Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 26-27, 2023

Comparative analysis of thermal and hydraulic correlations of chevron-type Plate Heat Exchanger for molten salt

Sunghyun Yoo [a], In Woo Son [a], Sungwook Choi [a], Jeong Ik Lee [a*]
[a] *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 Reactor (MSR), Plate Heat Exchanger (PHE), Nusselt number, Friction factor, Correlations

1. Introduction

The suitable design of the intermediate heat transport system for a Molten Salt Reactor (MSR) is important because it allows MSR systems to achieve higher thermal efficiencies and develop more compact systems. A Plate Heat Exchanger (PHE) is one of the representative compact heat exchanger types that stand out for their compactness, operational flexibility, and high heat transfer performance over conventional shell and tube type heat exchangers. With these advantages, PHEs are widely used in many applications, from HVAC systems and refrigeration units to chemical processing and power generation [1]. The characteristics of PHEs are sufficient to be considered as one of the main candidates for the primary intermediate heat exchanger for MSR systems.

These advantages are due to the unique structural characteristics of PHEs. The multiple corrugated plates that make up a PHE provide a larger surface area and enable high turbulence at low flow rates to enhance heat transfer performance. However, Due to high-pressure drop penalties, plate heat exchangers are best suited for liquid-to-liquid heat transfer applications and are not suitable for gas-to-gas heat transfer applications [2].

Different corrugation patterns of the plates significantly change the thermal-hydraulic characteristics of the heat exchanger. Fig. 1. shows the typical corrugation patterns used in commercial PHEs. Among these, a chevron or herringbone pattern and washboard pattern are the most widely used. The geometrical parameters of the plates also, significantly characterize the thermal-hydraulic performance of PHE. Fig. 2. shows the main geometrical parameters of a chevron-type PHE. The main geometrical parameters of the plate that determine the thermal-hydraulic performance of the PHE are as follows:

- Corrugation inclination angle, β
- Corrugation pitch, λ or P_c
- Corrugation depth, b
- Surface enlargement factor, ϕ

where ϕ is the ratio of the actual developed surface area and projected area.

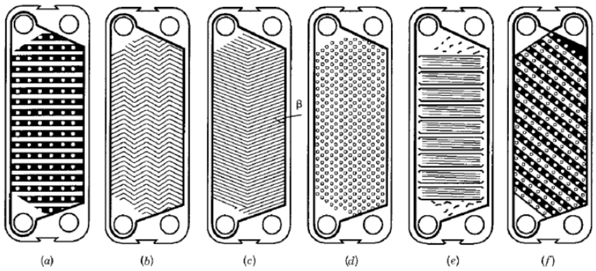


Fig. 1. Typical plate corrugation patterns of PHE; (a) washboard, (b) zigzag, (c) chevron or herringbone, (d) protrusions and depressions, (e) washboard with secondary corrugations, (f) oblique washboard [3]

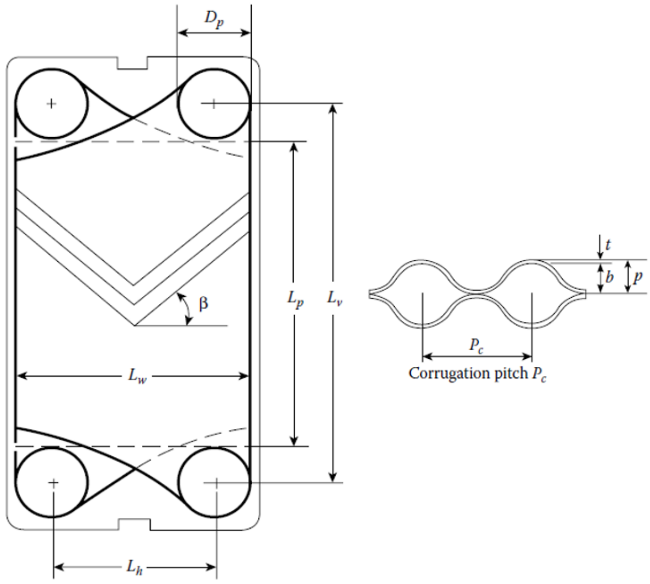


Fig. 2. The main structures of chevron-type PHE [4]

