Thermal-sizing of the molten salt reactor system with gas Brayton cycle

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Introduction

▣ The Molten Salt Reactor (MSR), one of the generation IV nuclear reactors, has recently received much attention worldwide due to its technology, safety, and economic feasibilities.

▣ MSR have a high core power density and can operate at atmospheric pressure and maintain high safety by keeping the surplus reactivity low

▣ During the development of MSR design concepts, determining which power conversion system is suitable for the system is an important issue.

▣ To design the power conversion system, thermal sizing of the entire MSR is first required, which is carried out by referring to the Molten Salt Reactor Experiment (MSRE) conducted at ORNL (*Oak Ridge National Laboratory)*

▣ The MSRE system does not have a temperature range suitable for the efficient power production

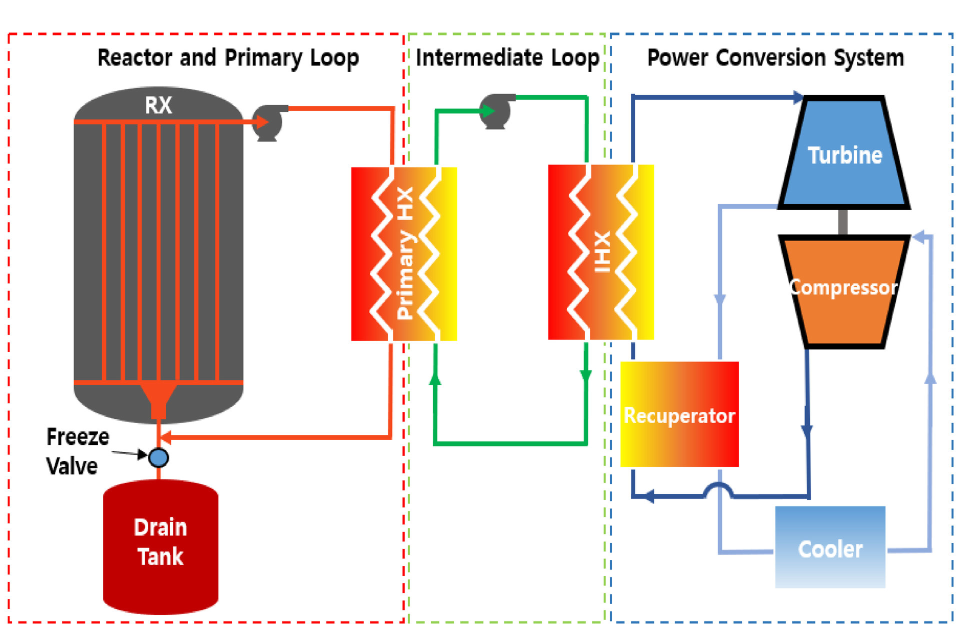
▽ **Primary Heat exchanger design parameter of the MSRE system**

	Shell side (Fuel salt)	Tube side (Coolant salt)
Inlet / Outlet temperature [°C]	662.78 / 635	551.67 / 593.33
Inlet / Outlet Pressure [kPa]	379.2 / 241.3	530.9 / 324.0
Pressure drop [kPa]	165.47	199.95
Mass Flow Rate [kg/sec]	163.31	103.083

▣ The objectives of this study are as follows: 1. Reconfiguration and thermal-sizing of MSRE system suitable for power production. 2: Selection of a suitable power conversion cycle for the modeled MSRE system.

Methods

▣ In this study, the primary and intermediate loops suitable for the power conversion system are modeled as shown in right figure.



△ **The modeled MSRE system with power conversion system**

▣ The fuel salt is assumed to be based on NaCl-$MgCl_2$ because chlorine salt can dissolve major radioactive substances such as Cs, Sr, and I. These chemical properties prevent the leakage of radioactive materials when fuel salt is leaked to the outside.

▣ The design parameters of the primary side are selected as shown in below table.

▽ **Primary heat exchanger design parameter of the modeled MSRE system**

Primary Heat exchanger design parameter	
Heat load	10MWth [MSRE]
Hot side mass flow rate	163.31 kg/s [MSRE]
Hot side inlet temp.	650°C
Effectiveness	90%
$\Delta T_{hot\ side\ inlet-cold\ side\ outlet}$	10 K

▣ The PCHE type primary heat exchanger is conceptually designed using the KAIST-HXD code which is a MATLAB-based 1D-FDM in-house code.

▣ The used thermal properties and correlation are summarized in right table

▽ **Thermal property and heat exchanger correlation of the NaCl-$MgCl_2$**

Thermal property
$C_P = 1.08019 \times 1000\ [\frac{J}{kg \cdot K}]$
$\rho = (2.2971 - 0.000507 \times (T - 273.15)) \times 1000\ [\frac{kg}{m^3}]$
$\mu = \left(0.0286 \times exp\left(\frac{1441}{T}\right)\right) \times 0.01\ [\frac{kg}{m \cdot s}]$
$k = 0.000267 \times (T - 273.15) + 0.3133\ [\frac{W}{m \cdot K}]$
Heat exchanger Correlation
Nu = 4.089 (Laminar flow)
f = 15.78/Re (Laminar flow)

▣ The primary heat exchanger could be designed by adjusting the relationship between the length of the heat exchanger and the pressure drop

