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Debris Bed Analysis in Discharge of the Molten Fuel through Lower Structure of Fuel Assembly in PGSFR

Min Ho Lee [a], Hyo Heo[a], Dong Wook Jerng [b], In Cheol Bang [a*]
[a]*Department of Nuclear Engineering, Ulsan National Institute of Science and Technology (UNIST),*
50 UNIST-gil, Ulju-gun, Ulsan 44919, Republic of Korea
[b]*School of Energy Systems Engineering, Chung-Ang Univ.,*
84 Heukseok-ro, Dongjak-gu, Seoul 06974, Republic of Korea
[*]*Corresponding author: icbang@unist.ac.kr*

1. Introduction

Sodium-cooled fast reactor (SFR) is the one of the generation-IV reactors and most promising one thanks to its operation experience and good thermal properties of the sodium. In Korea, prototype generation-IV SFR (PGSFR) was selected as government lead project and research about PGSFR has been conducting. The main characteristic of the PGSFR is metallic fuel [1]. Metallic fuel showed superior performance to oxide fuel in terms of safety as higher power at rupture in transient overpower (TOP) accident situation [2]. Not only accident tolerance in TOP accident, in unprotected loss of flow (ULOF) and unprotected loss of heat sink (ULOHS), metallic fuel showed its safety in both experimental and numerical way in EBR-II [3]. Metallic fuel has advantageous in the point of reactivity feedback in accident situation, thermal performance, and compatibility with sodium coolant [4].

Despite of these good safety characteristics, safety analysis should be conducted in each phase of the accident. If fuel melts, it is often ejected into coolant channel after failure of the cladding by accumulated pressure by fission gas inside of the cladding. Some part of the ejected molten fuel goes upward by expansion of the pressurized fission gas and sodium boiling. The others stick to the cladding or discharge to the downward direction through lower structures of the fuel assembly. Discharge behavior of the molten fuel is crucial for negative feedback for early termination of the accident and coolability of discharged fuel in terms of re-melting. To discharge the molten fuel easily and assure safety in severe accident, fuel assembly with inner duct structure (FAIDUS) has been suggested in Japan for oxide fuel [5]. If discharged fuel forms not coolable geometry or sufficient mass debris bed which makes us consider re-criticality of the debris bed, the accident will be more complicated and progressed.

To analyze behavior of the molten fuel, in this paper, it will be conducted that molten fuel discharges from the core to sodium pool through lower structures of the fuel assembly of PGSFR focusing on coolability of the debris bed. It will be analyzed that the place where sedimentation of the fragmented fuel can take place inside of the lower structures and porosity of the deposited debris bed using simulants. Visualization analysis will also simultaneously be conducted to provide physical and phenomenological insight.

2. Experimental Method

There are two kinds of experimental apparatus for discharge of the molten fuel. One is simplified one with transparent materials for visualization, which was used in LOF-DT01 experiment and the other is exact same structure with lower structures of PGSFR, which was used in LOF-DT02 experiment.

Lower structures of the fuel assembly consist of lower reflector, nose piece, and receptacle. Apparatus for LOF-DT01 was made of transparent acryl and inner structure which has very similar equivalent diameter of each part. It is illustrated in figure 1, about 2/5 scaled down in axial direction, and about 1/2 scaled down in radial direction to get phenomenological insight before main experiment. Lower reflector was simplified with similar equivalent diameter of three branched flow path. Nose piece which were anticipated to play an important role were not simplified. Orifice in the receptacle were reflected as stainless steel orifice with 1/2 scaled down to original scale.

Each part LOF-DT02 is separately arranged in figure 2. Objective of LOF-DT02 is to conduct experiment with exact same geometry with lower structures of PGSFR. Accordingly, apparatus for LOF-DT02 was 1/2 scaled down in both axial and radial direction. It was made of opaque plastic and made by using 3D printer to describe the geometry in detail.

