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Solidification Characteristics of Wood's metal Simulating Debris in SFR Severe Accident

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1. Introduction

Though the occurrence of hypothetical core disruptive accident (HCDA) for metal-fueled sodium-cooled fast reactors (SFRs) is extremely unrealistic due to the denying actuations of all multiple safety systems, it is still emphasized from the viewpoint of safety designs and evaluation. One of major concerns in the safety of fast reactors has ensured the core coolability for the decay heat removal by natural convection. The HCDAs are considered to occur from both serious loss of cooling and transient overpower conditions without activation of reactor scram. Under the initiating phase of HCDA, the pin failure occurs with the ejection of molten fuel into the subchannel. The melt stream is fragmented by its impact onto surrounding claddings and core structures and instantaneously frozen inside the core. The frozen melt particulates, called debris, form the debris bed with their deposition. Since the porosity of debris bed is basically determined by the debris characteristics like its morphology, solidification behavior of the melt should be clearly clarified.

Numerous studies on debris coolability are found in the scientific literature, ranging from the fundamental studies in the early 80's [1-4]. In previous studies for the debris coolability, wood's metal (Bi-Pb-Sn-Cd eutectic alloy) was usually used to simulate molten fuel due to its low melting point of 72°C [5-8]. In addition, the simulant material was also used to simulate molten oxide fuel because the density ratio of wood's metal to water was comparable to that of the molten oxide fuel to the sodium [9-10]. The density ratio was a key parameter related to the hydrodynamic instability of melt-coolant system. Most of the debris coolability experiments have used typically wood's metal as the melt material, only considering thermal-hydraulic performance. While the realistic debris morphology is formed depending on the microstructural characteristics, the debris coolability study based on the crystallization was rarely performed. From this point of view, there was insufficient consideration as to whether it was appropriate to use wood's metal as the simulant material for in this respect.

In the present study, the microstructural analysis was carried out with both particulates of wood's metal before and after solidification. Since the wood's metal is eutectic alloy consisted of four materials (bismuth, tin, lead, and cadmium), solidification behaviors of that would be complicated during the solidification. Thus, using energy dispersive spectroscopy (EDS), changes of material compositions in the wood's metal during the solidification were experimentally investigated. Then such experimental results were discussed with the material similarity for the reactor material.

2. Experimental methods

Figure 1 shows a schematic diagram of UNIST test facility for molten fuel and coolant interaction (UNICORN). The test facility is composed of a crucible and a coolant channel. The initial temperature and pressure of melt was controlled in the crucible. The hydraulic diameter of the coolant channel is 50 mm. The inner diameter of the melt injection nozzle is 10.4 mm. The molten material was injected horizontally into the channel by controlling of two pneumatic valves. The test conditions of the experiment are listed in Table I. All tests were performed under zero-flow condition assuming the unprotected loss-of-flow (ULOF) accident.

Physical properties of reactor and simulant materials used in the experiments are listed in Table II [11]. Since the cooling rate is key parameter in the solidification of melt, the molten wood's metal of 250°C is frozen both in water and air considering the effect of cooling rate in such molten material and coolant interaction. The present study focused on microstructural characteristics of both wood's metal particulate before and after solidification.

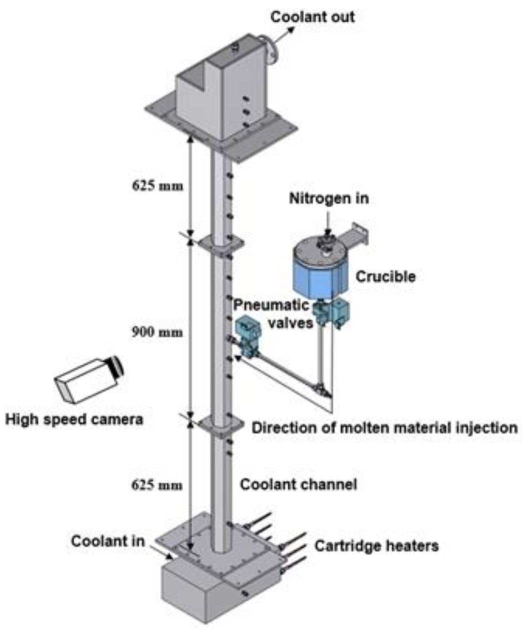


Fig. 1. Schematic diagram of UNICORN

Table I: Test matrix

Test No.	1	2
Melt/Coolant material	Wood's metal/ Water	Wood's metal/ Air
Initial melt injection pressure (bar)	5	5
Melt/Coolant temperature (°C)	250/22	250/23
Melt weight (kg)	0.18	0.18
Maximum cooling rate (K/s)	1.01·108	8.73·107

Table II: Physical properties of reactor and simulant materials [11]

	Reactor materials		Simulant materials		
	Metal fuel	Sodium	Wood's metal	Water	Air
Density (kg/m^3)	17400	966	9383	998	1.2
Thermal conductivity (W/m/K)	26	71.2	12.8	0.6	0.03
Specific heat (J/Kg/K)	201	1272	172	4179	1005
Thermal diffusivity ($\times10^{-6}$ m^2/s)	7.4	57.9	7.9	0.1	24.9
Thermal effusivity ($J/m^2/K^1/s^{0.5}$)	9542	9353	4545	1582	6
Melting /boiling point (°C)	1340/-	98/883	72/-	0/100	-/-

3. Results and discussion

To obtain wood's metal debris, the solidification tests were conducted according to the test matrix. Then, material compositions for wood's metal were investigated using EDS analysis. In addition, as a reference data, the microstructural analysis of bare wood's metal particulate is also performed for evaluating the material composition.

