

Development of Nusselt Number and Darcy Friction Factor Correlations for a NACA 0020 Airfoil PCHE Using $\text{MgCl}_2\text{-KCl}$ Molten Salt

Dogyun Kim^a, Taewoo Kim^{a*}, Sang Ji Kim^a

^aKorea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 34057, Korea

*Corresponding author: twkim91@kaeri.re.kr

***Keywords :** Airfoil PCHE, $\text{MgCl}_2\text{-KCl}$, Turbulence model, Correlations

1. Introduction

Small Modular Reactors (SMRs) have attracted considerable attention as next-generation nuclear reactors owing to their enhanced safety and economic feasibility. Among various SMR concepts, Molten Salt Reactors (MSRs) employ molten fuel salts and operate at high temperatures. Therefore, high-performance heat exchangers are essential for efficient heat transfer in MSR systems.

Printed Circuit Heat Exchangers (PCHEs) are promising heat exchangers for MSR applications. They offer compact size, high heat transfer performance, and high mechanical strength. Their thermal-hydraulic performance is strongly affected by channel geometry. Representative geometries include straight, zigzag, S-shaped, and airfoil channels. Among these, airfoil channels provide favorable heat transfer performance with reduced pressure drop.

To evaluate the thermal-hydraulic characteristics of airfoil PCHEs, a validated reference geometry is required. Chung et al. [1] experimentally investigated a NACA 0020 airfoil PCHE for an N_2 Brayton cycle recuperator. They proposed Nusselt number and Fanning friction factor correlations based on the experimental results. Therefore, their experimentally validated geometry was adopted as the computational model in this study.

Most previous studies on airfoil PCHEs have used helium, supercritical CO_2 , or nitrogen as working fluids. In contrast, studies using molten salts remain limited. This is mainly due to the high operating temperatures and corrosion issues associated with molten salts.

Wang et al. [2] numerically investigated a NACA 0025 airfoil PCHE using Hitec molten salt. They developed a Nusselt number correlation for Reynolds numbers range of 500-1,548. They also proposed correlations based on experimental and CFD results. The correlations agreed with the experimental results within $\pm 11\text{--}12\%$. Subsequently, Shi et al. [3] investigated an airfoil PCHE using $\text{MgCl}_2\text{-KCl}$ molten salt. They developed Nusselt number and Darcy friction factor correlations for Reynolds numbers range of 500-2,500.

Previous correlations for molten-salt airfoil PCHEs are generally limited to Reynolds numbers

below approximately 2,500. Therefore, correlations covering a wider Reynolds number range are required.

In this study, $\text{MgCl}_2\text{-KCl}$ was selected as the working fluid. The thermal-hydraulic characteristics of a NACA 0020 airfoil PCHE were numerically investigated over Reynolds numbers ranging from 500 to 10,000. Based on the CFD results, Nusselt number and Darcy friction factor correlations were developed.

2. Model parameter and Numerical Method

2.1 Model and Hydraulic diameter

Figure 1 illustrates the computational domain and the geometry of the NACA 0020 airfoil PCHE used in this study. The left side of figure 1 shows the computational domain composed of 10 sets with a total flow length of 108 mm, which corresponds to the airfoil array length. Whereas the right side of figure 1 presents the geometry of single airfoil fin. The array dimensions and principle geometric parameters of the airfoil fin are summarized in Table I.

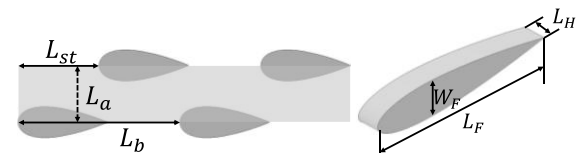


Fig.1. Schematic of the airfoil PCHE

Table I: NACA 0020 airfoil PCHE geometry dimensions [1]

L_{st}	5.4 mm
L_a	2.2 mm
L_b	10.8 mm
L_F	6 mm
W_F	1.2 mm
L_H	0.7 mm

The hydraulic diameter (D_h) is an important geometric parameter for calculating the Nusselt number and Darcy friction factor (f_D) in an airfoil PCHE. However, because the airfoil channel geometry continuously varies along the flow direction, it is difficult to define a unique hydraulic diameter, and different definitions have been adopted in

previous studies. In this study, the hydraulic diameter definition proposed by Yoon et al. [4] was adopted.

