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Preliminary Study of Single-Phase Natural Circulation for Lab-scaled Molten Salt Application

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1. Introduction

In nuclear industry, molten salt has been studied for a long time as a promising medium in aspect of heat transfer and storage. Advanced reactors such as MSR (FHR), VHTR and AHTR utilized molten salt as a coolant for efficiency and safety which has advantages in higher heat capacity, lower pumping power and scale compared to liquid metal. Furthermore, as the energy dependence on nuclear increases, reprocessing technique for a spent fuel, especially pyro-processing which has an advantage of non-proliferation, has been issued recently. Molten salt is also used on the stage of electro-refining which is a part of pyro-processing that extract minor actinide from the fuel using molten salt. Thus, it becomes more necessary to study on the characteristics of molten salt. However, due to several characteristics such as high operating temperature, large-scale facility and preventing solidification, satisfying that condition for study has difficulties. Thus simulant fluid was used with scaling method for lab-scale experiment. Scaled experiment enables simulant fluid to simulate fluid mechanics and heat transfer behavior of molten salt on lower operating temperature and reduced scale.

In this paper, as a proof test of the scaled experiment, simplified single-phase natural circulation loop was designed in a lab-scale and applied to the passive safety system in advanced reactor in which molten salt is considered as a major coolant of the system. For the application of the improved safety system, prototype was based on the primary loop of the test-scale DRACS, the main passive safety system in FHR, developed at the OSU [1].

For preliminary experiment, single-phase natural circulation under low power was performed. DOWTHERM A and DOWTHERM RP were selected as simulant candidates. Then, study of feasibility with simulant was conducted based on the scaling law for heat transfer characteristics and geometric parameters. Additionally, simulation with MARS code and ANSYS-CFX with the same condition of natural circulation was carried out as verification. For the accurate code simulation, thermo-physical properties of DOWTHERM A and RP were developed and implemented into MARS code.

2. Methods

2.1 Selections of simulant and scaling law

Standard for a simulant selection was based on FLiBe and FLiNaK which are the representative molten salt of the advanced reactors and LiCl-KCl eutectic which is used in electro-refining process in pyro-process. Through matching Pr on operating temperature, candidates of simulant were selected as DOWTHERM A and RP as shown in table I. An agreement of Pr gave similarity of fluid. For buoyancy-driven flows, Gr was also matched in the scale-down facility to observe convective heat transfer behavior of natural circulation. With DOWTHERM RP which was used as a working fluid in this experiment, geometric and other parameters were also applied to the scaling law. Gr separated into upper two equations, (2) and (3) [2]. Matching these two equations between prototype and model enables the scaled experiment to simulation of natural circulation. The scaling parameters of two reactor types are shown in table II. The inner diameter of primary loop was used as a fluid characteristic length scale, L.

$$Gr \equiv gL^3\beta\Delta T / \nu^2 \quad (1)$$

$$(\beta\Delta T)_m = (\beta\Delta T)_p \rightarrow \beta_m / \beta_p = \Delta T_p / \Delta T_m \quad (2)$$

$$\left(\frac{gL^3}{\nu^2}\right)_m = \left(\frac{gL^3}{\nu^2}\right)_p \rightarrow \left(\frac{L_m}{L_p}\right)^{\frac{3}{2}} = \frac{\nu_m}{\nu_p} \quad (3)$$

Table II: Scaling between prototype and model

		FLiBe (973.15 K)
DOWTHERM RP (503.15 K)	ν_m/ν_p	0.25
	$\beta_p/\beta_m=\Delta T_m/\Delta T_p$	3.39
	L_m/L_p	0.39
	Gr_m/Gr_p	1
	Q_m/Q_p	0.035

Table I: Simulants of liquid salt [3],[4]