To increase the thermal-hydraulic performance of these PHEs efficiently, the heat transfer and the pressure drop characteristics must be accurately estimated. Heat transfer and pressure drop correlations have long been researched to characterize the thermal and hydraulic characteristics of chevron-type PHEs. In particular, a large amount of *Nu*, *f* data have been obtained from experiments and based on them, various empirical correlations have been developed. However, since the geometrical details of the plates used in each experiment and the test conditions are different, the heat transfer and the pressure drop correlations will vary depending on the geometry of the plates, even if the same working fluid is used.

In this study, three thermal-hydraulic correlations of the PHEs were selected and compared for application to designing primary intermediate heat exchangers in MSRs. The thermal-hydraulic correlations selected in this study are three representative correlations most widely used in PHE, and they were compared within the range of the molten salt's thermal properties. Based on the heat transfer and the pressure drop characteristics of PHE with molten salt as the working fluid confirmed in this study, and is expected to be used as a basis for the optimal design of MSR primary heat exchangers in future studies.

2. Methodology

Before comparing the thermal-hydraulic correlations of PHE, the Prandtl numbers (*Pr*) of chloride-based molten salts within the operating temperature conditions ($450°\mathrm{C} - 700°\mathrm{C}$) of the MSR were first compared. As shown in Figure 3, the *Pr* of the two molten salts (NaCl-$MgCl_2$ and KCl- $MgCl_2$) are approximately within the range of $2.5 < Pr < 8$. *Pr* was calculated as in equation (1) below, and the thermal properties (C_p, μ, k) of each molten salt were obtained from references [5, 6].

$$Pr = \frac{C_p \mu}{k} \tag{1}$$

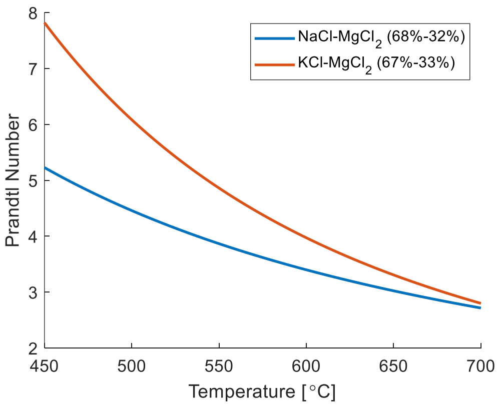


Fig. 3. Compare *Pr* of chloride-based molten salts within the MSR operating temperature range [5, 6]

To account for the variation of *Pr* in chloride-based molten salt with temperature and to consider other potential molten salt candidates in addition to the two chloride-based molten salts in Fig. 3, the heat transfer correlations of PHE were compared for the case of $Pr = 1$ and $Pr = 10$.

The three representative correlations for PHEs compared in this study are empirically derived from experiments.

Muley and Manglik have obtained *Nu* and *f* data in precisely controlled experiments and reported the thermal-hydraulic correlations for Newtonian fluids, in laminar and turbulent regimes, with symmetric and mixed-plate arrangements where $\beta_{\text{avg}} = 30°$, $45°$, and $60°$ [1, 7, 8]. The corrugation angle (β) of the plate was set to three representative angles, 30°, 45°, and 60°, the same as in Muley and Manglik's study.

