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Single-phase Natural Circulation of High-Pr Heat Transfer Simulant oil

Yukyung Shin, Seok Bin Seo, In Guk Kim, In Cheol Bang*
School of Mechanical and Nuclear Engineering
Ulsan National Institute of Science and Technology (UNIST)
50 UNIST-gil, Ulju-gun, Ulsan, 44919, Republic of Korea
**Corresponding author: icbang@unist.ac.kr*

1. Introduction

Molten salt utilization was started in the nuclear industry from the 1950s for the aircraft reactor experiment (ARE) in U.S., and recently the molten salt has been reconsidered as the promising coolant in the advanced reactors. For the use of molten salt in nuclear industry, prior experience with experiment is required.

However, in experimental condition, molten salt gives some difficulties due to the characteristics including high operating temperature and high temperature corrosion and toxicity with materials. It made the previous experimental studies of the molten salt encountered several challenges on the construction and operation of experimental facility. The similarity techniques were developed which enabled a lab-scaled molten salt experiments using the simulants to solve the difficulties. The similarity experiment enables research to reproduce the thermal behavior and fluid dynamics of molten salt at reduced temperature, pressure, dimension, and power scale [1].

Natural circulation is the fundamental heat transfer mechanism which is adopted in existing and advanced nuclear reactors as a principle of the passive safety system. Thus, evaluating the heat transfer characteristics of molten salt at the natural circulation condition is necessary to molten salt application.

In this paper, simulant oil was adopted as a heat transfer simulant of molten salt by matching the dimensionless number related to the natural circulation, Prandtl number (Pr), with the molten salt. Single-phase natural circulation loops were designed to study the performance of natural circulation ability. MARS-LMR code was utilized to validate the experimental data. Finally, the experiment results with the two types of natural circulation loops were compared with the existing results of the previous molten salt and simulant fluid experiment from ORNL and UC Berkeley.

2. Molten salt similarity and simulant oil

In these days, several high temperature molten salts are studied for the application in the nuclear industry, such as LiF-BeF_2 (FLiBe) or LiF-NaF-KF (FLiNaK), with various simulant salts and fluids. UC Berkeley used DOWTHERM A as a simulant oil of FLiBe in natural circulation operation [3]. However, DOWTHERM A also has toxicity considering the long term exposure due to the experiment. In addition, development of simulant fluid for molten salt is insufficient in aspect of the experiment and code simulation for advanced application. Therefore, in this paper, alternative simulant oil, DOWTHERM RP, was utilized for the molten salt similarity. DOWTHERM RP, which is very stable so that it is good for simulation, will be developed as alternative simulant oil for molten salt. Table I and Figure 1 shows the suitability of DOWTHERM RP as a molten salt simulant. It has wider range of Pr within its operating temperature and it includes Pr range of FLiBe and FLiNaK on lower temperature range.

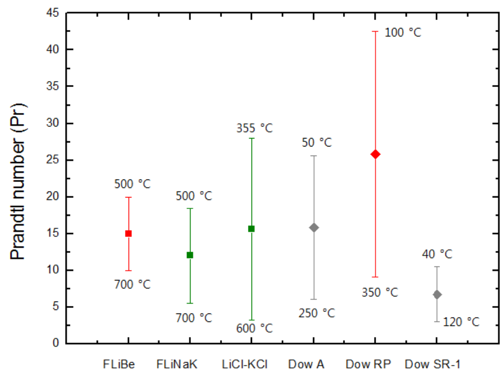


Fig. 1. Comparison of Pr range between molten salts and its simulant oils.

3. Natural circulation experiment

3.1 Single-phase natural circulation loop

Single-phase natural circulation loops were designed and utilized in UNIST thermal-hydraulics and reactor safety laboratory. As seen in the Figure 2, natural circulation loops consist of one vertical heating section and three cooling sections. Heating section is located in the lower part of the left side in the loops. Other sections are adiabatic. To minimized heat loss in the experiment, especially for the power loss in the heating section, a furnace was designed. It maintains an indoor temperature except cooling sections. Power was controlled and provided by coil heater with indirect heating.

Additionally, the comparison of the effect of the height difference between heating section and cooling sections to the mass flow rate and temperature distribution was conducted. As shown in the Figure 2 and Table II, cooling sections were changed to the upper part of the furnace. It made the height difference from 0.415 m to 1.415 m. In the second experimental loop, visualizing section was also installed in the upper section of the heating section for the identification of the natural circulation and observation of the flow behavior.

