

# Heat Transfer and Friction Characteristics of NaCl-KCl-MgCl<sub>2</sub> in PCHE Zigzag Channels Coupled with sCO<sub>2</sub> Using CFD

Seungkyu Lee<sup>a</sup>, Jeong Ik Lee<sup>a\*</sup>

<sup>a</sup>Dept. Nuclear & Quantum Eng., KAIST, 373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea

\*Corresponding author: jeongiklee@kaist.ac.kr

**\*Keywords :** Molten salt, Printed Circuit Heat Exchangers, Computational Fluid Dynamics, Nusselt number

## 1. Introduction

High-temperature molten salts have been extensively investigated as promising heat transfer fluids for concentrated solar power, energy storage systems (ESS), and advanced nuclear reactors, due to their high boiling point, large volumetric heat capacity, and low vapor pressure. In nuclear applications, molten salts serve both as coolants and thermal energy storage media, offering the potential for load-following operation and enhanced safety. When coupled with supercritical carbon dioxide (sCO<sub>2</sub>) power conversion systems, molten salts offer several advantages: their high outlet temperature allows for higher sCO<sub>2</sub> turbine inlet temperatures, resulting in increased cycle efficiency, and the chemical stability of chlorides enables long-term operation without decomposition.

Among various compact heat exchanger designs, the Printed Circuit Heat Exchanger (PCHE) is particularly attractive for high-temperature applications due to its high surface area-to-volume ratio and robust mechanical integrity under high pressure. In this study, a zigzag channel PCHE is considered, where the hot side flows NaCl-KCl-MgCl<sub>2</sub> molten salt and the cold side flows sCO<sub>2</sub>, reflecting a realistic configuration for next-generation nuclear– sCO<sub>2</sub> hybrid systems. Although extensive studies exist on Nusselt number and Fanning friction factor correlations for fluids such as water, helium, and sCO<sub>2</sub>, experimental and numerical data for chloride-based molten salts in zigzag PCHE channels remain extremely limited. Only a few experiments using nitrate salts have been reported, and no CFD investigations have previously been conducted for molten chloride salts.

## 2. Methods and Results

In this study, the heat transfer performance and friction characteristics of a NaCl-KCl-MgCl<sub>2</sub> molten salt in a PCHE zigzag channel with a 115° bend angle were investigated using CFD, while the cold side was sCO<sub>2</sub>. Detailed dimensions and figure are shown in Figure 1. Property expressions of the NaCl-KCl-MgCl<sub>2</sub> adopted in this simulation are shown in Table I [1]. Inlet conditions of molten salt and sCO<sub>2</sub> are shown in Table II. Though the Reynolds number is in the laminar flow region, k-omega SST model is adopted because zigzag channel flow creates eddies in every turn and therefore turbulence can be generated for both molten salt and sCO<sub>2</sub> flows

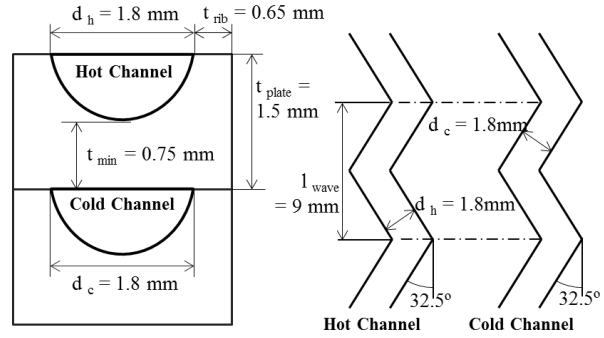


Fig. 1. Dimensions and figure of the PCHE zigzag channel

Table I: Properties of NaCl-KCl-MgCl<sub>2</sub> [1]

| Property                        | Expression                       |
|---------------------------------|----------------------------------|
| Density<br>[kg/m <sup>3</sup> ] | 1940 – 0.42 * T[°C]              |
| Heat capacity<br>[J/kg/K]       | 1100                             |
| Dynamic viscosity<br>[Pa s]     | 0.027728 * exp(-0.00364 * T[°C]) |
| Thermal Conductivity<br>[W/m/K] | 0.53 – 0.000132 * T[°C]          |

Table II: Inlet conditions of the working fluids

| Cold side         | Molten salt      |
|-------------------|------------------|
| Reynolds number   | 100 ~ 1200       |
| Inlet temperature | 913 K            |
| Inlet pressure    | 1.5 bar          |
| Hot side          | sCO <sub>2</sub> |
| Inlet velocity    | 3.7 m/s          |
| Inlet temperature | 759 K            |
| Inlet pressure    | 19.7 MPa         |

