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Degradation of natural circulation by lower discharge of the molten fuel in severe accident of SFR

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1. Introduction

Prototype of the SFR has been developed, named as prototype Gen-IV SFR (PGSFR) with metallic fuel. Because of low power about 150 MWe and large volume of the sodium pool, PGSFR has large safety margin for hypothetical core disruptive accident (HCDA). Moreover, characteristics of the metallic fuel have advantageous to accident resistance [1]. Safety under transient over power (TOP), even unprotected transient over power (UTOP) was demonstrated by using system code [2]. In the experiments, metallic fuel contributed to the accident mitigation by its inherent safety in terms of reactivity [3].

However, in loss of flow (LOF) accident, safety margin of temperature for sodium boiling, which is a criterion for safety, was estimated the lowest so that probability of HCDA is highest in the LOF condition [4]. As fuel pins were failed in the LOF condition, it was revealed that sodium coolant was already boiled [5, 6]. In that kind of situation, ejected molten fuel cannot move upward and it will be discharge downward. Downward discharge fuel will be deposited in the lower structures of the assembly and it can degrade coolability of the overall assembly. There have been some researches related to debris formation of the metallic fuel. However, coolability degradation with debris bed in the lower structures of the assembly has not been researched.

In this study, coolability of the lower structures of the damaged subassembly was analyzed through three parts. Sedimentation positions of the debris were obtained from LOF-DT series, pressure drop of the lower structures of the fuel assembly was experimentally studied, and various situations were parametrically analyzed with CFD.

2. LOF-DT experiments

2.1 Experimental methods

LOF-DT series is the experiments designed as drop of the molten metal on to the top of the lower structures of the PGSFR fuel assembly which is filled with coolant. Wood's metal Wood's metal was selected for simulant of metallic fuel considering density, heat capacity and thermal conductivity. And water was selected for simulant of the sodium coolant because water have similar density to sodium coolant and highest thermal conductivity and surface tension compared to other candidates.

Test matrix was summarized in Table I. DT-01 was conducted in transparent test section with equivalent hydraulic diameter for visualization of sedimentation process. From DT-02 to DT-06, they were tested in the exact same geometry with PGSFR lower structure, which was made by 3D printer. The original shape of DT02 - 06 and modified by equivalent hydraulic diameter of DT 01 were presented in figure 1.

Table I. Test matrix of LOF-DT series

#	T_{melt}	T_{pool}	M_{melt}	V_{jet}	D_{jet}
DT01	280℃	10℃	157.5 g (41 pin)	1 m/s	1/8 “
DT02					
DT03			233.1 g (61 pin)		
DT04					
DT05					
DT06	117℃				

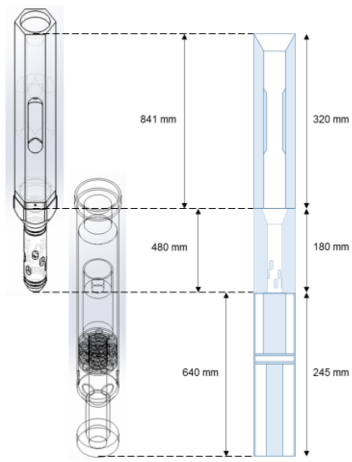

Fig. 1. Schematic of LOF-DT series experimental apparatus.

2.2 Results and discussion

To get the visualization result, X-ray was selected and its images are in figure 2. Bright white regions represent debris bed and pale white regions represent solid part of the experimental apparatus. Based on the X-ray results, debris distribution and porosity were summarized in Table II and figure 3. To distinguish closed pore and open pore, both mass-based and volume-based measuring technique were used.

In the all cases, about 80 % of the debris were deposited in the lower reflector region. And the porosity was about 0.7. About 15 % of the debris were deposited in the nose piece and its porosity is about 0.8. Although various melt temperature, melt mass case had been tested, there was no significant difference in the porosity or deposited fraction. The only exceptional case was the LOF-DT02's lower reflector. Compared to other cases, porosity was the lowest and there was significant difference between mass-based porosity and volume-based porosity. This was because of flaw in the beginning of the branched path in the lower reflector. After revising it, both porosity showed similar values and it means that no closed pore was observed.