	T (K)	ρ (kg/m^3)	ν (m^2/s *10^6)	C_p (J/kg K)	k (W/m K)	Pr
FLiBe (LiF-BeF_2)	973.15	1940	2.90	2420	1.00	**13.5**
FLiNaK (LiF-NaF-KF)	973.15	1971	1.47	2010	0.91	6.46
LiCl-KCl Eutectic (58-42 mol%)	773.15	1710	1.29	1202 (at 973.15 K)	0.42 (at 973.15 K)	6.31
DOWTHERM A	473.15	907.1	0.43	2080	0.11	7.37
	513.15	878.7	0.36	2160	0.10	6.58
	523.15	859.0	0.33	2220	0.10	6.09
DOWTHERM RP	473.15	901.0	0.89	2160	0.11	15.9
	503.15	878.8	0.72	2250	0.10	**13.6**
	623.15	768.1	0.40	2600	0.09	8.97

Temperature difference, ΔT (difference between maximum and minimum temperature in test loop) and length scale were obtained. Temperature difference, ΔT_m is calculated as 29.53 K.

The input power range was calculated from the heat removal capacity of DHX. Corresponding to 1 % of the nominal core power, the capacity of DRACS of OSU was 200 kW [1]. The heating power of model (Q_m) was calculated with the following formula, (4) and (5). $\dot{V}$ is a volumetric flow rate and U_b is a buoyant velocity scale. From the scaling power between prototype and model, Q_m for FHR was obtained as 6.94 kW.

$$U_b \equiv (gL\beta\Delta T)^{1/2} \quad (4)$$

$$Q_m = \rho C_p \Delta T \cdot \dot{V} = \rho C_p \Delta T U_b L^2 \quad (5)\ [2]$$

2.2 Natural circulation experiment with simulant (DOWTHERM RP)

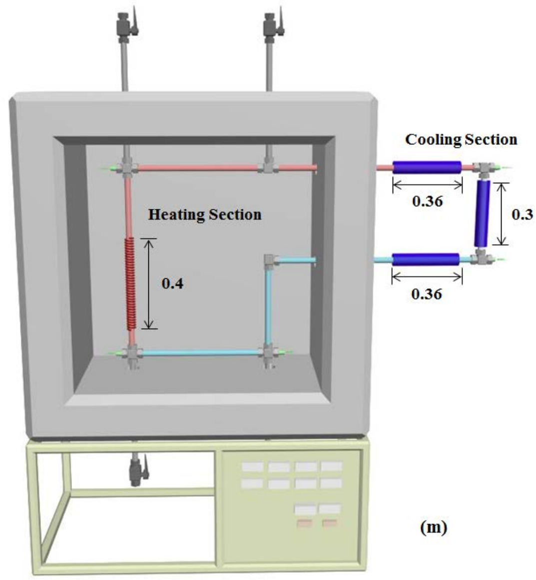

Fig. 1. Test loop facility of natural circulation

The natural circulation loop (fig. 1) consists of one vertical heating section, three cooling sections and other adiabatic sections. Furnace maintains indoor temperature for heat balance except cooling section. The whole pipes of the loop are SS304. The preliminary experiment was performed with three different power levels, 80, 120 and 180 W. DOWTHERM RP was used as a simulant fluid. Furnace temperature was maintained at 323.15 K. The initial water temperature of chiller was set to 277.15 K.

Table III: Dimensions of natural circulation loop

	(m)
Loop height	0.80
Loop width	1.54
Inner/outer diameter	0.023/0.0254
Heating section length	0.40
Cooling section length	1.02

2.3 Code verification

Before code simulation, thermo-physical properties of DOWTHERM A and DOWTHERM RP were developed. Using them, natural circulation was simulated in MARS code with the properties. CFD simulation with ANSYS-CFX has been also utilized for the study of thermal-hydraulic behavior of molten salt. For both simulations, DOWTHERM RP and water (cooling sections) were used as working fluid. Structural part (SS304) was applied only heating and cooling sections.

Fig. 2 shows the developed nodalization of our natural circulation loop simulated with MARS code. Heat structures were utilized for two heaters and three heat exchangers (coolers). Same power with experimental condition was applied. For water of heat exchangers, inlet temperature and mass flow rate for each junction were set a constant value based on the experimental result.

