Primary PFHE design for chloride based molten salt fast reactor

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1. Introduction

The Molten Salt Reactor (MSR), which has advantages such as inherent safety, high economy, and compact size, is one of the Gen-IV reactors and is attracting global attention as a next-generation reactor [1]. In the previous studies, a conceptual design of a power conversion system applicable to MSR was conducted by referring to the Molten Salt Reactor Experiment (MSRE) conducted by Oak Ridge National Laboratory (ORNL) [2].

In the previous study, FLiBe, a type of fluoride salt, was selected as a coolant salt and a fuel salt. This is because MSRE uses fluorides-based salts, so there is sufficient information on the properties of fuel salts and coolant salts. However, in this study, the conceptual design of an intermediate heat transport system for a molten salt fast reactor is to be carried out. Since the neutron moderation has to be prevented in the molten salt fast reactors, chlorine-based salts are preferred over fluorine-based salts.

The chloride salt has a lower neutron absorption than the fluoride salt, making it more suitable for reactor with fast spectrum, and has a lower melting point (450°C or lower) than the fluoride salt, enabling better reactor operational envelope. Since the chloride salt has a lower corrosion property for stainless steel than the fluorine salt, a stainless steel can be used as a structural material instead of a Ni-based alloy. In addition, chloride salt can dissolve fission materials such as Cs, Sr, and I generated in the reactor, thereby preventing leakage of radioactive materials in the event of a fuel salt leakage accident. Chloride salt has an advantage of high economic efficiency because it has a lower viscosity than fluoride salt and requires much less pumping power [3].

Plate Fin Heat Exchanger (PFHE) was selected as the type of primary heat exchanger. As a result of comparison with PCHE and STHE in the previous study, it was confirmed that PFHE has a high potential as an intermediate heat transport system of MSR. [5]. Based on these advantages, this study conducted a conceptual design of primary PFHE for MSR with working fluid as $NaCl\text{-}MgCl_2$.

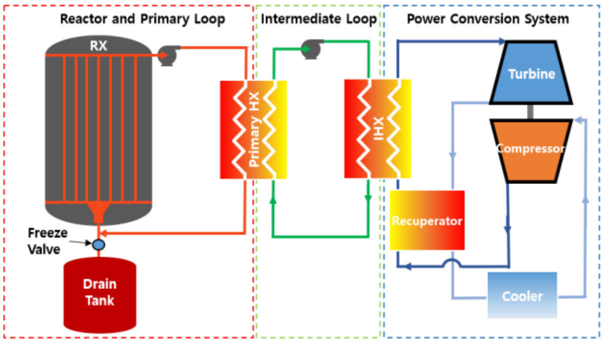

Fig 1. The layout of MSR with power conversion system [2]

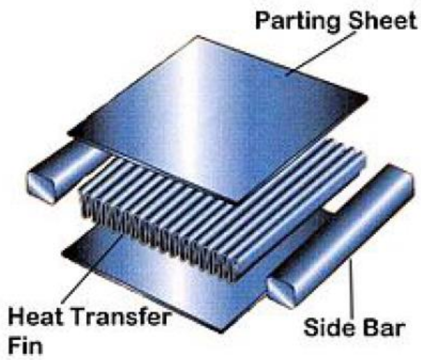

Fig 2. The basic structure of PFHE [5]

2. Methodology

First, the power conversion cycle for MSR is optimized using the KAIST-OCD code (Open Cycle Design). The maximum temperature of a molten salt reactor is fixed in 650°C referring to the previous study, and the pinch temperature of intermediate heat exchanger is selected to be 10K. Therefore, the turbine inlet temperature of the power conversion system is set to 630°C. Fig. 2 shows the algorithm of the KAIST-OCD code used for the cycle optimization. The air open Brayton cycle optimization design conditions and optimization results are as follows.

Table 1. Cycle optimization parameters

Fixed variable	
Air intake Temperature / Humidity	40 °C / Dry
Max Temperature	630 °C
Thermal heat	6.5 MW_{th}
Compressor inlet Pressure	101.325 kPa
Turbine efficiency	90%

Compressor efficiency	86%
Recuperator effectiveness	0.92
Component pressure drop ratio	-
Heater Cold side	0.02
Recuperator Hot side	0.01
Recuperator Cold side	0.01
Ratio of exhaust pressure to atmosphere	0.98

Table 2. Cycle optimization results

Cycle thermal efficiency (%)	32.01
Cycle work (MWe)	2.08
Specific work (MWe/kg)	0.0814
Thermal heat (MWth)	6.5
Pressure ratio	3.222
Max. Pressure (MPa)	0.347
Mass flow rate (kg/s)	25.55

After the cycle optimization, the thermal sizing of the MSR system is performed. The minimum temperature of $NaCl\text{-}MgCl_2$ in the heat exchanger is set to 550°C to avoid freezing risk. The mass flow rates of the primary and secondary heat exchangers that can simultaneously satisfy the maximum temperature and the pinch temperature of 10K conditions are calculated. Table 3 summarizes the thermal sizing results. The thermal properties of $NaCl\text{-}MgCl_2$ are calculated as shown in Table 4 [11].

