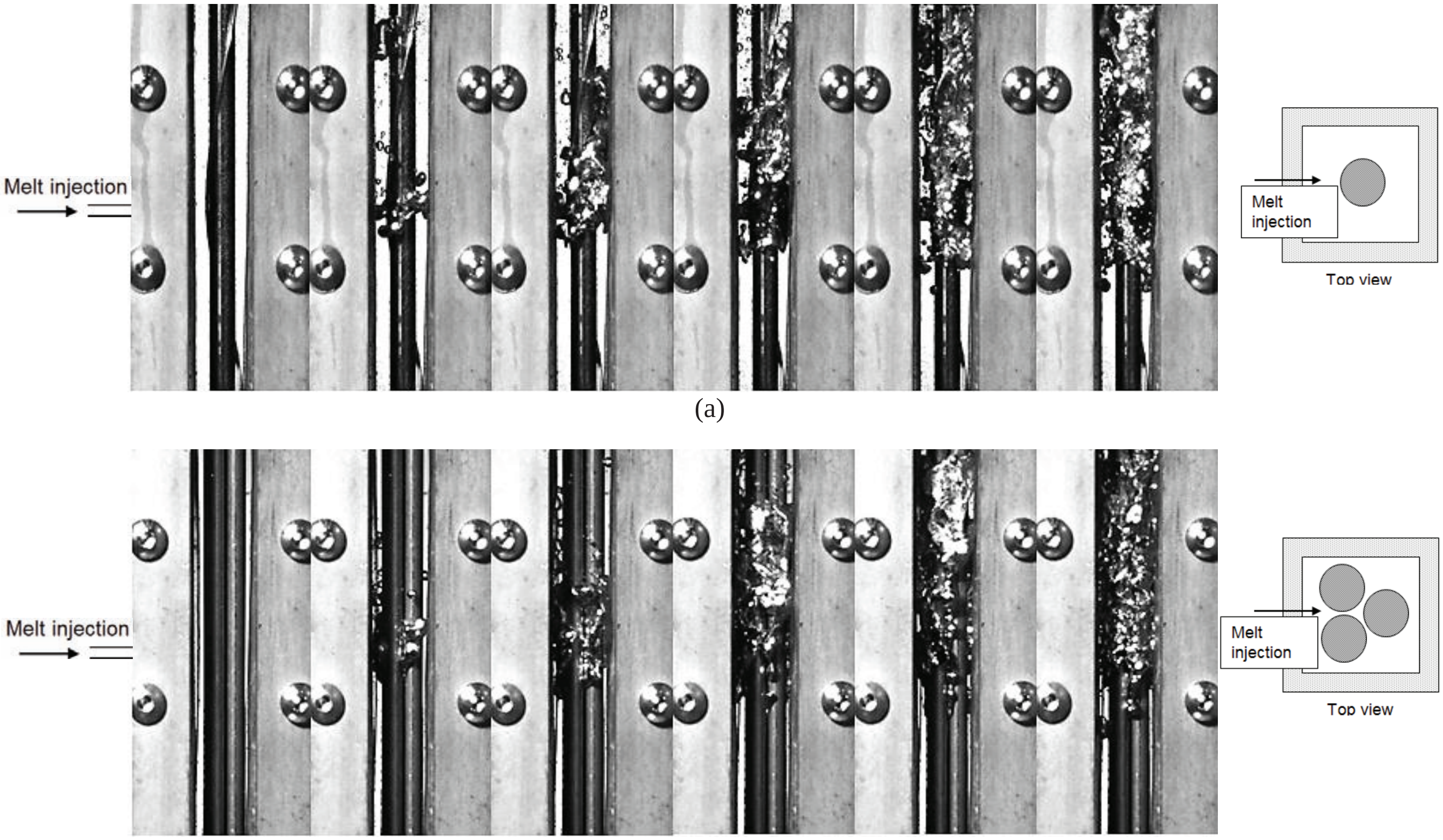

Figure 2. FCI behavior of melt in (a) single pin-inserted water channel in test 1, and (b) three pins-inserted water channel in test 2.