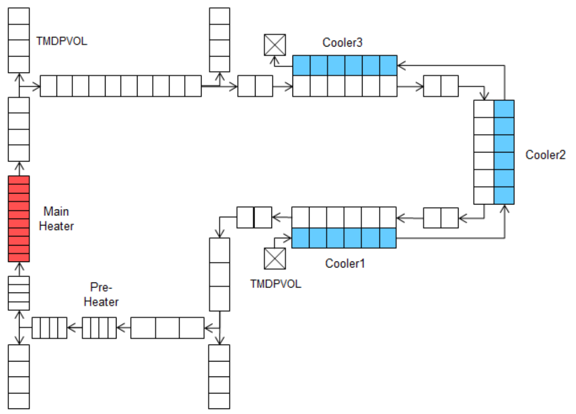

Fig. 2. Scheme of the nodalization for NC loop

For CFD analysis with ANSYS-CFX, same condition with MARS simulation was applied. For natural circulation, gravitational force and buoyancy model were applied. Experimental temperature was used as reference data. Heat flux was applied on heating section. The rest of part was set to be adiabatic.

3. Results and Discussion

3.1 Experimental result

For 80, 120 and 180 W, temperature data of each section was obtained. From the inlet and outlet temperature data of heating section and cooling section, theoretical mass flow rate was calculated by $Q = \dot{m}Cp\Delta T$ equation considering pressure drop by friction loss and form loss using the following equations, (6) to (9). Calculated mass flow rate had maximum deviation of 4.6 %. Temperature and mass flow rate for each power are shown in fig. 3. For each power, both inlet and outlet temperature of cooling sections had a tendency of increase.

$$f = \frac{64}{\mathrm{Re}} = \frac{64\mu}{\rho VD} \quad (6)$$

$$\Delta P_1 = f\frac{\rho L V^2}{2D} \quad (7)$$

$$\Delta P_2 = K\frac{V^2}{2g} \quad (8)$$

$$\Delta P_B = \beta\rho_0 (T_1 - T_2) g \Delta H \quad (9)$$

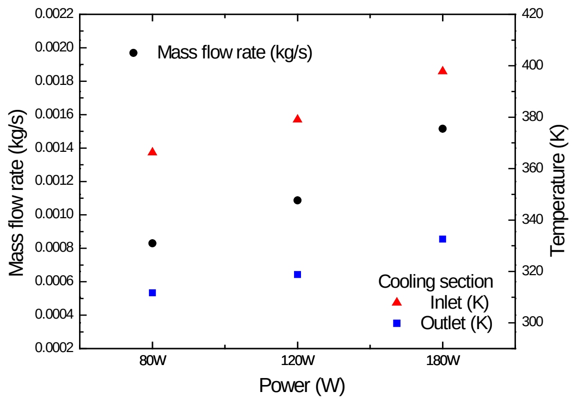

Fig. 3. Experimental mass flow rate for each power (80,120,180 W)

