Pipe design for intermediate heat exchanger of the molten salt reactor

In Woo Son[a], Sungwook Choi[a], Sunghyun Yoo[a], Sang Ji Kim[b], Jeong Ik Lee[a*]
[a]*Dept. Nuclear & Quantum Eng., KAIST, 373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea*
[b] Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseoung-gu, Daejeon, 34057, Korea
[*]*Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

Recently, with the pressing global climate crisis issues, the generation IV reactor is receiving substantial attention as a new eco-friendly and efficient heat source [1]. Among many concepts of the next-generation reactors, the molten salt reactor is being studied by many countries around the world due to its advantages of low vapor pressure, high core power density, and inherent safety features [2-4]. However, many studies are focused only on the MSR (Molten Slat Reactor) core, and there are few studies on the intermediate heat transfer system and the power conversion system. To perform the MSR system concept design, the heat transport system and power conversion system designs are also important.

Therefore, in the previous study, the thermal sizing and intermediate heat exchanger of the $6.5MW_{th}$ molten salt reactor system was performed as shown in Figure 1 [5]. However, to carry out the conceptual design of the intermediate loop, it is necessary to select a pipe diameter suitable for the heat exchanger. Therefore, in this study, the pipe design is performed using the intermediate heat exchanger design results from the previous study [5].

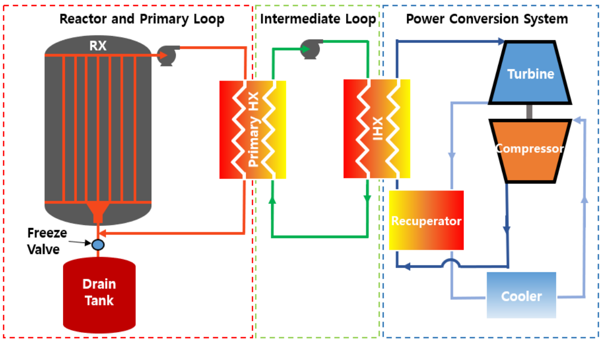

Fig 1. The MSR system with power conversion system [5]

2. Methods and Results

In this study, a pipe design suitable for the heat exchanger is performed using the design result from the previous study. In the previous study, the STHE (Shell and Tube Heat Exchanger), PCHE (Printed Circuit Heat Exchanger), and PFHE (Plate fin Heat Exchanger) types were conceptually designed and compared for the intermediate heat exchanger [5]. As a result, the PFHE was selected as the appropriate intermediate heat exchanger type, since the PFHE has better heat transfer performance than STHE and requires lower manufacturing cost and mass than PCHE. The primary and secondary PFHE concept design results in the previous study are as follows [5].

Table 1. Primary PFHE heat sizing results

Primary PFHE			
	Inlet (°C)	Outlet (°C)	mass flow rate (kg/s)
Hot side	650	560	100.38
Cold side	550	640	65.21

Table 2. Secondary PFHE heat sizing results

Secondary PFHE			
	Inlet (°C)	Outlet (°C)	mass flow rate (kg/s)
Hot side	640	550	65.21
Cold side	398	630	25.55

Table 3. Primary and Secondary PFHE design results

	Primary	Secondary
HX width [m]	0.5	1.25
HX length [m]	2.56	0.51
Hot Fin height [m]	0.002	0.002
Cold Fin height [m]	0.002	0.006
Fin thickness [m]	0.0001	0.0001
Hot Fin frequency [m^{-1}]	1000	1000
Cold Fin frequency [m^{-1}]	1000	700
Fin offset length [m]	0.003	0.008
Number of hot side layers	80	130
Number of cold side layers	81	131
Plate thickness [m]	0.0005	0.0005
HX height [m]	0.40	1.18
Volume core [m^3]	0.51	0.75
Hot side pressure drop [kPa]	167	2.35
Cold side pressure drop [kPa]	108	6.87
Heat exchanger effectiveness [%]	90.0	95.87

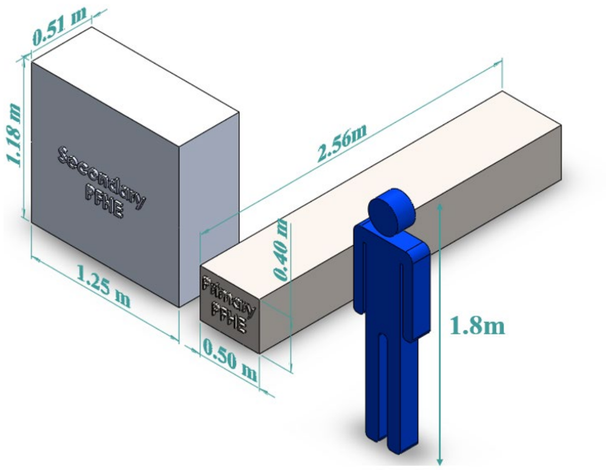

Fig 2. Comparison of the the primary and secondary PFHE design volume

The first step in pipe design is to calculate the suitable inner diameter using the heat exchanger design results. To estimate the inner diameter of the pipe, an optimum velocity of the fluid for each heat exchanger pipe is required. As a result of the literature review, Ronald's correlation for calculating the optimum flow velocity is used to compute the inner diameter [6].

$$V = \frac{f_{pv}}{\rho^{0.3}}$$

$$D = \sqrt{\frac{4\dot{m}}{\pi \rho V}}$$

Where V is the optimum flow velocity (m/s), f_{pv} is the pipe velocity factor ($m\left(\frac{kg}{m^3}\right)^{0.3}/s$), ρ is fluid density ($\frac{kg}{m^3}$), and D is the inner diameter of the pipe [6].