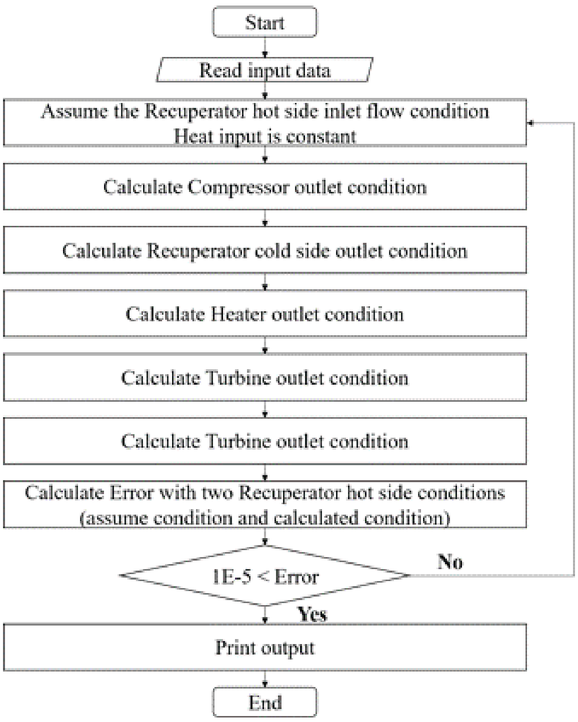

Fig 3. Algorithms of KAIST-OCD [4]

Table 3. heat sizing results for the MSR system [4, 10]

Heat load	6.5 MW_{th} [10]
$\Delta T_{hot\ side\ inlet-cold\ side\ outlet}$	10 K [4]
Primary PFHE hot side [10]	
Mass flow rate (kg/s)	100.38
Inlet temperature (°C)	650
Outlet temperature (°C)	560
Primary PFHE cold side	
Mass flow rate (kg/s)	65.21
Inlet temperature (°C)	550
Outlet temperature (°C)	640
Secondary PFHE hot side [10]	
Mass flow rate (kg/s)	65.21
Inlet temperature (°C)	640
Outlet temperature (°C)	550
Secondary PFHE cold side	
Mass flow rate (kg/s)	25.55
Inlet temperature (°C)	398
Outlet temperature (°C)	630

Table 4. Thermal properties of the $NaCl\text{-}MgCl_2$ [11]

$C_p = 1080.19\ [J/kg \cdot K]$
$\rho = (2518 - 0.406 \times T), for\ T < 973K$ $\rho = (2297.1 - 0.507 \times T), for\ T > 973K [kg/m^3]$
$\mu = \left(0.000286 \times exp\left(\frac{3775}{T}\right)\right)\ [kg/m \cdot s]$
$k = 0.3133 + 0.000267 \times T\ \ [W/m \cdot K]$

Finally, the conceptual design of the primary heat exchanger is conducted. There are several types of PFHE fins such as plain, wavy, louver, and offset strip. In this study, the offset strip fin type PFHE with a higher convective heat transfer coefficient compared to other fin types is used. Offset strip fin is one of the most preferred fin geometries in compact heat exchangers, with rectangular cross sections cut into smaller strips of length, *l* and displaced by about 50% of the fin pitch in the horizontal direction. Fig. 4 shows the shape of the offset strip fin. The offset strip fins consist of fin gap (s), fin height (h), fin offset length (l), and fin thickness (t) [4].

The ranges of heat exchanger design parameters are calculated by Korea Atomic Energy Research Institute (KAERI) based on the ASME code design criteria. The calculated design parameters for the conceptual design of the primary PFHE are summarized in Table 5.