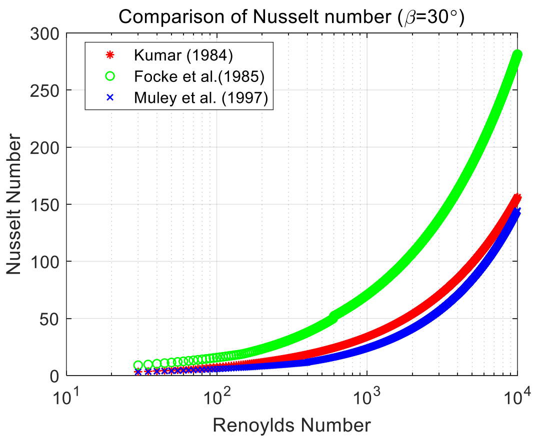
Kumar's correlation for the Nusselt number (*Nu*) and the friction coefficient (*f*) is calculated as follows, where each constant has a different value depending on the Reynolds number (*Re*) and the chevron angle (β) [9, 10]. The constants used in formulas (2) and (3) are listed separately in the Appendix:

$$Nu = C_h Re^n Pr^{0.33} \left(\frac{\mu_b}{\mu_w}\right)^{0.17} \tag{2}$$

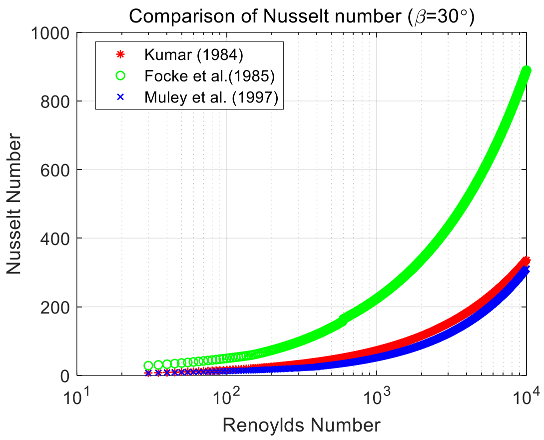
$$f = \frac{K_p}{Re^m} \tag{3}$$

3. Results and Discussions

The comparative analysis results of the thermal-hydraulic correlations for PHEs are shown in Figs. 4-7. Figs. 4-6 show the variation of *Nu* with the *Pr* and the β of the plate. Fig. 7 shows the comparison of *f* with respect to β.

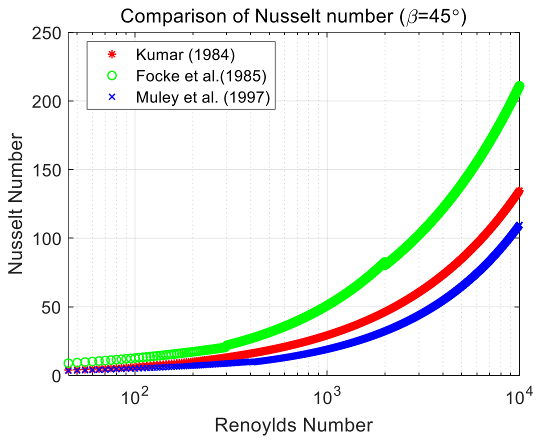


(a) Comparison of *Nu* for $Pr = 1$

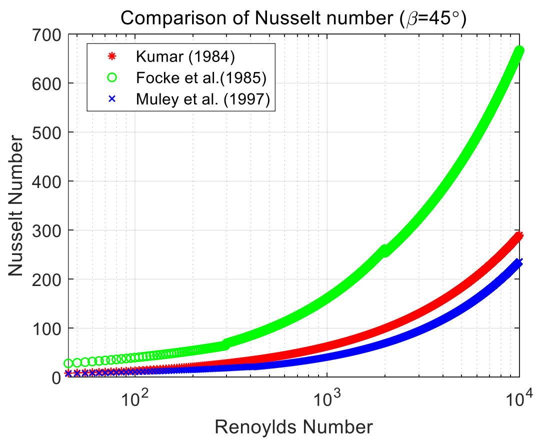


(b) Comparison of Nu for $Pr = 10$

Fig. 4. Comparative analysis results of Nu correlations for $\beta = 30°$ plate with respect to Pr

