Heat exchanger design study for micro molten salt reactor

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1. Introduction

The Molten Salt Reactor (MSR), one of the 4th generation nuclear power plants, is attracting a lot of attention due to its high core power density, compact size, and safety features. About twenty startups are developing the MSR design due to these advantages [1-4]. In the concept development of MSR, the design of an intermediate heat exchanger loop and power conversion system suitable for the system is a key issue. Therefore, in the previous study, thermal sizing of the MSR system was performed with respect to the Molten Salt Reactor Experiment (MSRE) conducted by the Oak Ridge National Laboratory (ORNL) as shown in Fig. 1 [5]. In the previous study, thermal sizing was performed by selecting the pinch temperature of the intermediate heat exchanger as 10K because MSRE did not have a temperature range suitable for power generation as shown in Table 1 [6-9].

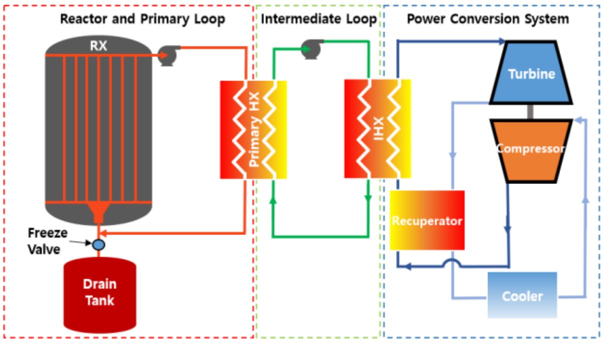

Fig 1. The MSR system with power conversion system [5]

Table 1. Primary heat exchanger design parameter of the MSRE system [6-9]

	Shell side (Fuel salt)	Tube side (Coolant salt)
Inlet / Outlet temperature [℃]	662.78 / 635	551.67 / 593.33
Inlet / Outlet Pressure [kPa]	379.2 / 241.3	530.9 / 324.0
Pressure drop [kPa]	137.9	206.9
Mass Flow Rate [kg/sec]	163.31	103.083

However, in the previous study, the intermediate heat exchanger type using liquid molten salt was selected the Printed circuit Heat Exchanger (PCHE) [5]. The PCHE is generally applied to the high-pressure operating conditions and may not be optimal option for molten salt which is operating at atmospheric pressure. This is because the high-pressure heat exchanger has typically higher cost compared to the low-pressure heat exchanger for the same heat transfer due to larger material cost due to high design pressure. Therefore, in this study, a heat exchanger type more suitable for the MSR system is selected and a concept design is re-performed.

2. Methodology

In this study, the design parameters of the MSR system for the primary heat exchanger are shown in Table 2 [5, 6].

Table 2. Primary heat exchanger design parameter of the MSR system [5, 6]

Heat load	$10MW_{th}$ [6]
Hot side mass flow rate	163.31 kg/s [6]
Hot side inlet temp.	662.78 [6]
$\Delta T_{\text{hot side inlet}-\text{cold side outlet}}$	10 K [5]

A plate-fin heat exchanger (PFHE) is used instead of the PCHE. The PFHE is a compact heat exchanger that performs heat transfer between fluids using a fin chamber between plates. The PFHE has the advantages of achieving compact size while having high effectiveness [10-12].

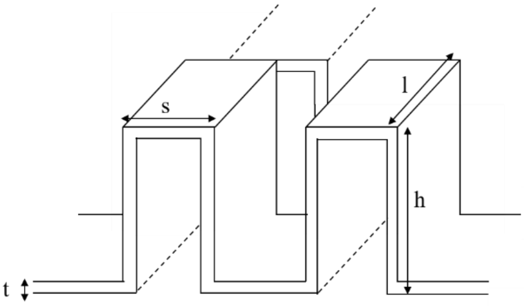

Fig 2. The shape of the offset-strip fin

Fig. 2 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). The PFHE is optimized for maximizing effectiveness and minimizing volume by adjusting these geometry parameters and the number of fin layers.

The correlation of the heat transfer *j* factor and friction *f* factor for the offset strip fin shape are adopted from the reference [13]:

$$j = 0.6522Re^{-0.5403}\left(\frac{s'}{h'}\right)^{-0.1541}\left(\frac{t}{l}\right)^{0.1499}\left(\frac{t}{s'}\right)^{-0.0678} \times \left[1 + 5.269\ \times 10^{-5}Re^{1.340}\left(\frac{s'}{h'}\right)^{0.504}\left(\frac{t}{l}\right)^{0.456}\left(\frac{t}{s'}\right)^{-1.055}\right]^{0.1} \quad (4)$$

$$f = 9.6243Re^{-0.7422}\left(\frac{s'}{h'}\right)^{-0.1856}\left(\frac{t}{l}\right)^{0.3053}\left(\frac{t}{s'}\right)^{-0.2659} \times \left[1 + 7.669\ \times 10^{-8}Re^{4.429}\left(\frac{s'}{h'}\right)^{0.902}\left(\frac{t}{l}\right)^{3.767}\left(\frac{t}{s'}\right)^{0.236}\right]^{0.1} \quad (5)$$

where $h' = h - t$, $s' = s - t$, Re is the Reynolds number. The equation (4) and (5) is valid for $0.134 < \frac{s'}{h'} < 0.997$, $0.012 < \frac{t}{l} < 0.048$, $0.041 < \frac{t}{s'} < 0.0121$ [13].