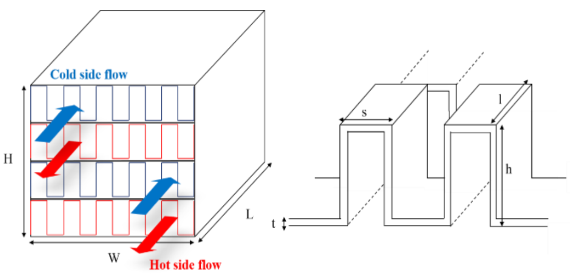

Fig 4. The shape of the offset-strip fin PFHE [4]

Table 5. Primary PFHE design parameters range

	Min.	Max.
Hot flow length (m)	0.1	2
Hot, Cold Fin height [H] (m)	0.002	0.02
Fin thickness [t] (m)	0.0001	0.0002
Hot, Cold Fin frequency [1/n] (m)	0.001	0.015
Fin offset length [l] (m)	0.001	0.015
Number of hot side layers	10	500
Plate thickness (mm)	0.5	

3. Results and Discussion

The design results of the primary PFHE are summarized in Table 6. The structural material for the primary PFHE is selected as SS316 (SA-213 TP316H) which can operate at maximum temperature of 800 °C. In the further study, according to the corrosion resistance test result of NaCl-$MgCl_2$ with structural materials, ASTM B163 (Ni-Cr-Fe), which is a nickel alloy with high corrosion resistance, or Hastelloy N (Ni-Mo-Cr) used in MSRE, will be investigated for the potential material for PFHE.

Table 6. MSR primary PFHE conceptual design results

Hot Fin height [m]	0.002
Cold Fin height [m]	0.002
Fin thickness [m]	0.00011
Hot Fin frequency [m^{-1}]	1000
Cold Fin frequency [m^{-1}]	1000
Fin offset length [m]	0.003
Number of hot side layers	80
Number of cold side layers	81
Hot side pressure drop [kPa]	167
Cold side pressure drop [kPa]	108
HX width [m]	0.5
HX length [m]	2.56
HX height [m]	0.40
Volume core [m^3]	0.51

4. Summary and Further works

In this study, the primary PFHE of a molten chloride salt fast reactor is conceptually designed. The chloride salt is used as a working fluid in this study because chloride salts have lower neutron moderating capability.

For the conceptual design of the primary heat exchanger, power conversion cycle optimization and thermal sizing of the MSR system are performed. Based on the optimization and thermal sizing results, the conceptual design of primary PFHE using fuel salt (NaCl-$MgCl_2$-$TRUCl_3$) and coolant salt (NaCl-$MgCl_2$) is performed in this study. In the further study, the concept design of the secondary heat exchanger with consideration of header and flow distribution will be performed.

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REFERENCES

[1] Dolan, T. J. (n.d.). Molten salt reactors and thorium energy. Elsevier.

[2] Son, I. W., Choi, S., Kim, S. J., & Lee, J. I. Thermal-sizing of the molten salt reactor system with gas Brayton cycle. Transactions of Korean Nuclear Society Virtual Autumn Meeting (2021)

[3] Holcomb, D. E., Flanagan, G. F., Patton, B. W., Gehin, J. C., Howard, R. L., & Harrison, T. J. (2011). Fast spectrum molten salt reactor options. ORNL/TM-2011/105.

[4] Son, I. W., Choi, S., Kim, S. J., & Lee, J. I. Heat exchanger design study for micro molten salt reactor. Transactions of Korean Nuclear Society Spring Meeting (2022)

[5] Kwon, J. S., Son, S., Heo, J. Y., & Lee, J. I. (2020). Compact heat exchangers for supercritical CO2 power cycle application. Energy Conversion and Management, 209, 112666.

[6] Shah, Ramesh K., and Dusan P. Sekulic. Fundamentals of heat exchanger design. John Wiley & Sons, 2003.

[7] Zarea, Hossein, et al. "Optimal design of plate-fin heat exchangers by a Bees Algorithm." Applied thermal engineering 69.1-2 (2014): 267-277.

[8] Mishra, Manish, P. K. Das, and Sunil Sarangi. "Second law based optimisation of crossflow plate-fin heat exchanger design using genetic algorithm." Applied thermal engineering 29.14-15 (2009): 2983-2989.

[9] Sanaye, Sepehr, and Hassan Hajabdollahi. "Thermal-economic multi-objective optimization of plate fin heat exchanger using genetic algorithm." Applied energy 87.6 (2010): 1893-1902

[10] Robertson, R. C. "MSRE design and operations report part I: description of reactor design." ORNL-TM-728, Oak Ridge National Laboratory (1965).

[11] Williams, D. F. Assessment of candidate molten salt coolants for the NGNP/NHI heat-transfer loop. No. ORNL/TM-2006/69. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States), 2006.