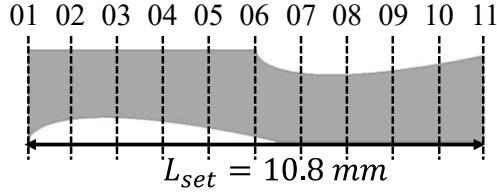


Fig.2. 11 sections division of an airfoil element

Figure 2 shows an airfoil element set divided into 11 sections for calculating the hydraulic diameter. The local hydraulic diameter at each section was calculated using Equation (1),

$$(1) D_h = \frac{4A_c}{P}$$

$$(2) \overline{D_h} = \frac{\sum_{k=1}^{11} D_{h,k}}{11}, k = 1, 2, 3, \dots, 11$$

Where, A_c is the cross-sectional area and P is the wetted perimeter. The average hydraulic diameter of an airfoil element set was then calculated by averaging the local hydraulic diameters using Equation (2).

Using Equation (2), the average hydraulic diameter of the airfoil PCHE considered in this study was determined to be 1.1 mm.

2.2 Thermal-hydraulic performance and Thermophysical properties

In this study, the Reynolds number and Nusselt number, and Darcy friction factor were defined as follows:

$$(3) Re = \frac{\dot{m} \overline{D_h}}{\mu A_c}$$

$$(4) Nu = \frac{h \overline{D_h}}{k}$$

$$(5) h = \frac{q''}{T_w - T_b}$$

Where $\dot{m}$ is the mass flow rate, h is the heat transfer coefficient, q'' is the wall heat flux, T_w is the average wall temperature, T_b is the bulk temperature mean fluid temperature.

$$(6) f_D = \frac{2\Delta P \overline{D_h}}{\rho L u^2}$$

Where ΔP is the pressure drop between the inlet and outlet, L is the effective flow length of the computational domain, and u is the mean fluid velocity.

The thermophysical properties of $MgCl_2$ -KCl molten salt required for Equations (4) and (6) are summarized in Table II.

Table II: Properties of $MgCl_2$ -KCl at 600 °C [3]

Density	1,573 kg/m ³
Specific heat capacity	1,007 J/kg·K
Thermal conductivity	0.45 W/m·K
Viscosity	0.004 kg/m·sec
Prandtl number	8.90

2.3 Turbulence model assessment

Due to the curvature of the airfoil geometry, flow disturbances are generated as the fluid passes around the leading and trailing edges, promoting transition to turbulence even at relatively low Reynolds numbers. Therefore, selecting an appropriate turbulence model is important for accurately predicting the thermal-hydraulic performance of the airfoil PCHE.

To select an appropriate turbulence model for the present study, the RNG k- ϵ and SST k- ω models available in ANSYS FLUENT 2022 R1 were evaluated. First, to evaluate the predictive performance of the two turbulence models for molten salt at low Reynolds numbers, the predicted Nusselt numbers over a Reynolds number range of 500–1,100 were compared with the correlation proposed by Wang et al.

As shown in Figure 3, the RNG k- ϵ model and showed good agreement with Wang's correlation and remained within the reported acceptable error range. However, since the present study covers Reynolds numbers up to 10,000, the predictive performance of the turbulence models also needs to be evaluated at higher Reynolds numbers.

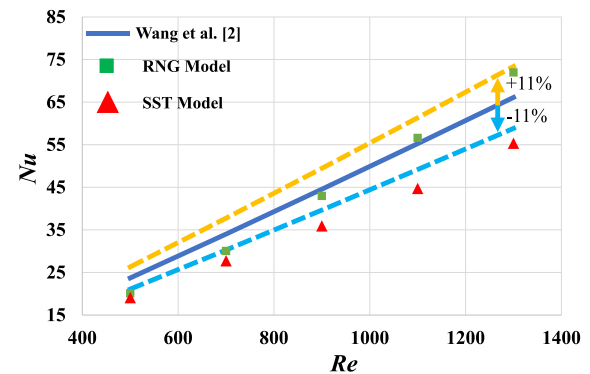


Fig.3. Validation of the present CFD results against Wang et al. correlation [2]

Since the present study extends to high Reynolds numbers, the predictive performance of the SST k- ω and RNG k- ϵ models was also evaluated in this range. However, studies on airfoil PCHEs using molten salts

are limited at high Reynolds numbers. Therefore, the correlation of Chung et al., developed from experimental data for N_2 at $Re=2,000-8,000$, was used as a supplementary reference. Although differences in thermophysical properties between N_2 and molten salts limit direct comparison, the correlation provides a useful basis for comparing their relative prediction trends.

As shown in Figure 4, the RNG k- ϵ model showed good agreement with Chung's correlation, whereas the SST k- ω model deviated from the acceptable error range at several Reynolds numbers. The SST k- ω model tended to predict lower Nusselt numbers than the RNG k- ϵ model due to the effect of the eddy viscosity limiter, as also reported by Tang et al. [5]. Based on the comparisons at low and high Reynolds numbers, the RNG k- ϵ model was selected for the numerical simulations in the present study.