Table I: Simulants of liquid salt[2]

	T (K)	ρ (kg/m^3)	ν (m^2/s *10^6)	C_p (kJ/kg·K)	k (W/m·K)	Pr
LiF-BeF_2 (FLiBe)	773.15	2035.7	7.3283	2.386	1.1	32.36
	1073.15	1889.3	2.0313	2.398	1.1	8.36
DOWTHERM RP	373.15	973.0	2.8469	1.858	0.1210	42.53
	423.15	937.3	1.4083	2.007	0.1145	23.14
	473.15	901.0	0.8879	2.156	0.1080	15.9
	623.15	768.1	0.3979	2.602	0.0886	8.97
DOWTHERM A	323.15	1035.8	1.9985	1.658	0.1339	25.63
	373.15	994.9	0.9750	1.800	0.1259	13.87
	423.15	952.2	0.6091	1.940	0.1179	9.54
	523.15	859.0	0.3260	2.218	0.1019	6.09

4. MARS code simulation of natural circulation

Code simulation for the natural circulation was performed with the thermal-hydraulic system analysis code, MARS (Multi-dimensional Analysis of Reactor Safety). It can be used as the verification of the experimental results and the similarity between molten salt and simulant by comparison of each result within same Pr range. The pre-existing MARS code included only the basic fluid properties such as water or liquid metal. For molten salt application, UNIST thermal-hydraulics and reactor safety laboratory in previous studies applied several fluid properties to MARS code. The thermo-physical properties of FLiBe, the target molten salt, were implemented using soft-sphere model based on Monte Carlo calculation [4]. Those of the selected simulants, DOWTHERM RP and DOWTHERM A, were also implemented based on the property tables from DOW Chemical Company and the previous implementation of DOWTHERM A into RELAP code in INL [5]. Two types of the single-phase natural circulation loops were applied to MARS input with the same design and dimensions. Figure 3 shows the developed nodalization of natural circulation loops. Power was provided equally to the each volume of the heating section (red). Heat structures were also utilized for the three cooling sections (coolers) with the constant temperature of water.

Table II: Dimensions of natural circulation loop

	(m)
Loop height	0.80
Loop width	1.54
Inner / outer diameter	0.023/0.0254
Heating section length	0.23
Cooling section length	1.02

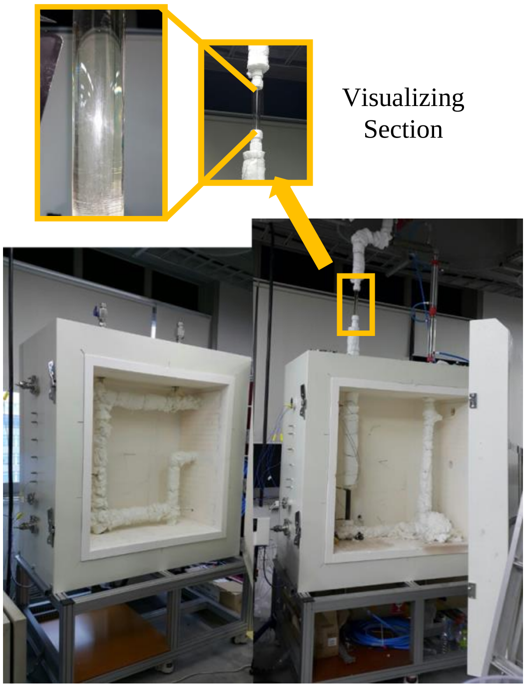
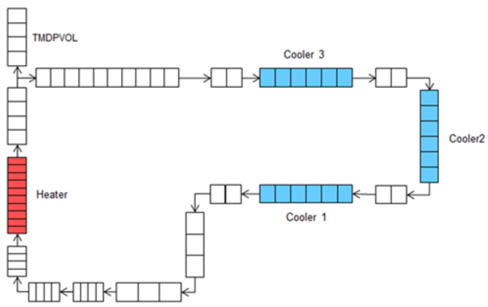
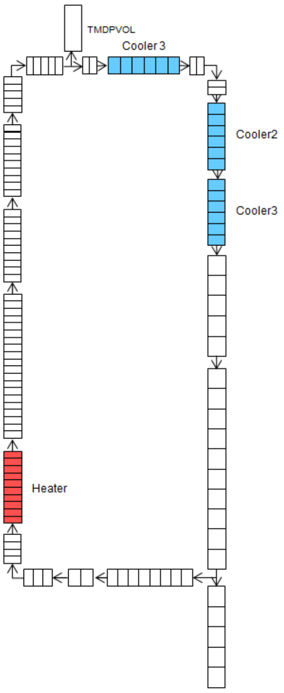


Fig. 2. Two types of natural circulation loop and furnace (left) ΔH_1=0.415 m, (right) ΔH_2=1.415 m.



(a)



(b)

Fig. 3. Nodalization of natural circulation loops
(a) ΔH_1=0.415 m, (b) ΔH_2=1.415 m.

5. Results and Discussion

5.1 Natural circulation experiment

In the natural circulation loops, 10 thermocouples and 2 pressure transducers were installed. Temperature distribution of inlet and outlet for heating section and cooling sections was obtained. Mass flow rate was calculated with the temperature data and power values. Figure 4 and Table III shows the comparison of the mass flow rate from the two experiments. Overall mass flow rate of the second case (ΔH_2) was higher due to the height difference between the heating section and cooling section. Higher value of the difference and the ratio of the width and height length affected the difference. The increasing trend of the mass flow rate between the two experiments showed more constant considering the ratio of the each value in Table III.