diameter of 6.33 mm and 1 mm. As shown in Fig. 2(a), there was the melt behavior surrounding the fuel pin after the melt injection. After that, the melt was discharged upward by the coolant flow and the melt was concentrated on the right side of the coolant channel during the melt discharge. The melt behavior was consistent with the direction of rotation of the wire wrap. With wire wrap, the melt behavior was moved upward while rotating in a spiral. This rotary movement of the melt increased the contact area between the melt and the coolant, which leads the melt to be well fragmented. In addition, it helps melt easily be discharged upward towards the outer of the core. In case of three pins structure, the structure was composed of three pipes of diameter of 6.33 mm. In this structure, the gap between the pins was 0.89 mm due to pitch of 7.22 mm. However, the melt penetrated into the gap and was dispersed depending on the geometry of the gap, as shown in Fig. 2(b). The partial melt was broken through the gap after the melt injection, but it was lumped together forming bulk melt as the melt moved upward. The melt was moved upward uniformly without being concentrated in a particular direction. It refers that the gap between the pins does not give a noticeable effect on the melt dispersion.

3.1.2. Unvoided coolant channel

Fig. 3 shows visual results of the melt discharged into the coolant channel under the fully charged coolant in the channel. Based on the previous studies, the unvoided coolant channel is formed at the outer core