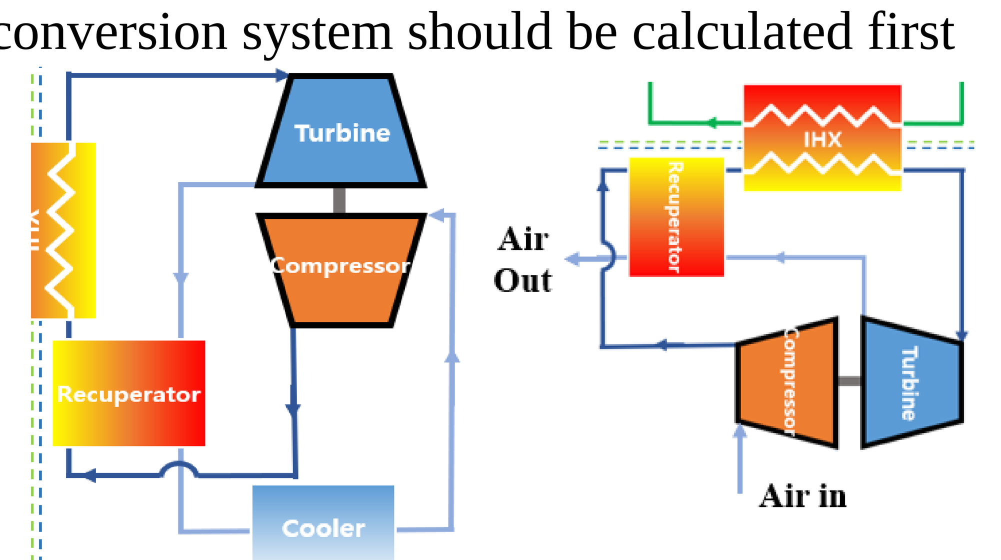
▽ **The Primary heat exchanger design results**

Design parameter	Cold side pressure drop = 30kPa	Cold side pressure drop = 50kPa	Cold side pressure drop = 100kPa
HX length (m)	2.36	3.05	4.32
Hot side outlet temp (K)	593.32	587.01	593.32
Cold side outlet temp (K)	587.01	587.01	587.01
Hot side pressure drop (kPa)	26	46	92
Hot side Average Re	648	836	1183
Cold side Average Re	683	882	1247
Cold side mass flow rate (kg/s)	174.72	174.72	174.72
HX Volume	3.27	3.27	3.27

▣ To design an intermediate heat exchanger connecting the secondary and tertiary sides, the mass flow rate of the power conversion system should be calculated first

▣ In the operating temperature range (550-630°C), the cycle with good efficiency while having high compactness is the gas Brayton cycle.

▣ The air open Brayton recuperated cycle and an sCO_2 (Supercritical CO_2) closed Brayton recuperated cycle are designed and compared in this study



△ **(a) sCO_2 recuperated power Brayton closed cycle**
(b) Air recuperated power Brayton open cycle

▣ The design parameters of each cycle are assumed as shown in below tables

▽ **Design parameters of the sCO_2 power conversion system**

Max Pressure	20 – 25 Mpa
Min Temperature	60°C
Max Temperature	630°C
Thermal heat	10 MW_{th}
Turbine efficiency	90%
Compressor efficiency	86%
Recuperator effectiveness	0.92
Component pressure drop	100-250 kPa
Heater Cold side	150 kPa
Recuperator Hot side	250 kPa
Recuperator Cold side	100 kPa
Cooler Hot side	100 kPa

▽ **Design parameters of the Air power conversion system**

Min Temperature	15 / 25 / 60°C
Max Temperature	630°C
Thermal heat	10 MW_{th}
Compressor inlet Pressure	101.325 kPa
Turbine efficiency	90%
Compressor efficiency	86%
Recuperator effectiveness	0.92
Component pressure Ratio	-
Heater Cold side	0.01
Recuperator Hot side	0.01
Recuperator Cold side	0.01
Ratio of exhaust pressure to atmosphere	0.98

▣ The cycle optimization variable is the turbine pressure ratio, and the optimization target is the maximum of cycle thermal efficiency and cycle-specific work product.

Result

▣ The air power cycle has relatively high thermal efficiency and specific work compared to the sCO_2 closed Brayton cycle.

▣ For the sCO_2 cycle, due to the limitation of the indirect air-cooling method, the minimum temperature was fixed at 60°C, so it did not show the best power cycle performance.

▣ Since the air cycle is an open Brayton cycle, it was able to have a lower minimum temperature compared to the sCO_2 cycle.

▽ **Cycle optimization results of the sCO_2 cycle**

Design parameter	sCO_2 Max pres. = 20MPa	sCO_2 Max pres. = 25MPa
Cycle Thermal efficiency (%)	32.99	34.13
Cycle work (MW_e)	3.30	3.41
Specific Work (MW_e/kg)	0.086	0.093
Thermal heat (MW_{th})	10	10
Pressure ratio	3.59	3.54
Min. Pressure (MPa)	5.16	6.63
Mass flow rate (kg/s)	38.59	36.82

▽ **Cycle optimization results of the air cycle**

Design parameter	Air Min Temp. = 60 °C	Air Min Temp. = 25 °C	Air Min Temp. = 15 °C
Cycle Thermal efficiency (%)	29.94	34.59	35.94
Cycle work (MW_e)	2.99	3.46	3.59
Specific Work (MW_e/kg)	0.072	0.092	0.099
Thermal heat (MW_{th})	10	10	10
Pressure ratio	2.95	3.45	3.63
Max. Pressure (MPa)	0.31	0.37	0.39
Mass flow rate (kg/s)	41.80	37.54	36.42

Conclusions

▣ A thermal sizing of MSR system is conducted in this study for efficient power production

▣ The air open Brayton cycle and the sCO_2 closed Brayton cycle suitable for the MSR are optimized and compared

▣ The air open Brayton power cycle has comparable thermal efficiency and specific work with the sCO_2 closed Brayton power cycle