Primary PFHE design for chloride based molten salt fast reactor

Sunghyun Yoo[a], In woo Son[a], Sungwook Choi[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

Introduction

▣ The Molten Salt Reactor (MSR) is attracting global attention as a next-generation reactor due to its advantages such as inherent safety, high economy, and compact size.

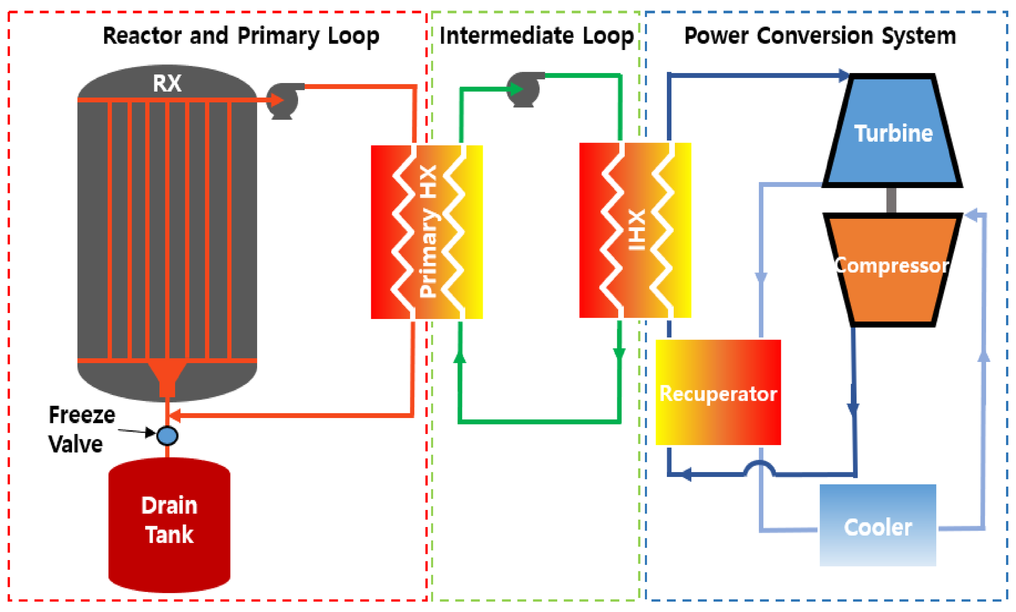
▣ The Molten Salt Fast Reactor (MSFR) has the advantage of reducing waste disposal requirements by incinerating actinides from LWR used fuel.

▣ Since the chloride salt has a lower neutron absorption than the fluoride salt, making it more suitable for molten salt fast reactor with fast spectrum.

▣ The conceptual design of an intermediate heat transport system for a chloride based molten salt fast reactor was carried out in this study.

▣ In previous study, the Plate Fin Heat Exchanger (PFHE) has a high potential as an intermediate heat transport system of MSR.

▣ This study conducted a conceptual design of primary PFHE for MSR with working fluid as NaCl-MgCl₂



△ The layout of MSR with power conversion system

Methods

▣ 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.

▣ The pinch temperature of intermediate heat exchanger is set to be 10K. Therefore, the turbine inlet temperature of the power conversion system is set to 630°C.

▣ The air open Brayton cycle optimization design conditions and optimization results are as shown in below tables.

▽ **Cycle optimization parameters and results**

Cycle optimization parameters (Fixed variable)	
Air intake temperature [°C]/ Humidity	40 / Dry
Max temperature [°C]	630
Thermal heat [MWth]	6.5
Compressor inlet pressure [kPa]	101.325
Turbine efficiency	90
Compressor efficiency [%]	86
Recuperator effectiveness [%]	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 atmospheric	0.98

Cycle optimization results	
Cycle thermal efficiency [%]	32.01
Cycle net 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 of NaCl-MgCl₂ (kg/s)	25.55

▣ The thermal sizing of the MSR system is performed as follows.

▣ The minimum temperature of NaCl-MgCl₂ in the heat exchanger is set to 550°C to avoid freezing risk.