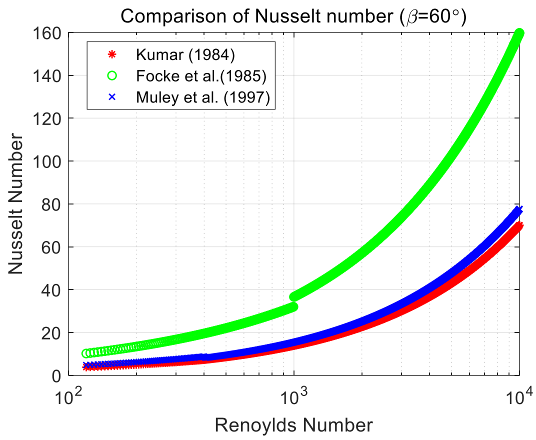


(a) Comparison of Nu for $Pr = 1$

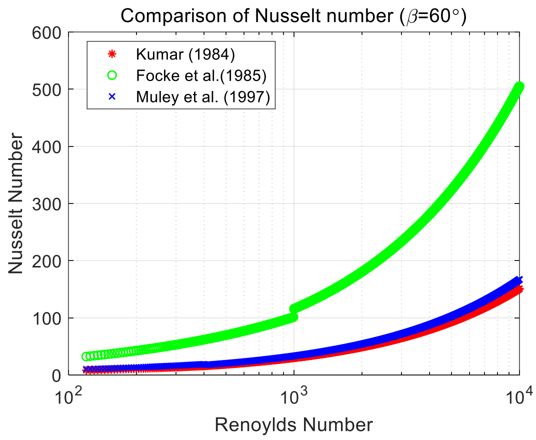


(b) Comparison of Nu for $Pr = 10$

Fig. 5. Comparative analysis results of Nu correlations for $\beta = 45°$ plate with respect to Pr

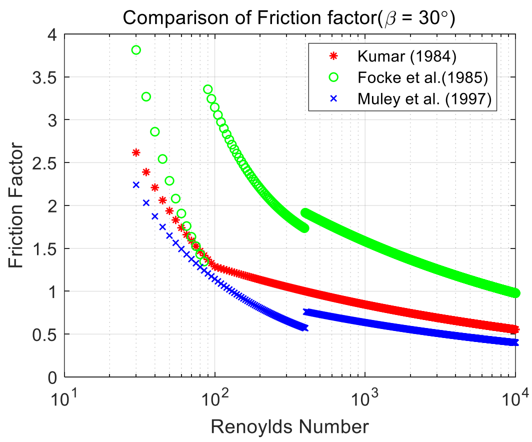


(a) Comparison of Nu for $Pr = 1$

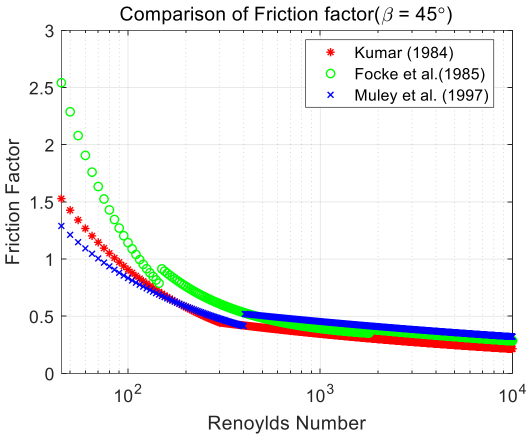


(b) Comparison of Nu for $Pr = 10$

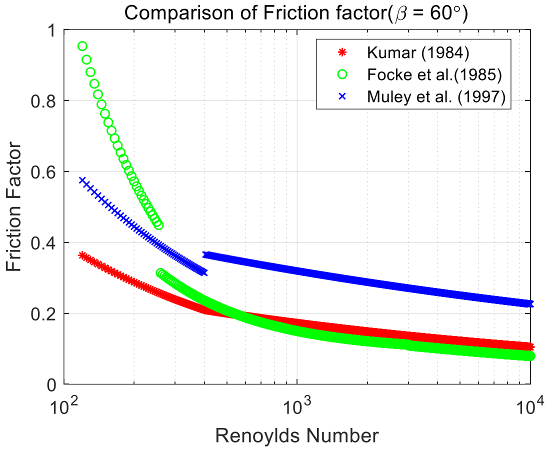
Fig. 6. Comparative analysis results of Nu correlations for $\beta = 60°$ plate with respect to Pr