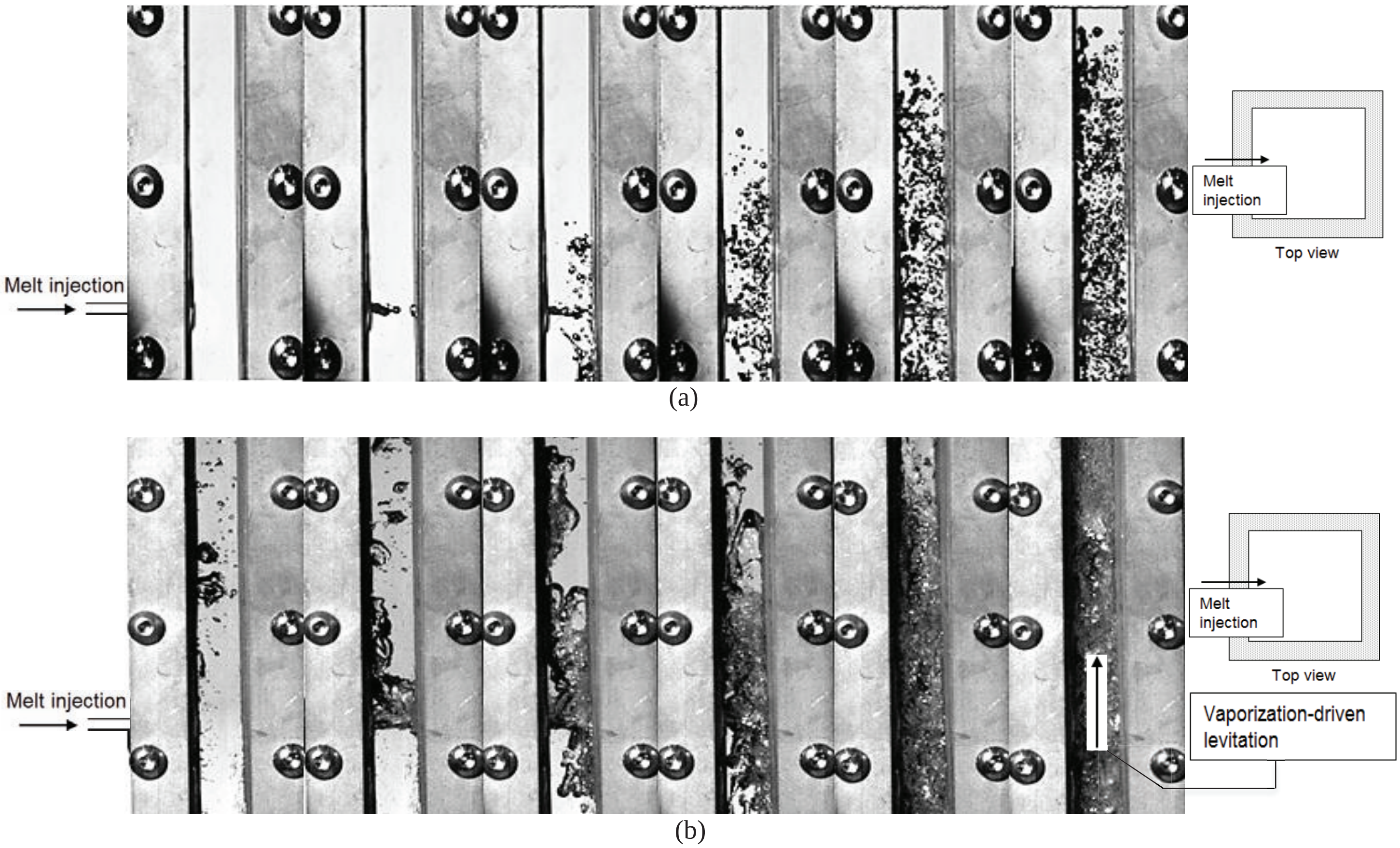

Figure 3. FCI behavior of melt in (a) unvoided water channel in test 3, and (b) unvoided R123 channel in test 4.

region in ULOF initiating phase scenario. In order to simulate the behaviors of the melt dispersion in the outer core region, the following experimental conditions were applied. The initial melt injection pressure was 0.1 MPa and the initial temperatures of the melt and coolant were 50 ℃ and 22 ℃, respectively. Under same initial temperature of coolants, the boiling took place only in test 4 due to different boiling point of the coolant. While the boiling point of water is 100 ℃ at 1 atmosphere of pressure, the R123 has boiling point of 28 ℃. The initiating behavior of the melt injection of test 3 was identical to that of test 4, except for coolant boiling caused by the heated the injection point. The melt was injected continuously by the melt injection system, and melt-coolant mixing occurred in the vicinity of the melt injection point. In test 4, the coolant void volume increased due to coolant boiling and the melt moved upward along the coolant channel, while the melt continued to be mixed only with the coolant in test 3. With the increase of the coolant void volume, a void development was established with the continuous melt injection. Small vapor columns were coalesced to a large vapor column, which filled the coolant channel. Fig. 3(b) shows a two phase flow regime where the melt fragments were dispersed upward along the coolant vapor. The coolant vapor pressure was generated by the contact between the hot melt and the coolant in the void boundary, and the build-up vapor pressure arose in the coolant channel. Although the coolant flow velocity was zero, the melt was dispersed upward against gravity. It refers that the melt will move towards the outside of the core region even under zero flow condition if vapor pressure is built up sufficiently within the coolant channel. In test 4, the 1.61 kg of the melt was injected into the coolant channel. The amount of injected