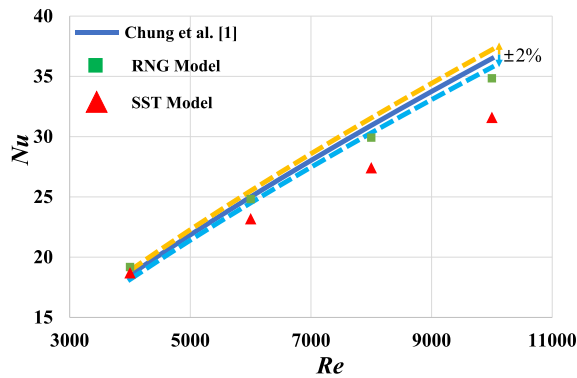


Fig.4. Validation of the present CFD results against Chung et al. correlation [1]

2.4 Mesh test

A mesh independence test was performed to ensure that the numerical results were independence of the computational grid. The inlet temperature and mass flow rate were set to 500.15 K and 3.83 kg/sec, respectively. The mesh size was systematically increased from 1×10^5 to 42×10^5 , and the corresponding Nusselt numbers were compared to evaluate mesh independence.

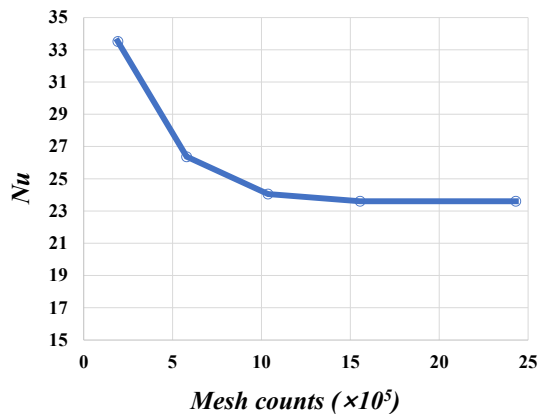


Fig. 5. Grid independence test based on the Nusselt number

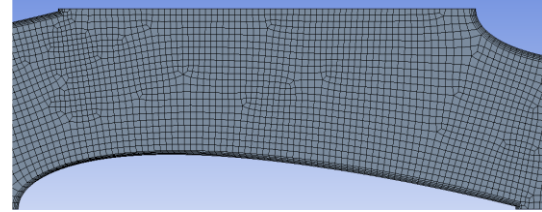


Fig. 6. Mesh generation for the airfoil PCHE

As shown in Figure 5, grid independence was confirmed when the number of mesh elements exceeded 1,55,168. In addition, the computational grid was generated to maintain a y^+ value below 1 under all simulation conditions to accurately resolve the boundary layer near the airfoil fin walls. The effects of the first-layer thickness, growth rate, and number of boundary layers were also examined. Based on the mesh test results, a first-layer thickness of 0.01 mm, a growth rate of 1.2, and five boundary layers were adopted for the numerical simulations, as illustrated in Figure 6.

3. Result

Based on the turbulence-model validation described in Section 2.4, the RNG k- ϵ model was selected for the numerical analysis of the NACA 0020 airfoil PCHE using $MgCl_2-KCl$ molten salt. Numerical simulations were performed over a Reynolds number range of 500–10,000 to investigate the Nusselt number and Darcy friction factor. The CFD results showed that the Nusselt number increased with increasing Reynolds number, whereas the Darcy friction factor decreased. Based on these results, correlations for the Nusselt number and Darcy friction factor were developed.

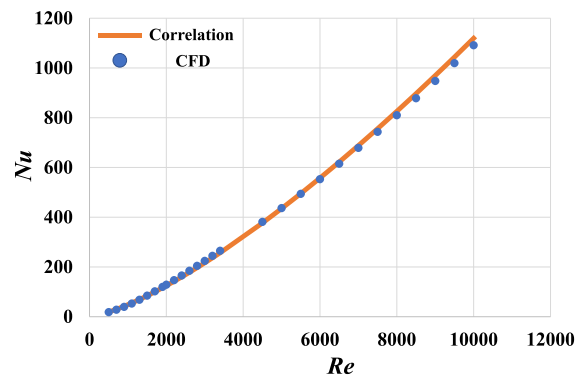


Fig. 7. CFD results and developed Nusselt number correlation for $MgCl_2-KCl$ molten salt

Figure 7 shows the variation in the Nusselt number with Reynolds number. The Nusselt number increased continuously with increasing Reynolds number, indicating enhanced heat transfer at higher Reynolds numbers. Based on the CFD results, the Nusselt

number correlation was expressed in the following form:

Figure 7 shows the variation in the Nusselt number with Reynolds number. The Nusselt number increased continuously with increasing Reynolds number, indicating enhanced heat transfer at higher Reynolds numbers. Based on the CFD results, the Nusselt number correlation was expressed in the following form:

$$(7) \ Nu = aRe^bPr^c$$

The coefficients of Equation (7) were determined using nonlinear regression based on the CFD results. The resulting coefficients were $a=0.0083$, $b=1.48$, and $c=1/3$.