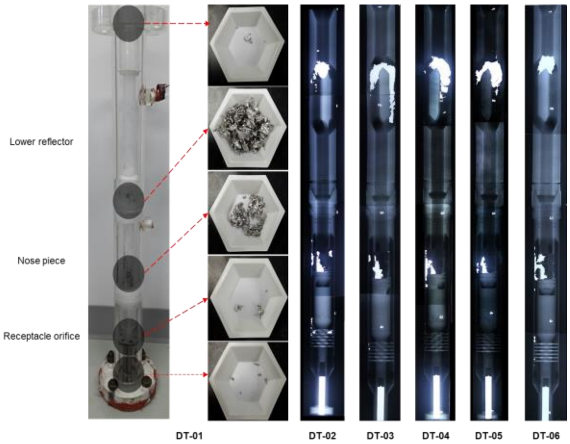

Fig. 2. Debris distribution of the LOF-DT series by X-ray

Table II. Summary of LOF-DT series

#	Location	Deposited fraction	Porosity	
			(mass based)	(volume based)
DT01	Lower reflector – Nose piece	0.811	0.801	0.833
	Nose piece	0.174	0.845	0.796
DT02	Lower reflector	0.787	0.6	0.511
	Nose piece	0.16	0.895	0.871
DT03	Lower reflector	0.864	0.732	0.701
	Nose piece	0.129	0.865	0.838
DT04	Lower reflector	0.879	0.705	0.678
	Nose piece	0.113	0.881	0.868
DT05	Lower reflector	0.897	0.702	0.698
	Nose piece	0.1	0.847	0.878
DT06	Lower reflector	0.82	0.654	0.663
	Nose piece	0.174	0.847	0.878

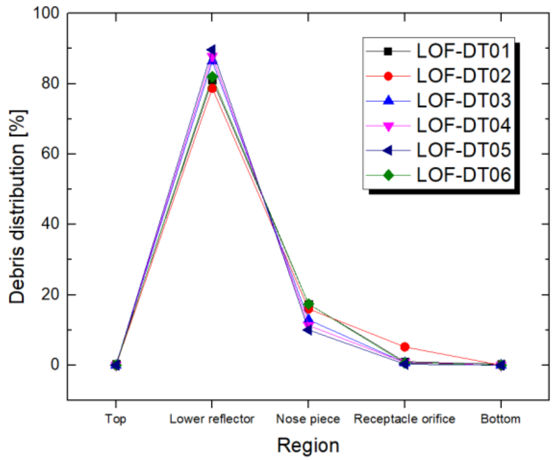

Fig. 3. Debris distribution of the LOF-DT series

3. Pressure drop Experiments

3.1 Experimental method

In the accident condition, decay heat of the core was removed by natural circulation of the sodium. In the natural circulation condition, pressure drop of the fuel assembly determines the flow rate and coolability of the assembly itself. Therefore, increase of the pressure drop after lower discharge of the molten fuel was selected as parameters for evaluating coolability. In the aspect of coolability, single assembly failure case is the most severe scenario. Because in the parallel flow channel, flow decreases the most in single channel. Flow decrement in the damaged subassembly will be transferred to adjacent subassembly. Therefore, flow decreases the most in the damaged assembly.

Among the LOF, one pump seizure (OPS) case showed the most drastic decrease of the flow rate and small natural circulation flow rate. Based on OPS case, parameters related to the flow rate was determined like Table III. It is well known that drag or pressure drop coefficient ξ is the function of the Reynolds number. To obseve increment of the ξ after lower discharge of the molten fuel, similarity was assured by Reynolds number and its difference is less than 1 % between PGSFR and experiments condition. Average velocity in the unified flow path in the lower reflector is about 0.306 m/s in PGSFR. For given condition, Reynolds number is about 67,000 and it corresponds to the 1.310 m/s and 220 lpm in the experimental condition with water.