(a) Comparison of f for $\beta = 30°$



(b) Comparison of f for $\beta = 45°$



(c) Comparison of f for $\beta = 60°$

Fig. 7. Comparative analysis results of f correlations with respect to chevron angle, β

The heat transfer performance of a PHE is highly dependent on the chevron angle, β. The higher the value of β, the higher the Nu is, but the resulting pressure drop penalty also rises noticeably.

For Muley and Kumar's correlation, the trend of Nu in the heat transfer correlation is mostly similar. However, as Muley had noted in his paper, this comparative analysis shows that Focke's correlation calculates a significantly higher value of Nu compared to the other correlations. Focke's correlation overestimated Nu about three times higher than the other two correlations. The difference in these correlations can probably be attributed to geometric differences in the surface corrugations of the chevron plates used in each experiment. In heat transfer correlation, the Nu is highly dependent on Pr, so for $Pr = 10$, Nu is much larger than for $Pr = 1$. However, it was also confirmed that the overall trend of heat transfer correlation is almost similar for both $Pr = 1$ and $Pr = 10$.

For Focke's pressure loss correlation, it was observed that the friction factor improves significantly as the chevron angle, β increases. And for $\beta = 60°$, Muley's correlation conservatively estimated the friction factor.

In this comparative analysis, Focke's heat transfer and pressure loss correlations tend to be overestimated. The results of Muley's correlation show clear characteristics of heat transfer and pressure drop of PHEs as a function of the chevron angle of the plate.

4. Conclusions and Further Works

In this study, the thermal-hydraulic correlations of PHEs for different values of Pr and different chevron angles ($30°, 45°$, and $60°$) are compared. The Prandtl numbers of chloride-based molten salts under the operating temperature of the MSR were evaluated before analyzing the thermal-hydraulic correlations of PHE. The heat transfer correlations of PHE were compared for the case of $Pr = 1$ and $Pr = 10$ while considering the Pr variation of molten salt with temperature. Three most widely used thermal-hydraulic correlations in PHE design were compared within the range of the molten salt's thermal properties.

The chevron angle, β has a significant impact on the heat transfer performance of a PHE. The Nu increases with the value of β, but the pressure drop penalty that results also increases considerably.

The trend of Nu in the heat transfer correlation is similar in both Muley and Kumar's correlation. However, Focke's correlation calculated Nu about three times higher than the other two correlations. The comparative analysis shows that the overall trend of heat transfer correlation is similar for both $Pr = 1$ and $Pr = 10$. It was also shown that as the β increases, the friction factor decreases in Focke's pressure loss correlation. Additionally, Muley's correlation provided a conservatively estimated friction factor $\beta = 60°$. In this comparative analysis results, it was confirmed that Focke's heat transfer and pressure loss correlations tend to overestimate. The results of Muley's correlation demonstrate distinct heat transfer and pressure loss characteristics of PHEs with respect to the plate's chevron angle. As for now, the Muley's correlation is recommended for the conservative design of PHE. However, experimental data and computational approach have to confirm which correlation will be most suitable for the design of PHE operating with molten salt.

Since not much research has been conducted on PHEs using molten salt as the working fluid, whether the existing PHE correlations compared in this study are also applicable to PHEs for molten salt will be validated using CFD methods in further studies. Once validated, it is expected that the optimal design of a PHE-based primary intermediate heat transport system suitable for MSRs can be obtained.