Table III: Mass flow rate of the two types of natural circulation loops

Power (W)	Mass flow rate of ΔH_1 (0.415 m)	Mass flow rate of ΔH_2 (1.415 m)	Ratio of mass flow rate
60	0.0009	0.0025	2.82
180	0.0024	0.0065	2.70
240	0.0034	0.0081	2.38
300	0.0046	0.0091	1.97

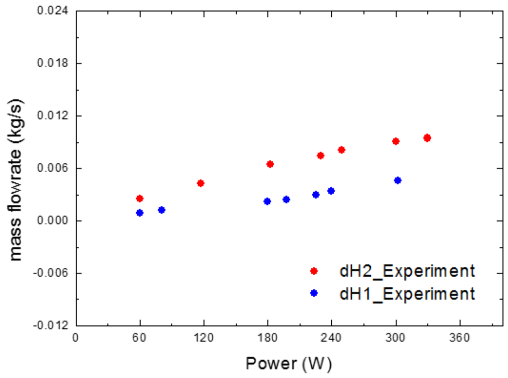
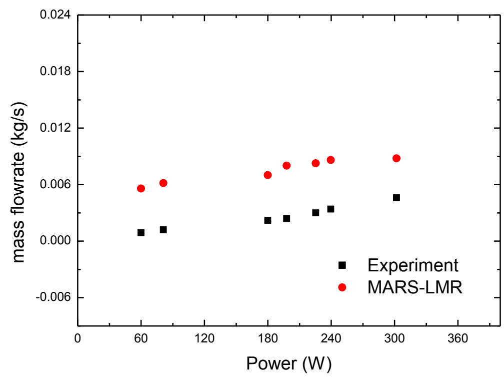


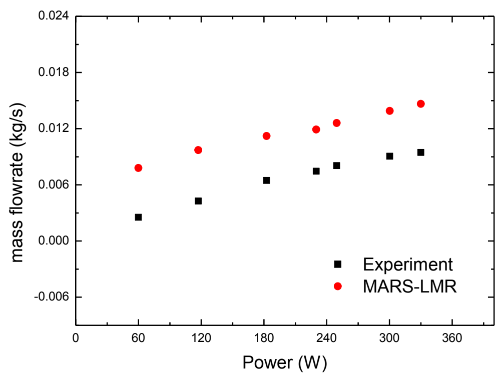
Fig. 4. Comparison of mass flow rate between the two types of natural circulation loops.

5.2 MARS-LMR code simulation

MARS simulation for the natural circulation with DOWTHERM RP properties was conducted. The mass flow rate of the simulation was compared with the experimental data in Figure 5. The increasing mass flow rate had the same trend between the MARS simulation and the experiment. However, heat loss near the heating section in experiment was not considered in MARS simulation. It led the lower, actual power supply in experiment to affect the difference of mass flow rate. As a result, mass flow rate in both MARS simulations was higher than that of the experimental data.



(a)



(b)

Fig. 5. Comparison of mass flow rate
(a) ΔH_1=0.415 m, (b) ΔH_2=1.415 m.

5.3 Comparison of natural convection results

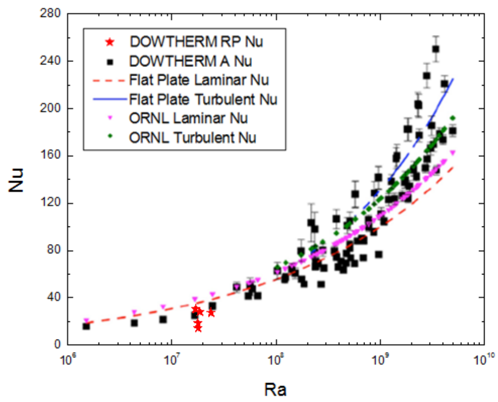


Fig. 6. Comparison of experimental data of natural convection with salt and simulant oils.

From the previous study of UC Berkeley, experimental data of natural convection from a heated vertical cylinder were compared. Salt and simulant oil, especially for DOWTHERM A, was used and the Figure 6 shows the results. Experimental results in this study with DOWTHERM RP were also added to compare with other data. The experimental range in this study were $6 \times 10^4 < Gr < 6 \times 10^5$ and $6 \times 10^6 < Ra < 2 \times 10^7$. The graph shows the similar trend between the salt (ORNL cases) and simulant oils. The comparison shows the similar trend with previous experimental data, which provides the feasibility of similarity technology between the molten salt and oil simulant.

6. Conclusions

In this paper, alternative simulant oil, DOWTHERM RP, was applied for the molten salt similarity. It was used for the experiment with two types of natural circulation loops. MARS code simulation for each natural circulation loop was also conducted. From the experimental results of the natural circulation, the second experiment showed the higher mass flow rate which had the large height difference between the heating section and cooling sections. The comparison between the MARS code result and the experimental data showed the higher mass flow rate in MARS simulation. Finally, the experimental data of natural circulation were compared with the existing natural convection results. From the comparison, the feasibility of similarity technology between the salt and the simulant oils was identified.

From this paper, further study will be performed. First of all, convergence study of the various parameters in MARS code input will be conducted for more accuracy of MARS simulation. In addition, MARS simulation with molten salt (FLiBe) also will be conducted for the comparison with the simulant oil. Finally, natural circulation with high power range will be performed. The experimental results also will be compared with other natural convection results.

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