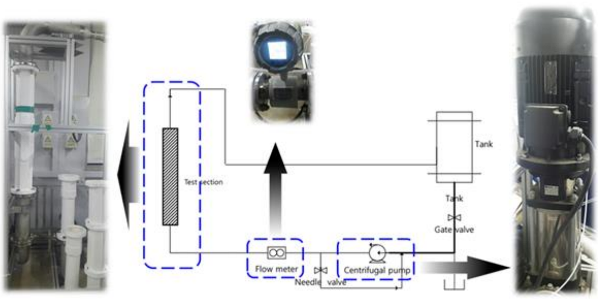

Fig. 4. Schematic of pressure drop experimental loop

Table III. Parameters of the experimental condition

	PGSFR	Experiments
Fluid	Sodium	Water
Density [kg/m^3]	828	997
Velocity [m/s]	0.306	1.46
Diameter [m]	0.06	
Viscosity [mPa.s]	0.227	1.310
Re [ ]	6.692 x 10^4	
$T_{reference}$	800 K	10^{o}C

Schematic diagram of the pressure drop experiments was presented in the figure 4. Similar to the LOF-DT series, test sections were made by 3-D printer in real scale. Considering the results of LOF-DT series, the porous debris bed had only open pores. Debris beds were simulated as porous body with open porous structures. In the aspect of porosity, from 0.60 to 0.73 were observed in the lower reflector and from 0.80 to 0.90 were observed in the nose piece. Representatively, 0.6 was selected for lower reflector and 0.8 was selected for nose piece for conservatism. By observing sedimentation position, meaningful debris beds were generated in the one branch of the lower reflector and dividing part. Representative debris bed height in the nose piece was about 70 mm and these regions were modeled as porous body, as previously mentioned. Pressure drop was measured by pressure tap and differential pressure gauge depending on the magnitude of the pressure drop.

3.2 Experimental results

The results of the pressure drop experiments and the error was summarized in Table IV. Each experimental value was obtained from the average of 10 times repeated test. For lower reflector, 1.34 kPa of the pressure drop was observed in bare case. Error of differential pressure gauge was 1.8 % of the measured value. However, after sedimentation of the debris bed, 160.51 kPa of the pressure drop was observed. Error of the pressure tap was 3.63 kPa and it was 2.3 % of the measured value. Approximately 119 times of the pressure drop was increase after debris bed sedimentation. It is significant large value compared to initial guess. It was because debris bed in the one damaged branched path makes increase the velocity of the other two intact branched and joining region of the three-forked branches. Relatively low porosity was other contributors of the higher pressure drop.

For the nose piece, 1.67 kPa of the pressure drop was observed in the bare case. After sedimentation of the debris bed, 1.86 kPa of the pressure drop was observed and it was slight increase of the pressure drop compared to lower reflector region. Approximately 11 % of the pressure drop was increased. Due to the geometrical characteristics of the nose piece, such a lower pressure drop increase was observed. Holes are arranged in the 3 by 3 array in the twisted position in the surroundings of the lower part of the nose piece. Debris bed with 70 mm of the height affected only the lowest rows of the hole array, 3 holes. Therefore, other holes can be free from the effect of the debris bed so that the lower pressure drop increase was observed in the nose piece region compared to the lower reflector.

Table IV. Pressure drop experiment results

Location		dP [kPa]	Error [kPa]	Error %
Lower reflector	Bare	1.34	0.025	1.8
	Damaged	160.51	3.63	2.3
Nose piece	Bare	1.67	0.025	1.5
	Damaged	1.86	0.025	1.4

4. Parametric study

The amount of downward discharged molten fuel and porosity of the debris bed can be changed with large uncertainty of the accident condition. Therefore, for representing two parameters, parametric studies were conducted using CFD.

The lower reflector has unique geometry that the number of the flow path is three. In the typical case in the LOF-DT series, debris beds were formed in the branched region and one of the three flow paths. Considering this geometry, the amount of the debris bed was translated as the number of the flow path with debris bed.