ACKNOWLEDGEMENTS

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)) (21-107-F00-018(KRIT-CT-22-017), Next Generation Multi-Purpose High Power Generation Technology (Development of Power Generating System Core-Technologies for Liquid Fuel Heat Generator), 2022)

REFERENCES

[1] Muley, A. (1997) Heat Transfer and Pressure Drop in Plate Heat Exchangers. Ph.D. Dissertation, Mechanical Engineering, University of Cincinnati, Cincinnati.
[2] Kumar, B., Soni, A., & Singh, S. N. (2018). Effect of geometrical parameters on the performance of Chevron Type Plate Heat exchanger. *Experimental Thermal and Fluid Science*, 91, 126–133.
[3] Sekulić, D. P., & Shah, R. K. (2023). *Fundamentals of heat exchanger design*. Wiley.
[4] Kakaç Sadik, Liu, H., & Pramuanjaroenkij, A. (2012). *Heat exchangers: Selection, Rating, and Thermal Design, third edition*. CRC Press.
[5] 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.
[6] Jerden, James. *Molten salt thermophysical properties database development: 2019 update*. No. ANL/CFCT19/6. Argonne National Lab. (ANL), Argonne, IL (United States), 2019.
[7] Muley, A., Manglik, R.M. and Metwally, H.M., Enhanced Heat Transfer Characteristics of Viscous Liquid Low Reynolds Number Flows in a Chevron Plate Heat Exchanger, *Journal of Heat Transfer*, vol. 121, no. 4, pp. 1011–1017, 1999.
[8] Muley, A. and Manglik, R.M., Experimental Study of Turbulent Flow Heat Transfer and Pressure Drop in a Plate Heat Exchanger with Chevron Plates, *Journal of Heat Transfer*, vol. 121, no. 1, pp. 110–117, 1999.
[9] Saunders, E. A. D., *Heat Exchangers – Selection, Design, and Construction*, John Wiley & Sons, New York, 1988
[10] Kumar, H., The plate heat exchanger: construction and design, 1st UK National Conference on Heat Transfer, University of Leeds, 3-5 July, *Inst. Chem. Symp.* Series, No. 86, 1275–1286, 1984.

Appendix

Table 1. Constants for heat transfer and pressure drop calculation in correlations of PHEs

Chevron angle (°)	Heat Transfer			Pressure Loss		
	Re	C_h	n	Re	K_p	m
Kumar's Correlation (1984)						
≤30	≤10 >10	0.718 0.348 -	0.349 0.663	<10 10 – 100 >100	50.000 19.400 2.990	1.000 0.589 0.183
45	<10 10 – 100 >100	0.718 0.400 0.300	0.349 0.598 0.663	<15 15 – 300 > 300	47.000 18.290 1.441	1.000 0.652 0.206
60	< 20 20 – 400 > 400	0.562 0.306 0.108	0.326 0.529 0.703	< 40 40 – 400 > 400	24.000 3.240 0.760	1.000 0.457 0.215
Focke's Correlation (1985)						
30	120 – 1,000 1000 – 42,000	0.77 0.44	0.540 0.640	260 – 3,000 3,000 – 50,000	57.500 0.898	1.000 0.263
45	45 – 300 300 – 2,000 2,000 – 20,000	1.67 0.405 0.84	0.440 0.700 0.600	150 – 1,800 1,800 – 30,000	91.750 1.460 -	1.000 0.177
60	20 – 150 150 – 600 600 – 16,000	1.890 0.570 1.112	0.460 0.700 0.600	90 – 400 400 – 16,000	188.750 6.700 -	1.000 0.209
Muley's Correlation (1997)						
30	30 – 400 ≥1,000	0.440 0.123	0.500 0.700	2 – 200 ≥1,000	$f=[(30.20/Re)^5+(6.28/Re^{0.5})^5]^{0.2}$ 0.900	 -0.150
45	30 – 400 ≥1,000	0.500 0.100	0.500 0.760	2 – 200 ≥1,000	$f=[(41.91/Re)^5+(8.28/Re^{0.5})^5]^{0.2}$ 1.280	 -0.150
60	30 – 400 ≥1,000	0.572 0.110	0.500 0.780	2 – 200 ≥1,000	$f=[(53.34/Re)^5+(11.38/Re^{0.5})^5]^{0.2}$ 2.530	 -0.200