The effectiveness (ε) of the plate fin heat exchanger offset strip counter current flow is estimated by,

$$\varepsilon = \frac{1 - \exp\left\{-\mathrm{NTU}\left[1 - \left(\frac{C_{\min}}{C_{\max}}\right)\right]\right\}}{1 - \left(\frac{C_{\min}}{C_{\max}}\right)\exp\left\{-NTU\left[1 - \left(\frac{C_{\min}}{C_{\max}}\right)\right]\right\}} \quad (6)$$

The flow area and the total heat area of the plate fin heat exchanger offset strip are estimated as follows [10]:

$$A_{\text{flow}} = \frac{WN_f h' s'}{s} \quad (8)$$

$$A_{\text{total heat}} = \frac{(2h' + s')WLN_f}{s} + 2N_f(2h't + (s + t)t) \quad (9)$$

where N_f is the number of the fin layer, W is the heat exchanger width, L is the heat exchanger length.

The pressure drop of the PFHE is estimated as follows [10]:

$$\Delta P = \frac{2fLG^2}{\rho d_h} \quad (10)$$

where ρ is the density of the fluid, *f* is the friction factor.

The range of design parameters for PFHE is determined with values summarized in Table 3 [10-12]. The thermal properties of FLiBe (66% LiF – 34% BeF_2) are calculated as shown in Table 4 [14].

Table 3. Primary heat exchanger design parameters range [10–12]

	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	0.01
Fin offset length [l] (m)	0.001	0.01
Number of hot side layers	10	200

Table 4. Thermal properties of the FLiBe [14]

$C_P = 2386\ \left[\frac{J}{kg \cdot K}\right]$
$\rho = (2518\ - 0.406 \times T), for\ T < 973K$ $\rho = (2763.7\ - 0.0687 \times T), for\ T >\ 973K\ \left[\frac{kg}{m^3}\right]$
$\mu = \left(0.000116\ \times exp\left(\frac{3775}{T}\right)\right)\ \left[\frac{kg}{m \cdot s}\right]$
$k = 0.629697\ + 0.0005\ \times \mathrm{T}\ \left[\frac{W}{m \cdot K}\right]$

The FLiBe should be used at temperatures above 550℃ to avoid the risk of freezing [15]. In addition, to minimize the volume of the heat exchanger, it is necessary to reduce the mass flow rate of the cold side as much as possible. Therefore, the cold side mass flow rate that satisfies the primary heat exchanger cold side inlet temperature of 550 ℃ as well as the heat exchanger pinch temperature of 10K simultaneously is calculated as shown in Table 5.

Table 5. MSR primary PFHE cold side design parameters

Primary PFHE hot side [6]	
Mass flow rate (kg/s)	163.31
Inlet temperature (°C)	662.8
Outlet temperature (°C)	635.0
Primary PFHE cold side	
Mass flow rate (kg/s)	40.8
Inlet temperature (°C)	550
Outlet temperature (°C)	652.8

3. Results and Discussion

The Primary PFHE and PCHE designs are obtained using values summarized in Table 6 and Table 7. Table 8 compares the design results of the MSRE shell and tube type heat exchanger, PFHE, and PCHE heat exchanger [5-8].

Table 6. MSR primary PFHE conceptual design results

Hot Fin height [m]	0.005
Cold Fin height [m]	0.002
Fin thickness [m]	0.00011
Hot Fin frequency [m^{-1}]	500
Cold Fin frequency [m^{-1}]	600
Fin offset length [m]	0.003
Number of hot side layers	40
Number of cold side layers	41
Hot side pressure drop [kPa]	205
Cold side pressure drop [kPa]	135

Table 7. MSR primary PCHE conceptual design results

Hot semi-circular diameter [mm]	2
Cold semi-circular diameter [mm]	2
Hot channel number	40000
Cold channel number	20000
Plate minimum thickness [mm]	1
Gap between hot channels [mm]	1
Gap between cold channels [mm]	1
Hot side pressure drop [kPa]	205
Cold side pressure drop [kPa]	135

Table 8. Comparison of MSRE shell and tube heat exchanger, PFHE, and PCHE design results

	MSRE Primary Shell and tube type HX	Primary PFHE	Primary PCHE
Pinch temperature (K)	69.4	10	10
HX width [m]	0.84	0.5	0.6
HX length [m]	2.44	1.79	1.02
HX height [m]	0.84	0.32	0.6
Volume core [m^3]	1.34	0.29	0.36

As a result, it is confirmed that when PFHE is used, it can achieve lower pinch temperature and smaller volume of about 4.6 times compared to the shell and tube type heat exchanger. In addition, under the same pinch temperature and pressure drop conditions, there is no significant difference in the volumes of PFHE and PCHE. However, for PCHE, diffusion bonding technology at high temperature and pressure is essential. Therefore, the PCHE cost is expected to be more than PFHE.

4. Summary and Conclusions

In this study, the PFHE type primary heat exchanger is conceptually designed with reference to the previous study. The offset-strip fin PFHE is used for primary heat exchanger instead of PCHE. This is because molten salt, which is primary heat exchanger working fluid, operate in the low-pressure conditions (1bar~5bar). However, the PCHE used in the previous study is a heat exchanger suitable for high-pressure operating conditions. Therefore, in this study, the concept design of the MSR primary heat exchangers is performed using the PFHE type, which is a low-pressure heat exchanger. As a result, it is confirmed that the primary PFHE has a volume about 4.6 times smaller than that of the conventional shell and tube type heat exchanger while achieving lower pinch temperature. These results suggest that PFHE has a high potential for the primary heat exchanger of MSR. In addition, the volume of PFHE can be smaller than that of PCHE while potentially have lower cost. These results suggest that PFHE can be more favorable than PCHE for the molten salt system.

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