Evaluation of Melt Behavior with initial Melt Velocity under SFR Severe Accidents

Hyo Heo [a], Dong Wook Jerng [b], In Cheol Bang [a*]
[a]Ulsan National Institute of Science and Technology (UNIST)
50 UNIST-gil, Ulju-gun, Ulsan, 689-798, Republic of Korea;
[b]Chung-Ang Univ., 84, Heukseok-ro, Dongjak-gu, Seoul 156-756, Korea
[*]Corresponding author: icbang@unist.ac.kr

1. Introduction

In the current Korean sodium-cooled fast reactor (SFR) program, early dispersion of the molten metallic fuel within a subchannel is suggested as one of the inherent safety strategies for the initiating phase of hypothetical core disruptive accident (HCDA). The safety strategy provides negative reactivity driven by the melt dispersal, so it could reduce the possibility of the recriticality event under a severe triple or more fault scenario for SFR [1,2]. Since the behavior of the melt dispersion is unpredictable, it depends on the accident condition, particularly core region. While the voided coolant channel region is usually developed in the inner core, the unvoided coolant channel region is formed in the outer core [3]. It is important to confirm the fuel dispersion with the core region, but there are not sufficient existing studies for them.

From the existing studies [4,5,6], the coolant vapor pressure is considered as one of driving force to move the melt towards outside of the core. There is a complexity of the phenomena during intermixing of the melt with the coolant after the horizontal melt injections. It is too difficult to understand the several combined mechanisms related to the melt dispersion and the fragmentation. Thus, it could be worthwhile to study the horizontal melt injections at lower temperature as a preliminary study in order to identify the melt dispersion phenomena. For this reason, it is required to clarify whether the coolant vapor pressure is the driving force of the melt dispersion with the core region.

2. Experimental setup

The experimental apparatus was composed of test section, condensers, power controller, and data acquisition system. The first stage of power is 250W. After the steady-state condition has been reached, a stepwise power escalation was initiated with increments of 250W. Each power step lasted 10 min until a new steady state was achieved. In the test, two candidates were proposed as the flooding conditions, as shown in Figure 2. The bubble behavior for heat removal characteristics of new ERVC was observed on the heated surface, using a high-speed video camera (1000 frames per second).

The melt injection system was pressurized by 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. The experimental conditions were set up to get visibility for the melt dispersion behavior. In all cases, the initial melt injection pressure was kept at around 0.5 MPa under zero flow condition. The first case and the second case were intended to confirm the contribution of the build-up vapor pressure in the unvoided coolant channel. The third case was intended to investigate the effect of the coolant void, so the experiment was conducted in the voided coolant channel. The fourth case seemed similar to the third case, but the coolant boiling was considered only in the fourth case.

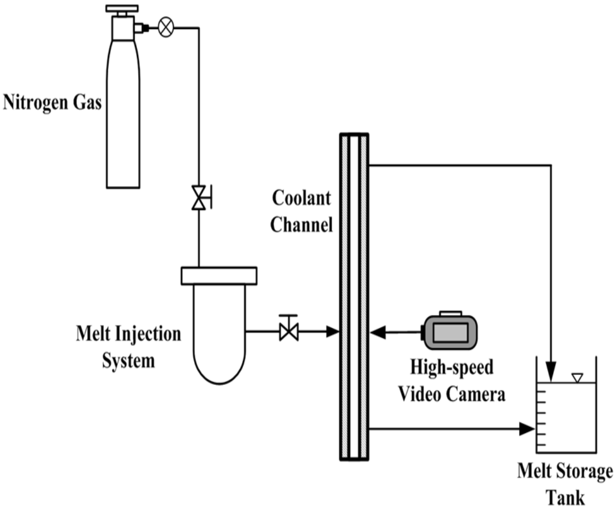


Fig. 1. Scheme of experimental apparatus.