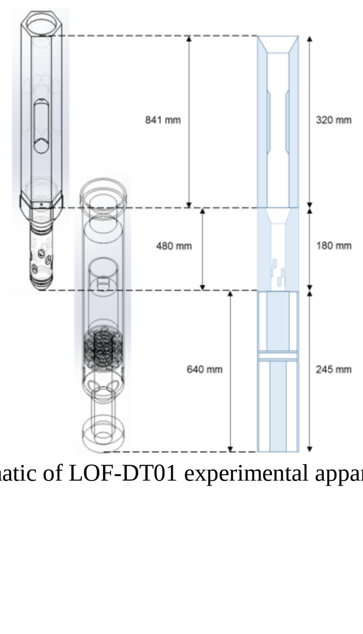

Fig. 1. Schematic of LOF-DT01 experimental apparatus.

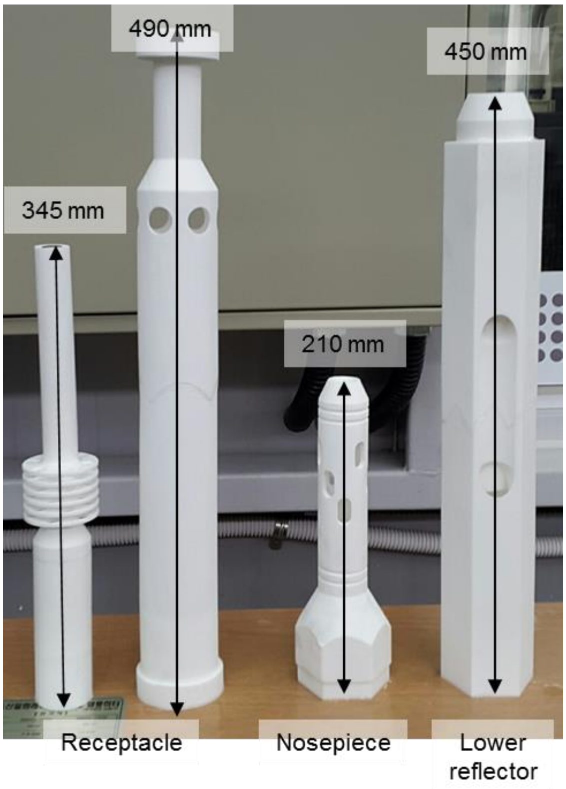

Fig. 2. Each part of for LOF-DT02 experimental apparatus.

Experimental conditions were set considering phenomena and properties of the original and simulants. Comparison between real material and simulants are in Table I. Wood's metal was selected for similar density, conductivity and surface tension, and water was selected for similar density and visualization. Parameters of this experiment are melt temperature, mass of melt, melt jet velocity, melt jet diameter, pool temperature, and height of the pool. Melt temperature was set as superheat of the melt from its melting point. In SAS4A analysis, 400°C of the superheat was observed in maximum. 200°C of the superheat was set to understand phenomena. Mass of melt was set as 7-pin failure case. In real scale, 180 g of the wood's metal has same volume with single pin failure case. By linear scaling, 1/8 of the 180 g is single pin rupture mass and for 7-pin, 157.5 g of the wood's metal was used. Jet diameter was 1/8 inch, which is similar with equivalent diameter of subchanel. Jet velocity depends on the height of the sodium pool. It was assumed that sodium in active core was evaporated, so melt jet speed can be calculated from vertical distance between active core and lower reflector, as 1 m/s. For pool temperature, it is hard to set the value because in real situation, boiling point of the sodium is lower than melting point of the fuel, however, boiling points of the water is higher than melting point of the wood's metal. Main characteristic of the metallic fuel is rapid cooling in the sodium coolant due to its high thermal conductivity and small heat capacity. To maximize temperature difference, temperature of the water was set as 10°C, to simulate rapid quenching in molten wood's metal and water.

Table I: Properties of the materials

	Material	Melting point (°C)	Liquid density (kg/m^3)	Heat capacity (kJ/kg.K)	Thermal conductivity (W/m.K)	Surface tension (N/m)
Molten material	Metal fuel	1077	14100	0.2	16	0.8
	Wood's metal	**72**	**9383**	**0.168**	**18.8**	**~1.00**
	Field's metal	62	6740	0.184	10	-
	Gallium	29.8	6095	0.026	13.6	0.7
Coolant	Sodium	881	966	1.23	142	0.2
	Water	**100**	**998**	**4.2**	**0.591**	**0.073**
	Acetone	57	75	2.21	0.161	0.035
	Glycerol	290	1261	2.4	0.285	0.063
	Paraffin oil	200	800	2.13	0.15	0.026