2.1 Bare wood's metal particulate

The wood's metal has the four material compositions and they are well mixed in all the grain because it is eutectic alloys. Figure 1 shows the result of EDS image for bare wood's metal particulate. As mentioned, there are mixture compositions in all grains of the particulate.

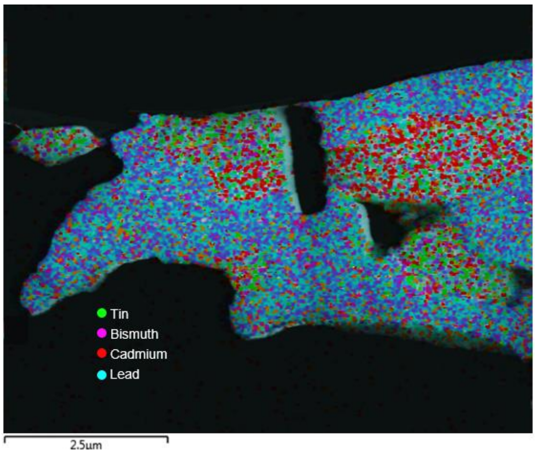


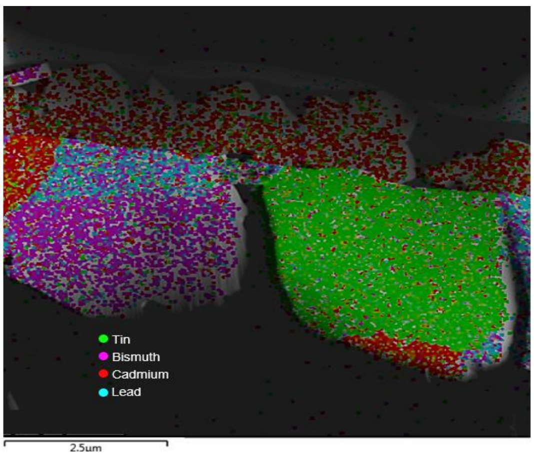
Fig. 2. Result of EDS image for bare wood's metal particulate

Although the component analysis was carried out only from EDS sample, such material compositions of the sample could be represented of bare wood's metal particulate because the metal has the identical crystal structure in the grain.

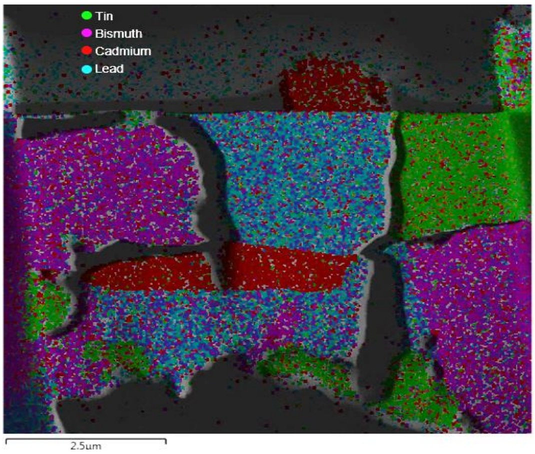
2.2 Wood's metal debris after solidification

During the solidification of the melt, the nucleation and crystal growth is mainly affected by the cooling rate. The two materials were used as the coolant for reflecting such effect of cooling rate: water and air. The cooling rates in water and air cooling condition were $1.01\cdot10^8$ K/s and $8.73\cdot10^7$ K/s, respectively. They were numerically calculated using the commercial CFD code.

Figure 2 shows the EDS images for wood's metal debris formed from the water and air cooling condition. In water cooling condition, the composed materials were clearly partitioned compared to that of bare wood's metal particulate. Although each material is not perfectly partitioned in eutectic matrix, it was found that rich-regions by each material were divided into different grains. This material partitioning was also observed in the air-cooled condition. As shown in Fig. 3 (b), each



(a) wood's metal debris from water-cooled condition (250 °C wood's metal-22 °C water)



(b) wood's metal debris from air-cooled condition
(250 °C wood's metal-23 °C air)

Fig. 3. Results of EDS images for wood's metal debris formed from (a) water and (b) air-cooled conditions

material which composed of eutectic alloy was partitioned. Thus, it was revealed that the material composition for wood's metal were individually partitioned during the solidification. The partitioned materials have their own crystal structure. It means that crystal growth rate of each material determining the debris morphology would vary with their crystal structures. Since the debris morphology is formed depending on such microstructural characteristics, the debris coolability evaluated using wood's metal might not give directly insight the debris coolability of the reactor material according to experimental conditions. To ensure effectiveness of material similarity in the cooling capacity of debris, reasonable solidification conditions that simulate the performances of the reactor material based on crystallization should be selected.

4. Conclusions

The solidification characteristics of wood's metal were experimentally investigated. After a solidification of wood's metal (Bi-Pb-Sn-Cd eutectic alloy), mixed-zone with various materials in bare wood's metal was partitioned into each material forming the eutectic alloy (under both water and air-cooling condition). Such microstructural characteristics should be examined whether the wood's metal is a proper material to simulate the reactor material concerning the debris coolability. As a further work, clear solidification conditions using the wood's metal, which could simulate the solidification behavior of the molten fuel, would be elucidated.

ACKNOWLEDGEMENTS

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