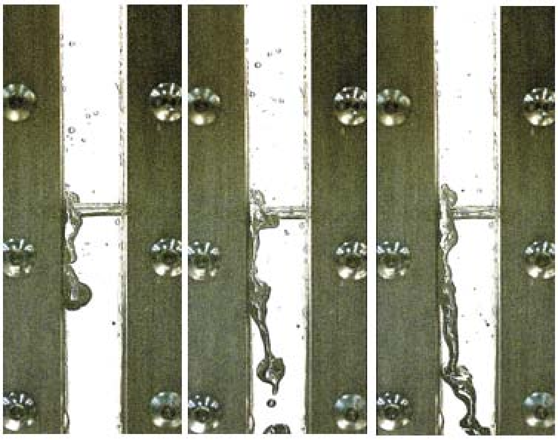
Table I: Physical properties of molten materials and coolants

	Actual materials		Simulant materials	
	Metal	Sodium	Gallium	Water

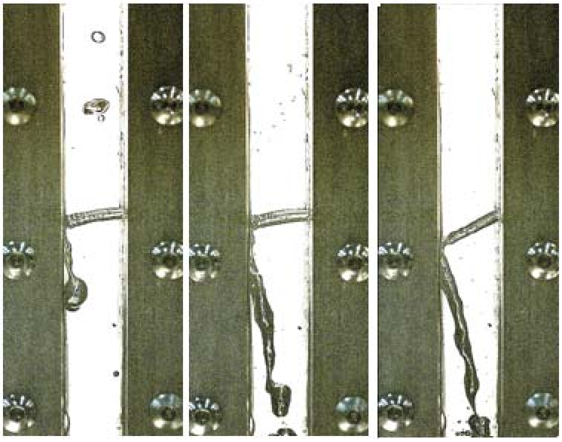
	fuel			
Density (kg/m^3)	14100	966	6095	998
Surface tension (N/m)	0.57	0.20	0.74	0.07
Viscosity (mPa·s)	$5.0 \cdot 10^{-3}$	1.1	$1.9 \cdot 10^{-3}$	1.0
Melting / Boiling point (℃)	1077 / -	- / 881	30 / -	- / 100

3. Experimental results and discussion

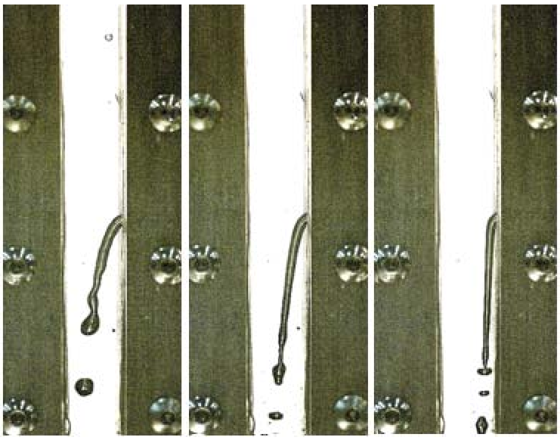
Figure 3 shows the bubble behavior on the heated surface with power and oil flooding condition. The difference between case 1 and case 2 is the effective boiling heat transfer area. The effective boiling heat transfer area would be different depending on the flooding condition. The area of the small hemispheric geometry made of the copper is an effective boiling heat transfer area in case 1. When the oil was flooded, the effective boiling heat transfer area changed. The effective boiling heat transfer area will be an enlarged area of the hemispheric geometry and a portion of the cylindrical geometry on the catcher structure.



