# Selecting Optimal Heat Transfer Chloride Salt for Molten Salt Fast Reactor: Heat Exchanger Design and Mass Comparison

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## 1. Introduction

In the pursuit of sustainable and efficient nuclear energy solutions, Molten Salt Fast Reactors (MSFRs) have emerged as promising candidates, distinguished by their inherent safety features and enhanced efficiency. A critical aspect influencing the performance of MSFRs lies in the choice of the heat transfer fluid. The selection of an optimal chloride salt needs to consider various aspects of the salt, such as thermal properties, heat exchanger design, and pumping work consumption. In previous studies, the thermodynamic properties and heat exchanger design of NaCl-$MgCl_2$, KCl-$MgCl_2$, and NaCl-KCl-$ZnCl_2$ were compared [1,2]. A Plate-Fin Heat Exchanger was selected for the intermediate heat exchangers based on the literature review. However, for the sake of simplicity and the limited amount of data, the fuel salt was assumed to have the same thermal properties as the heat transfer salt. This study introduces PFHE design considerations with NaCl-$UCl_3$ as the fuel salt, accompanied by an initial mass evaluation for each heat exchanger core.

## 2. Methods and Results

### *2.1 Thermal Sizing*

Table I. Air Brayton Cycle Information [2]

| Input Parameter | |
|---|---|
| Thermal output | 8.0 $MW_{th}$ |
| Air temperature | 15°C |
| Turbine inlet temperature | 630 °C |
| Turbine efficiency | 88 % |
| Compressor efficiency | 84 % |
| Recuperator effectiveness | 90 % |
| Result | |
| Mass Flow Rate | 35.70 kg/s |
| Thermal efficiency | 31.05 % |

Table II. Mass Flow Rate of each candidate & fuel salt [2]

| | Mass Flow Rate [kg/s] |
|---|---|
| NaCl-$MgCl_2$ | 147.61 |
| KCl-$MgCl_2$ | 138.05 |
| NaCl-KCl-$ZnCl_2$ | 174.48 |
| NaCl-$UCl_3$ | 271.19 |

Table I shows the Air Brayton cycle parameters, and Table II lists the mass flow rates for each candidate and fuel salt, derived from preceding research [2]. Based on the mass flow rate of the heat transfer salt, the mass flow rate of the fuel salt is calculated before designing the primary heat exchanger. The eutectic point of NaCl-$UCl_3$ (65.9%-34.1%, mol %) is selected as the fuel salt in this research. The thermal properties of the fuel salt are obtained from the literatures [3-5]. The density of NaCl-$UCl_3$, not directly available, is deduced using the additive molar volume method. The properties used in this study are given below. Based on the fuel salt mass flow rate and thermal properties, the primary heat exchangers are designed.

$$\rho\left[\frac{kg}{m^3}\right] = 4254.7 - 1.0621T[K] \tag{1}$$

$$C_p\left[\frac{J}{kg-K}\right] = 590 \tag{2}$$

$$\lambda\left[\frac{W}{m-K}\right] = 0.0012T[K] - 0.495 \tag{3}$$

$$\eta[Pa*s] = 0.1207\,exp(-0.0067T[K]) + 0.0037exp(-0.001T[K]) \tag{4}$$

### *2.2 PFHE Design*

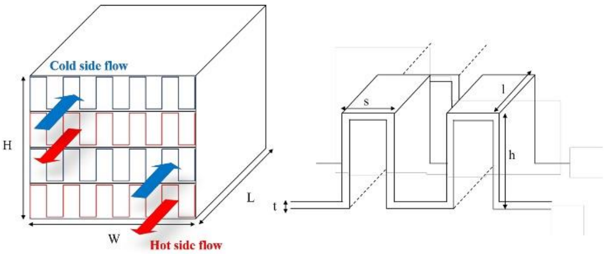

Fig 1. Schematic of PFHE and detailed view of the offset strip fin

As shown in Figure 1, counter flow PFHEs with offset strip fins are used as the primary and secondary intermediate heat exchangers for this paper. This study's methodology mirrors previous works, with NaCl-$UCl_3$ now introduced as the fuel salt [2]. Thus, PFHE core designs for secondary heat exchangers were the same. Table III presents the PFHE design result, leading to an estimation of each PFHE core's mass.

Table III. Primary and Secondary PFHE Core Design Result

| | **Primary PFHE** (With NaCl-UCl$_3$ as fuel salt) | | | **Secondary PFHE** (With air Brayton cycle) | | |
|---|---|---|---|---|---|---|
| | NaCl-MgCl$_2$ | KCl-MgCl$_2$ | NaCl-KCl-ZnCl$_2$ | NaCl-MgCl$_2$ | KCl-MgCl$_2$ | NaCl-KCl-ZnCl$_2$ |
| Hot side inlet/outlet temperature [℃] | 650 / 600 | | | 640 / 590 | | |
| Cold side inlet/outlet temperature [℃] | 590 / 640 | | | 426.09 / 630 | | |
| Plate Thickness [m] | $5.0 \times 10^{-4}$ | | | | | |
| HX width [m] | 0.75 | 0.75 | 1.5 | 1.8 | 1.8 | 1.8 |
| HX length [m] | 0.979 | 0.975 | 0.661 | 0.769 | 0.765 | 0.804 |
| HX height [m] | 0.546 | 0.546 | 0.770 | 0.629 | 0.629 | 0.658 |
| Hot side pressure drop [kPa] | 136.58 | 136.16 | 137.549 | 5.995 | 6.515 | 87.923 |
| Cold side pressure drop [kPa] | 80.10 | 83.79 | 193.137 | 8.424 | 8.379 | 9.3674 |
| Hot Side Mass Flow Rate [kg/s] | 271.19 | | | 147.612 | 138.054 | 174.482 |
| Cold Side Mass Flow Rate [kg/s] | 147.612 | 138.054 | 174.482 | 35.70 | | |