To estimate the inner diameter, the pipe velocity factor and the average density of each fluid are required. The pipe velocity factors are shown in Table 4 [6]. The fuel salt the thermal properties are provided by KAERI (Korea Atomic Energy Research Institute). The thermal properties of the coolant salt, NaCl-MgCl₂, are shown in Table 5 [7]. For the thermal properties of air are calculated using REFPROP 10.0 version developed by NIST [8]. Therefore, the result of the inner diameter suitable for each heat exchanger is shown in Tables 6 and 7.

Table 4. Pipe velocity factors for Ronald's correlation

Motive Energy Source	m (kg/m^3)$^{0.3}$ /s
Centrifugal Pump, Blower	14
Compressor Pipe diameter < 6in., Pipe diameter > 6in.	24, 29
Steam Boiler	63 ~ 68

Table 5. Thermal properties of the NaCl-MgCl₂ [7]

$\mu = \left(0.0286 \times exp\left(\frac{1441}{T}\right)\right) \times 0.01 \left[\frac{kg}{m \cdot s}\right]$
$\rho = (2.2971 - 0.000507 \times (T - 273.15)) \times 1000 \left[\frac{kg}{m^3}\right]$
$C_P = 1.08019 \times 1000 \left[\frac{J}{kg \cdot K}\right]$
$k = 0.000267 \times (T - 273.15) + 0.3133 \left[\frac{W}{m \cdot K}\right]$

The pipe thickness is computed using the pipe inner diameter result. The thickness of the pipe is selected as the NPS standard by referring to ASME section I, PG-27, and ASME B 36.10M & 36.19M.

The material of the pipe is selected as SS316L (SA-213 TP316H) by referring to the ASME section II, Part D, which has excellent oxidation resistance, high temperature corrosion resistance and strength by increasing the molybdenum and nickel content to the SS304.

Therefore, the pipe design results suitable for each heat exchanger are as follows.

Table 6. Pipe design results of the primary PFHE

Primary PFHE		
	Fuel salt inlet / outlet	NaCl-MgCl₂ inlet / outlet
Pipe velocity factor [m (kg/m^3)$^{0.3}$ /s]	14	14
Optimum velocity [m / s]	1.32 / 1.31	1.43 / 1.44
Pipe inner diameter (m)	0.19 / 0.19	0.17 / 0.17
Pipe thickness (m), [SCH]	0.00635 [SCH20] / 0.00635 [SCH20]	0.00635 [SCH20] / 0.00635 [SCH20]
Pipe outer diameter (m), [Inch]	0.20 [8] / 0.20 [8]	0.20 [8] / 0.20 [8]
Fluid density (kg/m^3)	2610.00 / 2676.67	2018.25 / 1972.62

Table 7. Pipe design results of the secondary PFHE

Secondary PFHE		
	NaCl-MgCl₂ inlet / outlet	Air inlet / outlet
Pipe velocity factor [m (kg/m^3)$^{0.3}$ /s]	14	29
Optimum velocity [m / s]	1.43 / 1.44	20.00 / 26.80

Pipe inner diameter (m)	0.17 / 0.17	1.00 / 1.00
Pipe thickness (m), [SCH]	0.00635[SCH20]/ 0.00635 [SCH20]	0.00953[STD] / 0.00953 [STD]
Pipe outer diameter (m), [Inch]	0.20 [8] / 0.20 [8]	1.02 [40] / 1.02 [40]
Fluid density (kg/m^3)	2018.25 / 1972.62	1.78 / 1.3

As a result, the NPS 8-SCH20 pipe is selected for fuel salt and coolant salt pipe. However, for air, larger pipe NPS 40-STD is chosen. This is because the density of air is about 1300 times lower than that of molten salt, thus, the required optimum velocity is higher. These results lead to an increase in the inner diameter of the air pipe.

3. Conclusions

In this study, the pipe design suitable for the MSR intermediate heat exchanger designed in the previous study is performed. As a result, NPS 8-SCH20 piping is selected for both the hot side and the cold side of the primary PFHE. Secondary PFHE hot side pipe with coolant salt is also selected as NPS 8-SCH20. However, the secondary PFHE cold side with air is selected as a relatively large pipe for NPS 40-STD. This is because the density of air is about three orders of magnitude lower than that of molten salt. Therefore, for air with low density, the optimum pipe velocity increases, and the inner diameter increases accordingly. As a further study, a header suitable for the selected pipe and heat exchangers will be designed and analyzed.

ACKNOWLEDGEMENTS

This work was supported by the Korean government (MIST) [KAERI grant number 522310-22]

REFERENCES

[1] Magwood IV, William D., and Henri Paillere. "Looking ahead at reactor development." Progress in Nuclear Energy 102 (2018): 58-67.
[2] IAEA. "Advances in Small Modular Reactor Technology Developments. A Supplement to: IAEA Advanced Reactors Information System (ARIS)." (2018).
[3] Dolan, Thomas James, ed. *Molten salt reactors and thorium energy*. Woodhead Publishing, 2017.
[4] Zhu, Guifeng, et al. "Low enriched uranium and thorium fuel utilization under once-through and offline reprocessing scenarios in small modular molten salt reactor." *International Journal of Energy Research* 43.11 (2019): 5775-5787.
[5] Son, In Woo, et al. "Heat exchanger design study for micro molten salt reactor."
[6] Ronald W. Capps, "Selecting the optimum pipe size", Chemical Engineering, 102.7 (Jul 1995) : 128.
[7] 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.
[8] Lemmon, Eric, Marcia L. Huber, and Mark O. Mclinden. "NIST standard reference database 23: reference fluid thermodynamic and transport properties-REFPROP, version 8.0." (2007).