The representative dimensionless number for heat transfer is the Nusselt number (Nu), while the representative dimensionless number for pressure drop is the Fanning friction factor (f). The Nusselt number can be expressed as a function of the heat transfer coefficient (h), hydraulic diameter (D<sub>h</sub>), and thermal conductivity (k), as shown in Equation 1. The heat transfer coefficient is defined in terms of the heat flux (q<sub>w</sub>) and the difference between the fluid bulk temperature and the wall temperature, as given in Equation 2. The bulk

temperature of the fluid ( $T_b$ ) is determined by the mass flux-weighted average over a periodic passage, as described in Equation 3, and the wall temperature ( $T_w$ ) of the fluid is defined as the area-weighted average along the wall surface over a periodic passage, as given in Equation 4. The Fanning friction factor ( $f$ ) is determined using the pressure difference over several channel passes, with additional parameters including the hydraulic diameter ( $D_h$ ), fluid density ( $\rho$ ), bulk velocity ( $U_{b,z}$ ), and the flow passage length ( $L_{zz}$ ) as shown in Equation 5.

$$Nu = hD_h/k \quad (\text{Equation 1})$$

$$h = q_w / (T_w - T_b) \quad (\text{Equation 2})$$

$$T_b = \frac{\int u \rho c_p T dA}{\int u \rho c_p dA} \quad (\text{Equation 3})$$

$$T_w = \frac{1}{A} \int T dA \quad (\text{Equation 4})$$

$$f = \frac{\Delta p D_h}{2 \rho U_{b,z}^2 L_{zz}} \quad (\text{Equation 5})$$

Preliminary results from the CFD simulation are shown in Figure 2, which illustrates the temperature contour in the zigzag PCHE channel. The CFD results indicate that the Nusselt number increases with Reynolds number, showing an enhancement due to secondary flows induced by the zigzag geometry. For Reynolds numbers ranging from 100 to 1200, the Nusselt number varied approximately from 9.6 to 58. The Fanning friction factor decreased with increasing Reynolds number, as presented in Table III. These results are preliminary, as no experimental validation currently exists for chloride salts in zigzag PCHE channels.

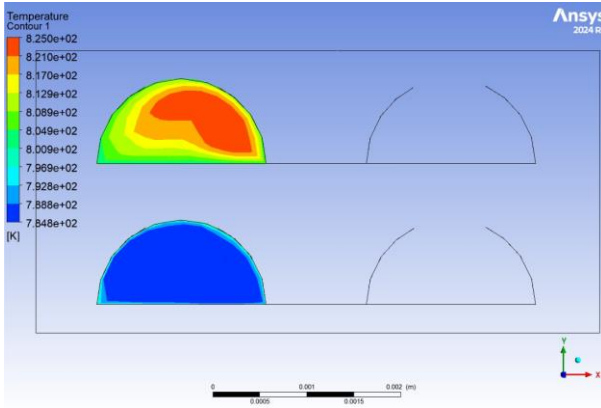


Fig. 2. Temperature contour in zigzag PCHE channel

Table III: NaCl-KCl-MgCl<sub>2</sub> number and friction factor along the Reynolds number

| Reynolds number | Nusselt number (Nu) | Fanning friction factor (f) |
|-----------------|---------------------|-----------------------------|
| 100             | 9.6235              | 0.2966                      |
| 200             | 13.577              | 0.2027                      |
| 300             | 19.115              | 0.1648                      |
| 400             | 24.175              | 0.1434                      |
| 500             | 28.323              | 0.1295                      |
| 600             | 31.834              | 0.1195                      |

|      |        |         |
|------|--------|---------|
| 700  | 35.856 | 0.1119  |
| 800  | 39.923 | 0.1060  |
| 1000 | 50.135 | 0.09720 |
| 1200 | 59.07  | 0.09090 |

A regression analysis was conducted to develop a correlation for the zigzag PCHE using molten salt. As a result, a Nusselt number correlation as a function of Reynolds number was obtained, as shown in Equation 6. Figure 3 presents a comparison between the CFD results, the regression-based correlation, and experimental data using solar salt. In the referenced experiment, the solar salt flows through a channel with a circular cross-section—unlike the semi-circular channel used in this study—and the bending angle is 120° [2]. Moreover, since solar salt has a kinematic viscosity approximately ten times lower than that of chloride-based molten salts, a direct comparison is not straightforward. Due to the low kinematic viscosity of solar salt, flow reattachment on the suction side after turning is less likely to occur. In contrast, for NaCl-KCl-MgCl<sub>2</sub>, which has higher kinematic viscosity, the improved reattachment may contribute to enhanced heat transfer performance in the zigzag channel. Nonetheless, the experiment is one of the few studies that provides an empirical correlation for molten salts in a PCHE channel showing Equation 7.

