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Selecting Optimal Heat Transfer Chloride Salt for Molten Salt Fast Reactor: Heat Exchanger and Pumping Work Perspectives

Sungwook Choi [a], In Woo Son [a], Sunghyun Yoo [a], Jeong Ik Lee [a*]
[a]*Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong Yuseong-gu, Daejeon 305-701, Republic of Korea*
[*]*Corresponding author: jeongiklee@kaist.ac.kr*

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1. Introduction

Molten Salt Reactor (MSR) is a promising next generation nuclear reactor due to its high efficiency, sustainability and safety. Especially, Molten Salt Fast Reactor (MSFR) is continuously being researched, because chloride-based salts, which is the working fluid of the MSFR, have lower melting points, and reduced waste production than the fluoride-based salts. The efficient operation of MSFR hinges significantly on the choice of the heat transfer salt. The selection of an optimal heat transfer chloride-based salt assumes paramount importance, as it profoundly influences both the reactor and the power conversion system performance. In the previous study, the thermodynamic properties of $NaCl\text{-}MgCl_2$, $KCl\text{-}MgCl_2$, and $NaCl\text{-}KCl\text{-}ZnCl_2$ were compared [1]. To select the optimal heat transfer salt for the MSFR application, not only the thermodynamic properties, but also the heat exchanger size and the pumping work should be compared for the candidate salts. In this context, this paper aims to explore the selection of optimal heat transfer chloride salt for MSFRs with a specific focus on its implications for heat exchanger design and the pumping work consumption.

2. Methods and Results

This section includes the methods for the selection of the optimal heat transfer chloride salts, including heat exchanger type selection, thermal sizing of the loops, heat exchanger design and pumping work calculation. Each step is carried out by referring to the Molten Salt Reactor Experiment (MSRE) [2].

2.1 Heat Exchanger Type Selection

During the MSRE operation, shell and tube type heat exchanger was used as the intermediate heat exchanger. However, compared to shell and tube type heat exchangers, other types of compact heat exchangers developed recently, such as Plate Fin Heat Exchanger (PFHE), can be preferred, because they are smaller in size and pressure drop. In the previous studies, various types of compact heat exchangers were compared, and it was confirmed that PFHE has a high potential as an intermediate heat exchanger for MSR [3]. Among many fin types in PFHE, the offset trip fin type allows larger heat transfer area than other fin types, and has high convective heat transfer coefficient relative to the friction factor. Thus, PFHE with offset strip fin type, as shown in Figure 1, is selected as the heat exchanger type in this study to increase the heat transfer area.

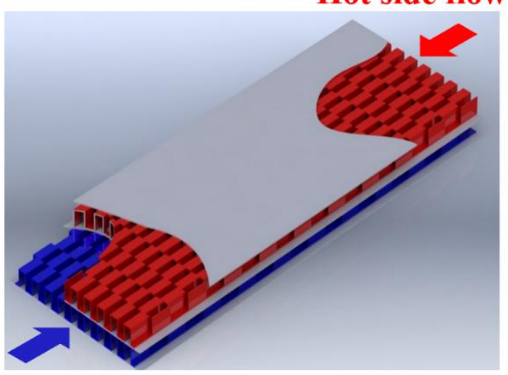

Fig 1. Basic geometry of PFHE

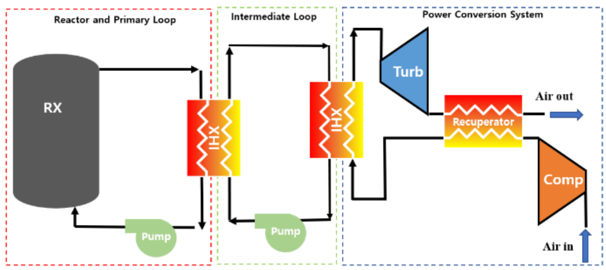

Fig 2. Layout of MSFR

2.2 Thermal Sizing

One of the characteristics of MSRE is that it did not have power conversion system. Since the main purpose of the MSRE was to observe the phenomena during MSR operation, the power conversion system was unnecessary. Thus, the heat generated in the fuel salt was cooled by the heat transfer salt, which was then cooled by air ultimately. In this study, a recuperated open air Brayton cycle, shown in Figure 2, is adopted as the power conversion system, and mass flow rate of each loop is calculated before designing the intermediate heat exchangers. The mass flow rate of air is calculated by KAIST-Open Cycle Design (OCD) code [4]. Since the reactor outlet temperature of MSRE was 1200 °F (650 °C), the turbine inlet temperature of the power conversion system is calculated with 10K pinch temperature at each intermediate heat exchangers. Table 1 shows the input parameter and result of KAIST-OCD code.