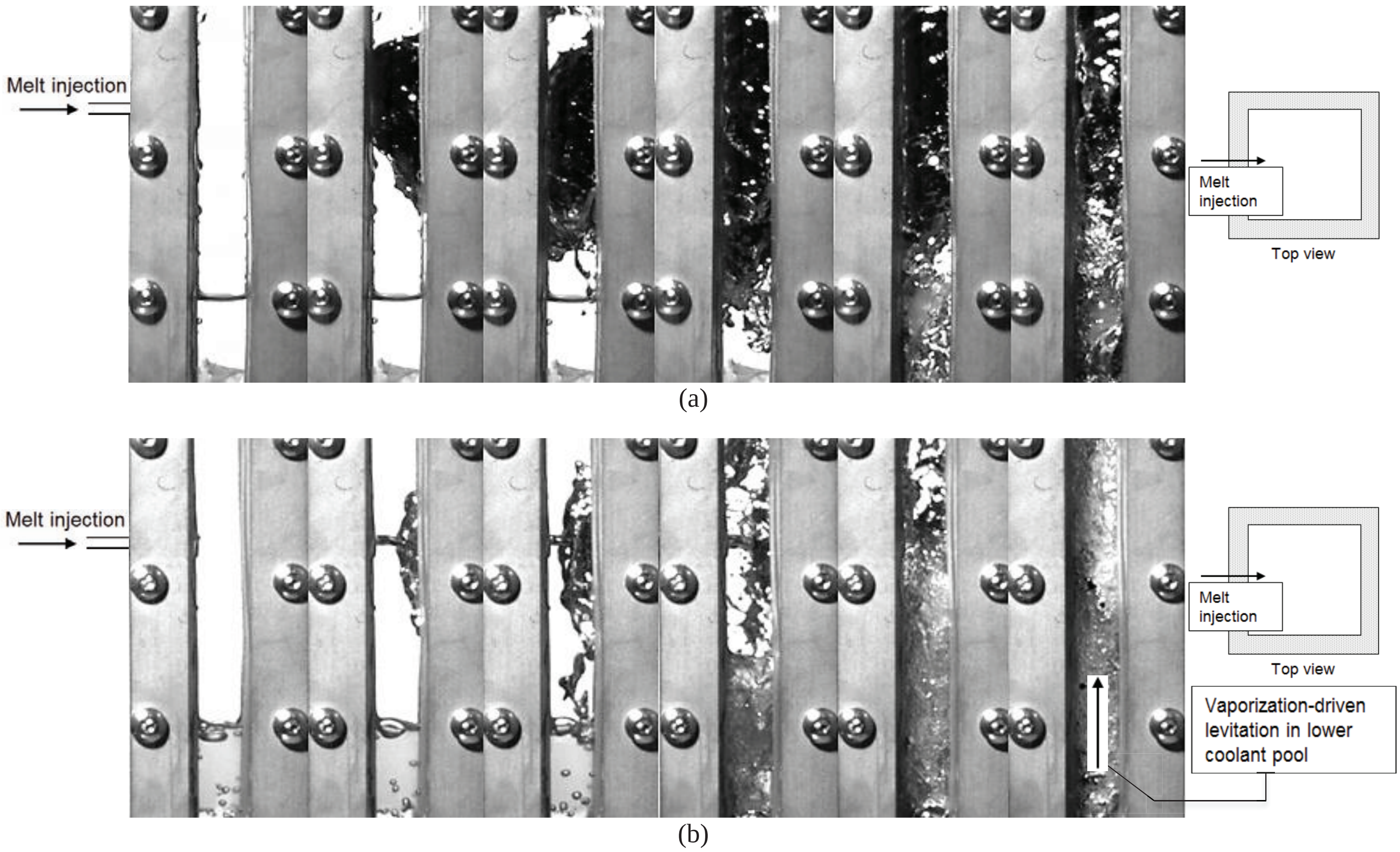

Figure 4. Melt behavior in (a) air voided water channel in test 5, and (b) air voided R123 channel in test 6.

melt was equal to the amount of the eight fuel pins based on Prototype Generation-IV Sodium-cooled Fast Reactor (PGSFR) fuel requirement. In contrast to test 4, there was not a visible driving force for the upward melt dispersion in test 3. The coolant boiling phenomena did not occur at the interface between the melt and the coolant, because the boiling point of water was higher than melt temperature. The melt was continuously injected into the coolant channel without active melt movements and was fragmented into fine particles after the melt injection. Fig. 3(a) shows melt behavior in the unvoided coolant channel under non-boiling condition.

During the melt injection, the melt was continuously injected into the coolant channel so that a part of the melt seemed to move upward by inertia of the melt. However, most of melt moved downward without refreezing phenomena due to its well fragmentation. The fragmented particles were in a various shape from sphere-like to flat sheet-like. The shapes of the particles were determined by surface solidification and contact conditions between two fluids. The fragmented particles were not agglomerated so that the coolant channel was not blocked by the fragmented particles. In this test, 1.22 kg of the melt was injected in the coolant channel, which was equal to the amount of the six fuel pins.

3.1.3. Voided coolant channel

In ULOF initiating phase scenario, the voided coolant channel is formed at the inner core region. Since there was no coolant to react with the melt after the injection, fuel-coolant interaction (FCI) did not occur. It refers that the melt fragmentation caused by reaction with the coolant did not take place. Fig. 4 shows visual results of the melt behavior injected into the coolant channel, which was observed under the voided coolant condition. The voided coolant region was formed around the melt injection point, and the coolant was filled in the bottom of the coolant channel.