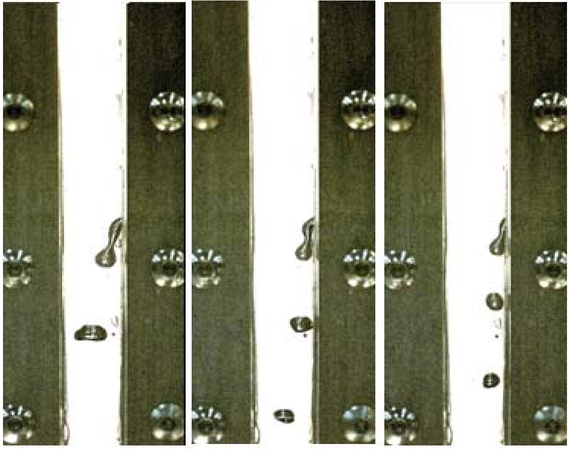
(a) Case 1



(b) case 2



(c) case 3



(d) case 4

Fig. 2 Behavior of the melt dispersion in coolant-filled channel

When the oil was flooded as the new IVR-ERVC concept, we can observe different nucleation site on the catcher structure in comparison with that of case 1 at the same power conditions. In case of oil flooding test, the nucleation site was localized on the surface of heated object, as shown in Figure 4. It was driven by natural convection of oil with high Prandtl number. The amount of generated vapor was increased when the high power of the cartridge was applied. The temperature of the surface would also be dropped owing to rapid quenching. The quenching was caused by the developed bubble which was gone away from the heated surface. The single phase heat transfer was in major heat transfer mode on the cooper structure.

The different bubble behavior was observed in the heated surface beyond 1000W at both flooding condition. The small-size bubble merged into larger one along with the heated surface. The formation of larger bubbles or higher void fraction is considered as an indicator of critical heat flux condition causing critical damage on the reactor vessel. The formation of larger bubbles or higher void fraction is considered an indicator of the CHF condition causing critical damage to the reactor vessel. In the oil flooding concept, heat was dissipated more slowly through the oil itself. This physical phenomenon can lead hot spot on the heated object. Even though the enlarged heat transfer area is considered the factor for preventing CHF, heat transfer mode by natural convection can increase thermal load to reactor pressure vessel.

4. Conclusions

The specific conditions to be well dispersed for the molten metallic fuel were discussed in the experiments with the simulant materials. The each melt behavior was compared to evaluate the melt dispersion under the coolant void condition and the boiling condition. As the results, the following results are remarked:

1. The upward melt dispersion did not occur 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.
2. Under boiling condition, the coolant vapor pressure was built up after the melt injection in both unvoided and voided coolant channel. Following the pressure buildup, 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 metallic 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 within coolant channel, including a structure to simulate fuel rod.

REFERENCES

[1] Y. Abe, T. Kizu, T. Arai, H. Nariai, K. Chitose, and K. Koyama, Study on thermal-hydraulic behavior during molten material and coolant interaction, Nuclear engineering and design, Vol. 230, pp. 277-291, 2004.

[2] T. H. bauer, A. E. Wirght, W. R. Robinson, and A. E. Klickman, Behavior of metallic fuel in TREAT transient overpower tests, Argonne National Laboratory, 1998.

[3] I. Sato, Y. Tobita, K. Konishi, K. Kamiyama, J. Toyooka, R. Nakai, S. Kubo, S. Kotake, K. Koyama, Y. Vassiliev, A. Vurim, V. Zuev, and A. Kolodeshnikov, Safety strategy of JSFR eliminating severe recriticality events and establishing in-vessel retention in the core disruptive accident, Journal of nuclear science and technology, Vol.48, no.4, pp. 556-566, 2010.

[4] E. Matsuo, Y. Abe, K. Chitose, K. Koyama, K. Itoh, Study on jet breakup behavior at core disruptive accident for fast breeder reactor, Nuclear engineering and design, Vol. 238, pp. 1996-2004, 2008.

[5] T. N. Dinh, V. A. Bui, R. R. Nourgaliev, J. A. Green, B. R. Sehgal, Experimental and analytical studies of melt jet-coolant interactions: a synthesis, Nuclear engineering and design Vol. 189.1, pp. 299-327, 1999.

[6] K. Matsuba, M. Isozaki, K. Kamiyama, and Y. Tobita, Experimental study on upward fuel discharge during core disruptive accident in JSFR: Results of and out-of-pile experiment with visual observation, The19th International Conference on Nuclear Engineering (ICONE-19), ICONE19-43993, 2011.

[7] K. Matsuba, M. Isozaki, K. Kamiyama, and Y. Tobita, Mechanism of upward fuel discharge during core disruptive accidents in sodium-cooled fast reactors, Journal of engineering of gas turbines and power, Vol. 135, 032901-1, 2013.

[8] Matsuba, K., Imahori, S., and Isozaki, M, Experimental Study on Void Development Behavior in a Simulated Coolant Channel, Proceedings of the 6th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Paper No. N6P077, 2004.