Table 1. Input parameter and result of KASIT-OCD

Input Parameter	
Thermal output	8.0 MW_{th}
Air temperature	15°C
Turbine inlet temperature	630 °C
Turbine efficiency	88 %
Compressor efficiency	84 %
Recuperator effectiveness	90 %
Result	
Mass Flow Rate	35.70 kg/s
Thermal efficiency	31.05 %

Based on the air mass flow rate, the mass flow rates of the candidate heat transfer salts are calculated. For the sake of simplicity and also due to the limited amount of data, the fuel salt is assumed to have the same thermal properties as the heat transfer salt. The thermal properties of the salts are obtained from the previous data [5-8]. The mass flow rate of each candidate salt is shown in Table 2. Using the calculated mass flow rate of each candidate salt, the PFHE type primary and secondary heat exchangers are designed.

Table 2. Mass Flow Rate of each candidate salt

	Mass Flow Rate [kg/s]
NaCl-$MgCl_2$	147.61
KCl-$MgCl_2$	138.05
NaCl-KCl-$ZnCl_2$	174.48

2.3 PFHE Design

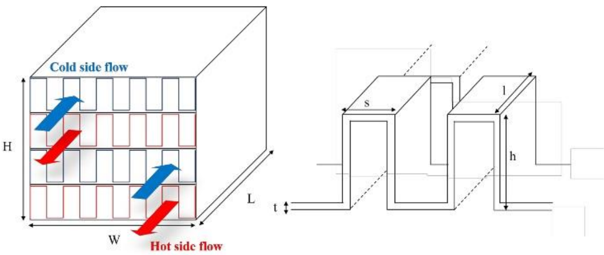

Fig 3. Schematic of PFHE and detailed view of the offset strip fin

As shown in Figure 3, the suggested MSR heat exchanger is a counter flow PFHE with offset strip fins. The geometry parameters of fins are fin gap (s), fin height (h), fin offset length (l), and fin thickness (t). The PFHE is optimized by altering the fin gap, height, offset length, number of fin layers, and the width and length of the heat exchangers [4]. For PFHE design, the Manglik and Bergles correlation is used. Table 3 summarizes the primary and the secondary PFHE design results. In the previous study, where the thermodynamic properties of the candidate salt are compared, NaCl-$MgCl_2$, and KCl-$MgCl_2$ were preferred over the NaCl-KCl-$ZnCl_2$, KCl-$MgCl_2$ being slightly better than NaCl-$MgCl_2$. Similarly, the volume of primary and secondary PFHE with NaCl-KCl-$ZnCl_2$ is the largest among the candidate salt. The volume of PFHE with KCl-$MgCl_2$ is slightly smaller than the volume with NaCl-$MgCl_2$, but the difference was subtle. Based on the pressure drops calculated during the PFHE design process, the pumping work in the heat transfer loop is calculated. Since the melting points of NaCl-$MgCl_2$, KCl-$MgCl_2$ and NaCl-KCl_2-$ZnCl_2$ are 445℃, 426 ℃, and 229℃, respectively, the temperature range of the heat transfer loop is well above the melting point of each candidate salt.