Table II: Experimental condition for LOF-DT01 and 02

Parameters	Value
Melt temperature	280°C
Pool temperature	10°C
Mass of melt	157.5 g
Jet velocity	1 m/s
Jet diameter	1/8 "
Height of pool	Out of active core region

3. Result & Discussion

3.1 LOF-DT01

LOF-DT01 test was conducted in transparent pipe. Fragmented fuel sedimentation was like in figure 3. There was little amount of the wood's metal was adhered on the channel wall. Adhered melt at the top is only 0.39 g of total 157.5 g. It means that the rapid quenching of the metal fuel was successful because the molten wood's metal was frozen rapidly before contact with channel wall.

Most of the fragmented melts were distributed in between lower reflector and nose piece. Debris in receptacle orifice was about 1.29 g, and discharged debris through all the lower structures was only 0.38 g. On the contrary, bottleneck between lower reflector and nosepiece had 117.74 g, and nosepiece has 25.07 g of debris. Bottleneck also exists in the lower reflector structure. However, inside of the lower reflector did not showed sedimentation of the debris. Because debris areal density at certain moment is the main parameter for blockage. If areal density of the debris is high, there are larger chance to blockage. Melt fell into the lower reflector as speed of 1 m/s and loss its speed till terminal velocity as 0.6 m/s due to water. It means that areal density of the debris at the upper region is 1.6 times lower than that of the higher region. In other words, areal density of the debris at the bottleneck in the lower reflector structure is lower than that at the bottleneck between lower reflector and nosepiece. Smaller amount debris which passed bottleneck before blockage accumulated in the nosepiece structure.

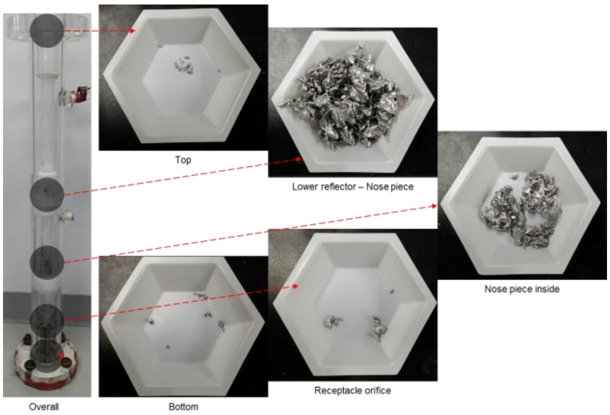

Fig. 3. Debris distribution and shape in LOF-DT01.

3.2 LOF-DT02

LOF-DT02 was conducted in detailed geometry by 3D printer. However, it did not show significant difference to LOF-DT01. Similarly, no debris was observed at the top. And before three branched flow path in the lower reflector structure, most of the debris accumulated forming almost blockage shape. Most of remaining debris were in nosepiece and very small amount of the exists orifice and the bottom. Exact amount of the debris is in the table III.

Table III: Debris distribution of LOF-DT01 and 02

Experiments	Location	Fraction	Amount
LOF-DT01	Top	0.3 %	0.39 g
	Lower reflector - Nosepiece	81.1 %	116.74 g
	Nosepiece	17.4 %	25.07 g
	Receptacle orifice	1.0 %	1.29 g
	Bottom	0.3 %	0.38 g
LOF-DT02	Top	0 %	0 g
	Lower reflector	78.7 %	120.83 g
	Nosepiece	16.0 %	24.62 g
	Receptacle orifice	5.2 %	8.00 g
	bottom	0 %	0 g