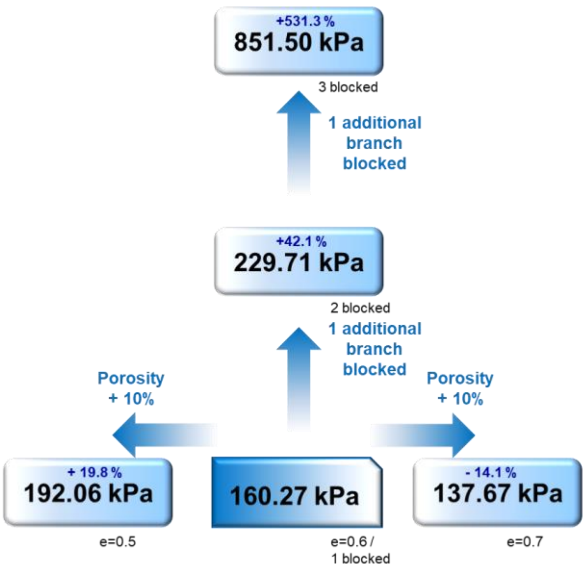

Fig. 5. Pressure drop parametric study in the lower reflector

The results of the parametric studies were summarized in the figure 5. For porosity change, 14 % of the pressure drop decrease while porosity was increased from 0.6 to 0.7. Approximately 20 % of the pressure drop increased while porosity was decreased from 0.6 to 0.5. Porosity has more sensitivity to the pressure drop when it decreases. However, for additional debris bed formation in the other branch, pressure drop was significantly increased. For all three branched paths blocked case, more than 5 times of the pressure drop increase was observed.

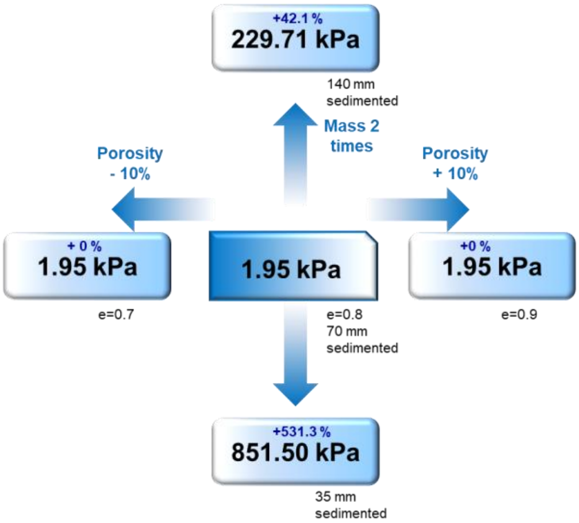

Fig. 6. Pressure drop parametric study in the nose piece

In the nose piece, it was previously discussed that the height of the debris bed has significant effect on the pressure drop. The results were summarized in the figure 6. For porosity, there was no change of the pressure drop along the porosity change. Because main flow passed through the other 6 holes, which was not affected by the debris bed, porosity change of the debris bed had almost no effect on the pressure drop. However, the sedimentation height affected on the pressure drop significantly. If the height of the debris bed changed to the half, about 20 % of the pressure drop was decreased and it is the same value with bare case. Actually, if 35 mm of the debris bed formed, the lowest row of the 3 by 3 holes was slightly affected. So that the pressure drop showed similar value to the bare case. If the height of the debris bed was doubled, the top of the debris bed reached to the top of the highest row of 3 by 3 holes. It means that all holes were affected by the debris bed. Therefore, approximately 6.5 times of the pressure drop was increased compared to the original debris bed formation.

5. Conclusion

Two kinds of experiments were conducted to evaluate degradation of the natural circulation of subassembly in the lower discharge of the molten fuel. To investigate the location of the debris bed, LOF-DT series was conducted, and to evaluate degradation of natural circulation, the pressure drop experiments were conducted. Based on the results of the pressure drop experiments, parametric studies were conducted with the amount and porosity of the debris bed.

Through the LOF-DT series, it was revealed that 80 % of the debris was deposited in the lower reflector and its porosity was about 0.6 – 0.7. For nose piece, 15 % of the debris was deposited and with 0.8 – 0.9 of the porosity. Negligible amount of the debris was deposited in the other regions. After such kind of debris bed formation, approximately 119 times of the pressure drop increased in the lower reflector region and approximately 19 % of the pressure drop increased. In the both lower reflector and nose piece, pressure drop was very sensitive to the volume of the debris bed for increase debris volume. Porosity showed moderate sensitivity to the pressure drop.

In these experiments, only single fuel assembly was simulated in pressure drop experiment and simulants were used in LOF-DT series. Further investigation with actual material and pressure drop with a group of subassemblies were needed for expansion and validation.

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