2.4 Pumping Work Calculation

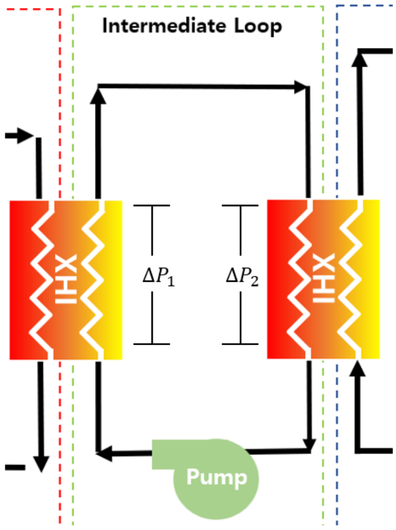

Fig 4. Layout of intermediate loop of MSFR

For the pumping work calculation, the pressure drop calculated in the PFHE design process is used. Assuming that there is no pressure loss in the pipes, the total pressure drop in the intermediate loop is equal to the sum of pressure drop in each intermediate heat exchanger (ΔP_1 and ΔP_2). The pumping work in the intermediate loop with each candidate salt is calculated using the equation below.

$$P_{pump} = \frac{\Delta P_{total}}{\rho_{Sec\ HX\ Outlet}} \times \dot{m} \qquad (1)$$

Table 4 shows the pumping work calculation result. The heat transfer loop with NaCl-KCl-$ZnCl_2$ consumes the most amount of power, and loop with NaCl-$MgCl_2$ consumes the least amount of power.

Table 4. Pumping work calculation result

Salt	ΔP_{total} [kPa]	$\dot{m}$ $\left[\frac{kg}{s}\right]$	P_{pump} [kW]
NaCl-$MgCl_2$	131.46	147.61	9.324
KCl-$MgCl_2$	143.27	138.05	9.636
NaCl-KCl-$ZnCl_2$	281.06	174.48	22.589

Table 3. Primary and Secondary PFHE Design Result

	Primary PFHE			**Secondary PFHE**		
	$NaCl-MgCl_2$	$KCl-MgCl_2$	$NaCl-KCl-ZnCl_2$	$NaCl-MgCl_2$	$KCl-MgCl_2$	$NaCl-KCl-ZnCl_2$
Hot side inlet/outlet temperature [℃]	650 / 600			640 / 590		
Cold side inlet/outlet temperature [℃]	590 / 640			426.09 / 630		
HX width [m]	0.6	0.65	1.95	1.8	1.8	1.8
HX length [m]	1.092	1.096	0.733	0.769	0.765	0.804
HX height [m]	0.546	0.482	0.716	0.629	0.629	0.658
Number of hot side layers	170	150	210	220	220	230
Number of cold side layers	171	151	211	221	221	231
Core Volume [m^3]	0.358	0.343	1.023	0.871	0.866	0.952
Hot side pressure drop [kPa]	125.97	136.354	137.549	5.995	6.515	87.923
Cold side pressure drop [kPa]	125.46	136.751	193.137	8.424	8.379	9.3674
Hot Side Mass Flow Rate [kg/s]	147.612	138.054	174.482	147.612	138.054	174.482
Cold Side Mass Flow Rate [kg/s]	147.612	138.054	174.482	35.70	35.70	35.70

3. Summary and Conclusions

In this paper, the selection of the optimal heat transfer chloride salt for the MSFR with focus on the intermediate heat exchanger size and the pumping work is discussed. By referencing the MSRE operating condition, the mass flow rates of the molten salt and air are calculated. Due to the lack of fuel salt data, the thermodynamic properties of fuel salt are assumed to be the same as the coolant salt. PFHE is selected as the intermediate heat exchanger type.

The PFHE with $KCl-MgCl_2$ as the working fluid showed the smallest volume, slightly less than that of $NaCl-MgCl_2$. For the pumping work, $NaCl-MgCl_2$ consumes the least power for the pump. On the other hand, PFHE with $NaCl-KCl-ZnCl_2$ has the largest volume and pumping work among the candidate heat transfer chloride salts. Thus, based on thermodynamic properties, heat exchanger size and pumping work, $KCl-MgCl_2$ is recommended for MSFR.

NOMENCLATURE

Symbol [Unit]	Definition
$\boldsymbol{\Delta P}$[kPa]	Pressure drop
$\boldsymbol{P_{pump}}$[kW]	Pumping Work
$\boldsymbol{\rho_{Sec\ HX\ Outlet}}$[kg m^{-3}]	Density at secondary heat exchanger outlet
$\dot{\boldsymbol{m}}$[kg s^{-1}]	Mass flow rate

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