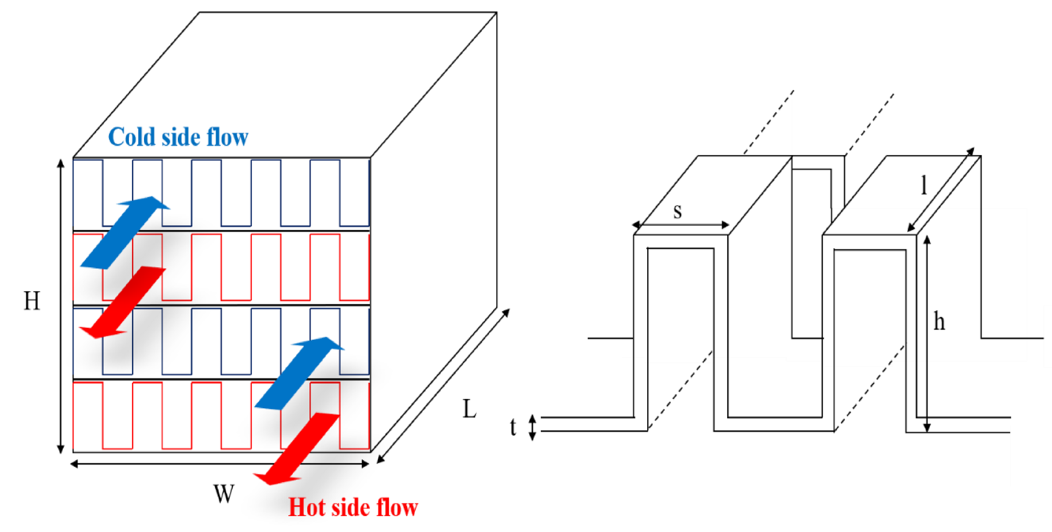
▣ The mass flow rate of the primary PFHE that can simultaneously satisfy the maximum temperature and the pinch temperature of 10K condition was calculated.

▽ **MSR Primary PFHE thermal sizing results**

$\Delta T_{hot\ side\ inlet-cold\ side\ inlet}$ [K]	10
Primary PFHE hot side	
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

▣ In this study, the offset strip fin type is used for PFHE, because it has a higher convective heat transfer coefficient compared to other fin types.

▣ The offset strip fins consist of fin gap (s), fin height (h), fin offset length (l), and fin thickness (t) as shown in the right figure.



△ **The shape of the offset-strip fin PFHE**

▣ The ranges of heat exchanger design parameters are calculated by Korea Atomic Energy Research Institute (KAERI) based on the ASME code design criteria.

▽ **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^{-1}]	0.001	0.015
Fin offset length, l (m)	0.001	0.015
Number of hot side layers	10	500

▣ The thermal properties of coolant salt (NaCl-$MgCl_2$) are calculated as shown in below table.

▽ **Thermal property and heat exchanger correlation for NaCl-MgCl₂**

Thermal property
Heat capacity, $C_P = 1080.19\ \left[\frac{J}{kg\cdot K}\right]$
Density, $\rho = (2297.1\ - 0.507 \times T), for\ T < 973K$ $\rho = (2297.1\ - 0.507 \times T), for\ T > 973K \left[\frac{kg}{m^3}\right]$
Dynamic viscosity, $\mu = \left(0.000286\ \times exp\left(\frac{1441}{T}\right)\right)$ [kg/(m · s)]
Thermal conductivity, $k = 0.3133\ + 0.000267\ \times T\ \left[\frac{W}{m\cdot K}\right]$

▣ The material properties of the fuel salt (NaCl-MgCl₂-[U-TRE-RE]Cl₃) required for the PFHE conceptual design were calculated by the radiochemical laboratory in KAERI.

▽ **Material properties of the fuel salt (NaCl-MgCl₂-[U-TRE-RE]Cl₃)**

Salt	Temperature [°C]	Heat Capacity [J/kg·K]	Viscosity [cP]	Thermal Conductivity [W/m·K]
		Mole fraction additive method	Mole fraction additive method	Igatieve and Khoklove correlation
NaCl-MgCl₂-(U-TRE-RE)Cl₃	550	688.183	2.646	0.333
	600	694.833	2.232	0.358
	650	701.791	1.918	0.383
	700	709.055	1.674	0.408

Result

▣ The conceptual design results of the primary PFHE are summarized as follows.

▽ **MSR primary PFHE conceptual design results**

Hot Fin height [m]	0.002	Number of hot side layers	80
Cold Fin height [m]	0.002	Number of cold side layers	81
Fin thickness [m]	0.00011	HX width [m]	0.5
Hot Fin frequency [m^{-1}]	1000	HX length [m]	2.56
Cold Fin frequency [m^{-1}]	1000	HX height [m]	0.40
Fin offset length [m]	0.003	Plate thickness [m]	0.0005
Hot side pressure drop [kPa]	167	Volume core [m³]	0.51
Cold side pressure drop [kPa]	108	Heat transfer effectiveness [%]	92.19

▣ The structural material for the primary PFHE is selected as SS316 (SA-213 TP316H) which can operate at maximum temperature of 800 °C.

Conclusions

▣ 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 molten salt fast reactor.

▣ Using the optimization and thermal sizing results, the conceptual design of primary PFHE using fuel salt (NaCl-MgCl₂-TRUCl₃) and coolant salt (NaCl-MgCl₂) is performed in this study.