Table IV. Primary and Secondary PFHE Core Mass Estimation

| | **Primary PFHE** (With NaCl-UCl$_3$ as fuel salt) | | | **Secondary PFHE** (With air Brayton cycle) | | |
|---|---|---|---|---|---|---|
| | NaCl-MgCl$_2$ | KCl-MgCl$_2$ | NaCl-KCl-ZnCl$_2$ | NaCl-MgCl$_2$ | KCl-MgCl$_2$ | NaCl-KCl-ZnCl$_2$ |
| Hot Side Fluid Volume [m$^3$] | 0.126 | 0.124 | 0.238 | 0.166 | 0.166 | 0.166 |
| Cold Side Fluid Volume [m$^3$] | 0.127 | 0.125 | 0.239 | 0.484 | 0.484 | 0.484 |
| Hot side Fluid Mass [kg] | 412.238 | 407.187 | 779.710 | 329.937 | 324.480 | 376.102 |
| Cold Side Fluid Mass [kg] | 253.037 | 247.053 | 498.378 | 0.592 | 0.589 | 0.647 |
| Structure Mass [kg] | 1687.100 | 1666.428 | 2937.027 | 2271.944 | 2259.660 | 2473.824 |
| Total Core Mass [kg] | 2352.375 | 2320.668 | 4215.115 | 2602.473 | 2584.728 | 2850.572 |

### *2.3 Mass Calculation*

Before calculating the PFHE core mass, the thick ness of the end plate and side plate need to be determined. The thickness is calculated based on ASME BPVC section VIII, Division 1.

$$t = \frac{P * R}{SE - 0.6P} \tag{5}$$

Hastelloy N is used as the material for the PFHE, because Hastelloy N has high corrosive resistance in molten salt environment. The maximum allowable stress of the material is obtained from the literature review [6]. Assuming the joint efficiency is 1 and factor of safety 3.5, the thickness of the heat exchangers is calculated to be 1.5 cm.

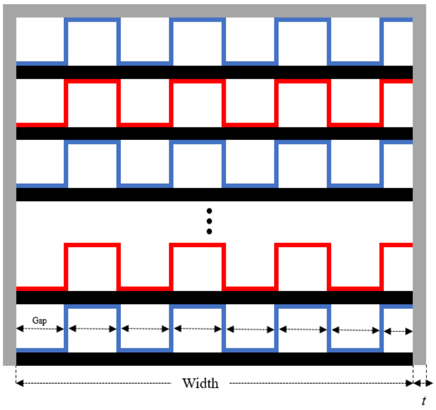

Fig 2. Frontal cross-section view of PFHE Core

Figure 2 offers a frontal cross-sectional view of a PFHE core, with Table IV summarizing the mass calculation results. The mass of the fluids and the structure are calculated using the density of the fluid and the material. As shown in the result, the calculation reveals a negligible mass difference between the PFHEs employing NaCl-$MgCl_2$ and KCl-$MgCl_2$. However, the NaCl-KCl-$ZnCl_2$-based PFHE needs a larger heat transfer area, owing to its inferior thermal properties, especially volumetric heat capacity, thus increasing the overall mass.

### 3. Summary and Conclusions

In this research, the selection of the optimal heat transfer chloride salt for MSFR with focus on heat exchanger design with NaCl-$UCl_3$ as the fuel salt and mass calculation are conducted. The use of NaCl-$UCl_3$ as the primary PFHE's hot side fluid unveils the significant impact of varying heat transfer salts on design parameters. Furthermore, the study meticulously calculates the mass and volume occupied by the fluids, adhering to ASME BPVC standards for structural components. The results of this study suggest KCl-$MgCl_2$ as the superior heat transfer salt, considering heat exchanger volume and mass constraints. In this paper, only the core part of the heat exchanger is included. For the further work, the design and the mass calculation of the header and fluid distributor should further proceed to compare options in more detail.

### NOMENCLATURE

| Symbol [Unit] | Definition |
|---|---|
| $\boldsymbol{\rho}\ \left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$ | Density |
| $\boldsymbol{C_p}\ \left[\frac{\mathrm{J}}{\mathrm{kg}-\mathrm{K}}\right]$ | Heat Capacity |
| $\boldsymbol{\lambda}\ \left[\frac{W}{m-K}\right]$ | Thermal Conductivity |
| $\boldsymbol{\eta}\ [Pa * s]$ | Dynamic Viscosity |
| $\boldsymbol{t}\ [m]$ | Thickness |
| $\boldsymbol{P}\ [Pa]$ | Design Pressure |
| $\mathbf{R}\ [m]$ | Equivalent Radius |
| $\boldsymbol{S}\ [Pa]$ | Maximum Allowable Stress |
| $\boldsymbol{E}\ [-]$ | Joint Efficiency |

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