As the melt was injected from the melt injection system, the injection pressure was gradually reduced in the injection system. The initiating behavior of the melt injection of test 5 was similar to that of test 6. The melt collided with the wall of the coolant channel shown in Fig. 4. A part of the melt seemed to move upward in the voided region, but most of melt moved downward without refreezing phenomena due to its high-density. When the melt fell to the coolant which was submerged in the bottom of the channel, the melt-coolant mixing took place in the boundary surface between the melt and the coolant. Through the intermixing of the melt with the coolant, the coolant boiling occurred only in test 6 due to low boiling point of R123. It led to the establishment of the coolant void from the intermixing point, where the melt and the coolant interacted with each other. The coolant void development can be established only after a stable void formation by a sufficient reduction of coolant subcooling in the coolant channel [10-11]. Since the vapor pressure was accumulated in the coolant channel, the melt in bottom of the coolant channel was upward discharged. In addition, the void development by the coolant vaporization filled the voided coolant region so that the melt in the voided coolant region moved to upper region of the coolant channel. After the coolant channel was dominated by the coolant void development, most melt fragments were dispersed upward along with the coolant vapor. Fig 3(b) shows that the melt was discharged upward beyond the coolant voided region, in which the additional driving force was induced by the build-up vapor pressure. It seems reasonable to support that melt can be discharged upward after melt dispersal in voided coolant region.

On the other hand, Fig. 4(a) shows the experimental results for the melt behavior under the non-boiling condition, in which 1.24 kg of the melt was injected into the coolant channel. In this test, the coolant boiling did not take place when melt met the coolant, due to boiling point of water of 100 ℃. Because there was no coolant boiling phenomena, there was no driving force to move the melt upward. After the melt is injected, the melt was not fragmented, and was stacked on the bottom of the coolant channel due to its high-density. It refers that if melt is refrozen and agglomerated in this case, the recriticality event may take place.

The upward melt dispersion is discussed regarding the observation and the evaluation of molten fuel discharge under several experimental conditions. The coolant vapor pressure build-up is suggested as a major cause in the upward dispersion of the melt. The sufficient reduction of the coolant subcooling can be completed under contact with the coolant. As a result, the coolant void development can be established at an earlier stage under the coolant boiling condition. From the viewpoint of the thermodynamics, the magnitude of the coolant vapor pressure build-up is related to the coolant vapor generation rate, which is dominated by the mixing ratio and the contact interface area between the melt and coolant, as well as their temperature difference [10-11]. The visual results of the current study with simulants showed that the coolant pressure build-up took place under coolant boiling condition both in voided and unvoided coolant channel. In addition, the upward melt dispersion occurred under the zero flow condition for the coolant. It should be noted here that, assuming that the coolant pressure can be built up in the coolant channel, the melt is dispersed into the outer of the core region even in ULOF initiating phase scenario. Therefore, if the reactor condition is under a certain condition similar to the current experimental condition, it will be possible to generate enough coolant vapor leading to coolant pressure build-up under the reactor conditions. That is, it refers that the molten metal fuel can be upward dispersed towards outside of the core by coolant pressure.

4. Conclusions

At the initiating phase of HCDA, the recriticality issue becomes the main safety issue of the SFR design with the metal fuel. In order to prevent the recriticality issue, the melt upward dispersion can be unique solution for early termination of the accident. Since the melt dispersion conditions are different with core region, in the present study, the specific conditions to be well dispersed for the molten metal fuel were discussed using the simulant materials. The each melt behavior was visually compared to evaluate the melt dispersion under the structural conditions, the coolant void conditions, and the boiling conditions. As the results, the following results are remarked:

1) The behavior of the melt dispersion followed the direction of rotation of the wire wrap which was tightly bound around the fuel pin. On the other hand, in the multi-pin structure, after the melt injection the partial melt was broken through the gap between pins. However, as the melt moved upward in the coolant channel, it was lumped together forming bulk melt without being concentrated in a particular direction.
2) The upward melt dispersion did not take place for a given melt and coolant temperature in the non-boiling range. Over current range of conditions, the behavior of the melt was so static that the melt was not dispersed in the coolant channel.
3) Under boiling condition, the coolant vapor pressure was built up after the melt injection in both unvoided and voided coolant channel. Following the pressure build-up, the melt was upward dispersed well enough. The build-up vapor pressure was one of driving forces for the upward dispersion of the molten materials.

These experimental results support the possibility of the upward dispersion of the molten metal fuel by the build-up coolant vapor at the initiating phase of HCDA. More experimental works for the upward melt dispersion are required to clarify the melt behavior quantitatively within coolant channel.

NOMENCLATURE

D	injection nozzle diameter	[mm]
U	velocity difference between jet and coolant	[m/s]
Fr	Froude number	[-]
We	Weber number	[-]
g	gravitational acceleration	[m/s^2]

Greek symbols

ρ	density	[kg/m^3]
σ	surface tension	[N/m]

Subscript

m	melt
c	coolant

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