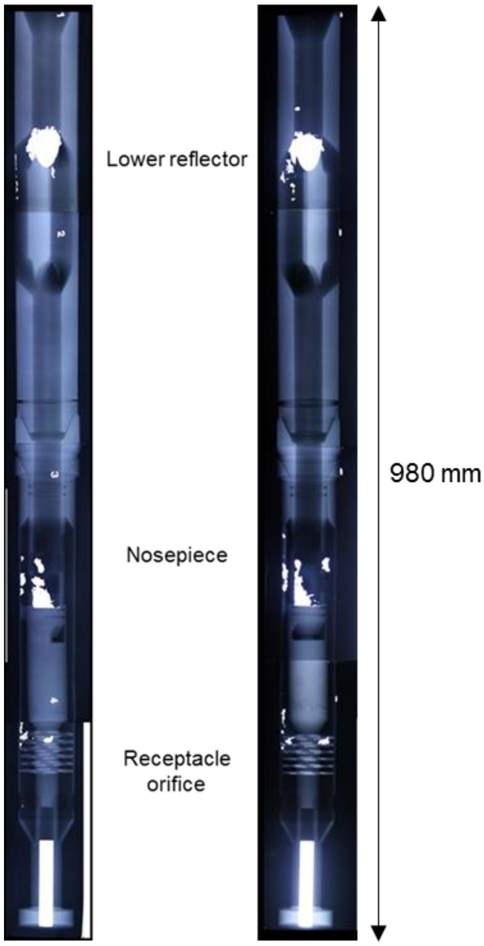

Fig. 4. Debris distribution in LOF-DT02 by X-ray.

To get the visualization result, X-ray was selected and its result is in figure 4. White regions represent debris and white bar at the bottom is weight to submerge experimental apparatus into water. LOF-DT02 showed that by simulating hydraulic equivalent diameter, fuel discharge behavior can be simulated.

3.3 Porosity Analysis

Natural circulation of sodium is necessary for passive cooling under ULOF. Therefore, coolability of the debris can be determined by pressure drop along the debris and porosity in the experiments can represents the pressure drop. The pressure drop values are summarized for both LOF-DT01 and 02 in table IV. Omitted part showed no significant amount of the debris to form the porous structure. Porosity of the debris was measured by two method. One was mass based and the other was volume based. For all the cases except for lower reflector in LOF-DT02, they showed high porosity as 0.8. It is sufficiently high to get small amount of pressure drop through debris. Only one, lower reflector in the LOF-DT02 showed significant lower porosity. It is because of existence of the obstacle inside the channel. Unlike other parts, three branched flow path has dividing structure in the center and this structure encourages debris sedimentation and debris bed formation. And by geometry of the flow path, the vertical component of the velocity is changed to transverse direction by collision between some structures, which can be dividing structure or pre-built debris bed. And this collision made the debris bed denser and had lower porosity than others.

Porosity showed similar values regardless of its measurement method in all cases except for the lower structures in LOF-DT02. Mass based porosity is larger than volume based porosity by significant difference about 10%. It means that there could be closed pore. Unlike other parts, it has three branch dividing structure in the center of the flow path. As mentioned in previous paragraph, debris bed undergoes compression by collision of debris changing direction. During this collision, the open pore can be changed to closed pore by compression. Therefore, porosity by the two methods were different each other.

Table IV: Porosity of the debris bed

Exp.	**LOF-DT01**		**LOF-DT02**	
Location	Lower reflector – Nosepiece	Nosepiece	Lower reflector	Nosepiece
Fraction	81.10%	17.40%	78.70%	16.00%
Volume of debris	12.9 ml	2.8 ml	15.2 ml	3.1 ml
Volume of debris region	63.3 ml	16.7 ml	31.1 ml	24.1 ml
Porosity (mass based)	80.10%	84.50%	60.00%	89.50%
Porosity (volume based)	83.30%	79.60%	51.10%	87.10%

4. Conclusion

Two kinds of experiments about discharge of the molten fuel through lower structures of the fuel assembly from the active core region to out of the core were conducted, LOF-DT01 and LOF-DT02. They were conducted by using simulants water and wood's metal. In both experiments, about 80 % of the melts was founded in lower reflector and 15 % of the melts was founded in nosepiece. Different to original concern, melt was not accumulated at the receptacle orifice because the most of the debris was stuck before receptacle.

Porosity was measured as high as about 80 %, which can secure low pressure drop. Three branched path in the lower reflector showed lowest porosity about 60 % by mass based and 51 % by volume based. Change of the flow direction from vertical to branch of the three paths caused compression of the debris bed. Simultaneously, it suggests existence of the closed pore in debris in the lower reflector region.

To develop analysis method for coolability, analysis on pressure drop of debris with location, mass and porosity should be conducted. And downward discharge behavior should be confirmed by more realistic simulant or real material.

ACKNOWLEDMENT

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