$$Nu_{cfd} = 0.1541 Re^{0.7394} Pr^{0.333} \quad (\text{Equation 6})$$

$$Nu_{Aakre} = 0.412 Re^{0.51} Pr^{0.333} \quad (\text{Equation 7})$$

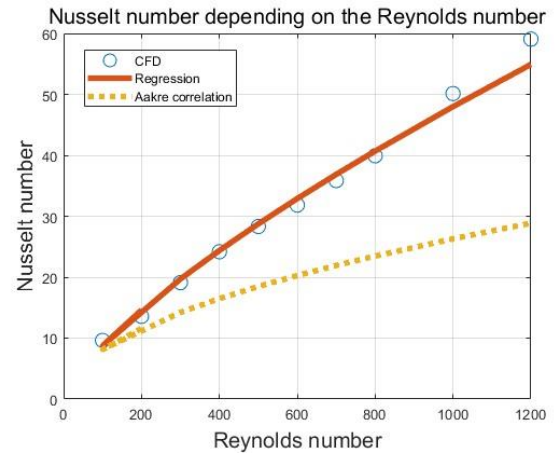


Fig. 3. CFD data and regression equation line with previous experimental data of solar salt Nusselt number

A nonlinear correlation for the Fanning friction factor was also developed based on the CFD data and is presented in Equation (8). The proposed model introduces a constant offset term in addition to the Reynolds number-dependent power-law component, which allows the expression to more accurately reflect the flattening behavior of the friction factor. To evaluate the accuracy and applicability of this model, it was compared with the empirical correlation reported by Aakre et al. [2], which assumes a conventional power-law form with an offset. As shown in Figure 4, both models show similar trends in the low Reynolds number

regime; however, the CFD-based correlation exhibits good agreement with the numerical data across the full range. The constant offset in the present model captures the residual pressure loss likely caused by secondary flow structures and repeated turning losses in the zigzag geometry. This indicates that for viscous fluids like chloride molten salts, accounting for such baseline resistance is important when predicting pressure drop in PCHE design.

$$f_{CFD} = 16.07Re^{-0.868} + 0.074 \quad (\text{Equation 8})$$

$$f_{Aakre} = 5.419Re^{-0.664} + 0.042 \quad (\text{Equation 9}) [2]$$

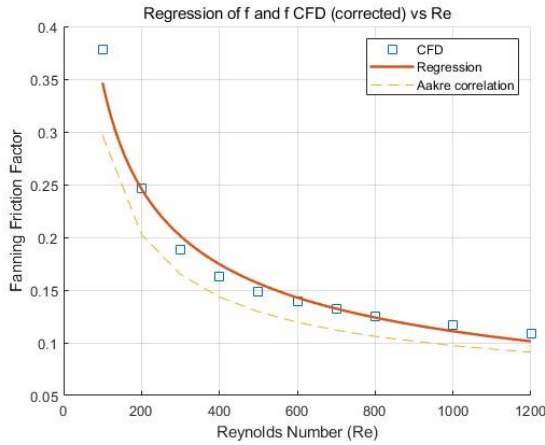


Fig. 4. CFD data and regression equation line with previous experimental data of solar salt friction factor

### 3. Conclusions

This study demonstrates that CFD can be used to predict heat transfer and friction behavior of NaCl-KCl-MgCl<sub>2</sub> in zigzag PCHE channels coupled with sCO<sub>2</sub>. The results show the significant impact of channel geometry ( $\alpha = 115^\circ$ ) and fluid properties on Nusselt numbers and Fanning friction factors. By providing the first correlations for chloride-based molten salts from the obtained numerical results, this work fills an important gap and offers guidance for designing high-temperature PCHEs in nuclear-sCO<sub>2</sub> hybrid systems. Future research could include experimental validation, extended Reynolds number ranges, and geometry optimization to enable reliable, high-efficiency heat exchanger designs.

### REFERENCES

- [1] Villada, C., Ding, W., Bonk, A., & Bauer, T. (2021). Engineering molten MgCl<sub>2</sub>-KCl-NaCl salt for high-temperature thermal energy storage: Review on salt properties and corrosion control strategies. *Solar Energy Materials and Solar Cells*, 232, 111344.
- [2] Aakre, S. R., & Anderson, M. H. (2022). Pressure drop and heat transfer characteristics of nitrate salt and supercritical CO<sub>2</sub> in a diffusion-bonded heat exchanger. *International Journal of Heat and Mass Transfer*, 189, 122691.