Figure 8 shows the variation in the Darcy friction factor with Reynolds number. In contrast to the Nusselt number, the Darcy friction factor decreased continuously with increasing Reynolds number. Based on the CFD results, the Darcy friction factor correlation was expressed in the following form:

$$(8) \ f_D = dRe^e$$

The coefficients of Equation (8) were determined using nonlinear regression based on the CFD results. The resulting coefficients were $d=5.711$ and $e=-0.544$.

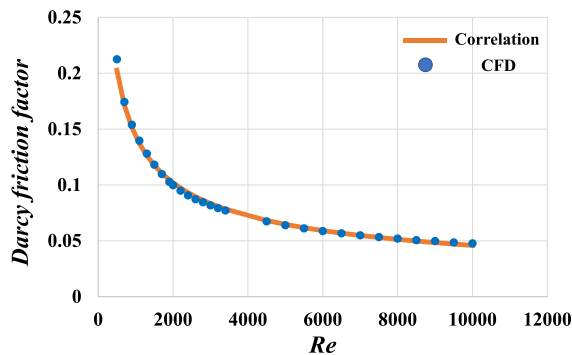


Fig. 8. CFD results and developed Darcy friction factor correlation for $MgCl_2$ -KCl molten salt

As shown in Figures 7 and 8, the developed correlations well represent the CFD results over the investigated Reynolds number range. Therefore, the proposed correlations can be used to predict the Nusselt number and Darcy friction factor of the investigated NACA 0025 airfoil PCHE $MgCl_2$ -KCl molten salt for Reynolds numbers range of 500-10,000.

4. Conclusion

In this study, the thermal-hydraulic characteristics of a NACA 0020 airfoil PCHE using $MgCl_2$ -KCl molten salt were numerically investigated, and correlations for the Nusselt number and Darcy friction

factor were developed over a Reynolds number range of 500–10,000. The RNG k- ϵ and SST k- ω turbulence models were first evaluated, and the RNG k- ϵ model was selected based on comparison with the reference data.

Using the selected turbulence model, the effects of Reynolds number on the Nusselt number and Darcy friction factor were investigated. The Nusselt number increased with increasing Reynolds number, whereas the Darcy friction factor decreased. Based on the CFD results, correlations for the Nusselt number and Darcy friction factor were developed using nonlinear regression. The developed correlations well represent the CFD results over the investigated Reynolds number range.

ACKNOWLEDGEMENT

This work was supported by Korea Research Institute for defense Technology planning and advancement (KRIT) grant funded by the Korea government (DAPA (Defense Acquisition Program Administration)) (KRIT-CT-22-017, Next Generation Multi-Purpose High Power Generation Technology(Liquid Fueled Heat Supply Module Design Technology), 2022)

REFERENCES

- [1] S. Chung, T. Kim, and S. Kim, Experimental study of printed circuit heat exchangers with airfoil and straight channels for optimized recuperators in nitrogen Brayton cycle, *Applied Thermal Engineering*, Vol. 218, 119348, 2023.
- [2] W. Q. Wang, Y. Qiu, Y. L. He, and Y. Shi, Experimental study on the heat transfer performance of a molten-salt printed circuit heat exchanger with airfoil fins for concentrating solar power, *International Journal of Heat and Mass Transfer*, Vol. 135, pp. 837-846, 2019.
- [3] H. Y. Shi, M. J. Li, W. Q. Wang, Y. Qiu, and W. Q. Tao, Heat transfer and friction of molten salt and supercritical CO_2 flowing in an airfoil channel of a printed circuit heat exchanger, *International Journal of Heat and Mass Transfer*, Vol. 150, 119006, 2020.
- [4] S. H. Yoon, H. C. Noh, and G. B. Kang, Assessment of straight, zigzag, S-shape, and airfoil PCHEs for intermediate heat exchangers of HTGRs and SFRs, *Nuclear Engineering*, Vol. 270, pp. 334-343, 2014.
- [5] L. Tang, L. Cui, and B. Sundén, Optimization of fin configurations and layouts in a printed circuit heat exchanger for supercritical liquefied natural gas near the pseudo-critical temperature, *Applied Thermal Engineering*, Vol. 172, 115131, 2020.