3.2 Comparison of experimental and code results

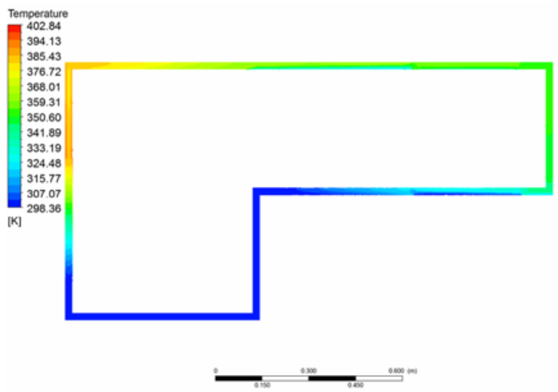

Fig. 4. Temperature profile in NC loop for 180 W in CFD simulation

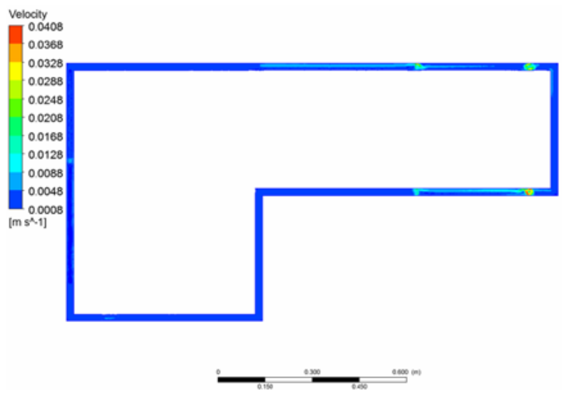

Fig. 5. Velocity profile in NC loop for 180 W heat input in CFD simulation

Experimental result was compared to MARS and CFD code simulation result. Temperature and velocity profile obtained from CFD analysis for 180 W heat input is shown in fig. 4 and 5. Velocity had a uniform value in the whole section. Table IV and fig. 6 show

Table IV: Results of simulations compared with experiment

Power (W)	Case	Heating section inlet (K)	Heating section outlet (K)	Heating section ΔT (K)	Mass flow rate (kg/s)
80	Experiment	311.69	366.24	54.54	0.00083
	MARS	308.43	402.81	94.38	0.00052
	CFD	299.08	353.58	54.50	0.00098
120	Experiment	318.81	379.07	60.26	0.0011
	MARS	321.13	402.17	81.04	0.00095
	CFD	299.10	367.40	68.30	0.0011
180	Experiment	332.57	397.84	62.26	0.0015
	MARS	344.05	400.52	56.47	0.0017
	CFD	298.54	384.18	85.64	0.0014

the main result of three cases. In terms of mass flow rate, MARS data had relatively lower values compared to the result of experiment and CFD. Utilization of calculated loss value in MARS input might affect the result. Calculated mass flow rate from experimental temperature data normally has higher value than actual mass flow rate due to the neglected parameters which occur pressure loss. Therefore, mass flow rate using a flowmeter is needed for more accurate data. In addition, some deviation existed between experimental and simulated temperature due to the low power and mass flow rate, the deviation of the result had a tendency of decrease as the power scale increases. Therefore, this result can be acceptable considering the overall trend and the power scale.

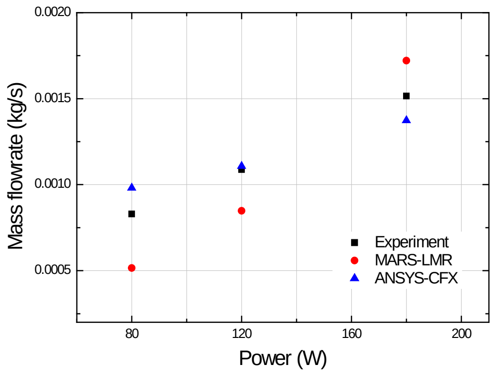

Fig. 6. Comparison of mass flow rate in natural circulation loop for heat input

4. Conclusions

In this study, single-phase natural circulation experiment was performed with simulant oil, DOWTHERM RP, based on the passive safety system of FHR. Feasibility of similarity experiment for molten salt with oil simulant was confirmed by scaling method. In addition, simulation with two different codes (MARS, CFD) for the natural circulation loop was conducted. Steady state with constant mass flow rate was obtained and temperature profile showed the flow with natural circulation from both results. From the comparison with experimental result, it was found that temperature difference and mass flow rate increased as the power was increased.

However, for the accurate scaled experiment of natural circulation, geometric similarity and power scale should be satisfied. Therefore, scaled experiment considering geometric parameters and power range will be conducted for simulation of the advanced reactor and pyro-processing system. Considering the importance of molten salt in advanced reactors and pyro-processing, this study will be meaningful for the nuclear industry and safety.

ACKNOWLEDGEMENTS

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