CHEMICAL ENGINEERING TRANSACTIONS

VOL. 70, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Timothy G. Walmsley, Petar S. Varbanov, Rongxin Su, Jiří J. Klemeš

ISBN 978-88-95608-67-9; **ISSN** 2283-9216

DOI: 10.3303/CET1870193

Thermal-hydraulic Performance Analysis of Corrugated Plate Heat Exchanger

Wei Q. Tan[a], Li Sun[a,*], Zhigang Jia[b], Jie Li[a]

[a]School of Chemical Engineering and Analytical Science, the University of Manchester, Manchester, M13 9PL, UK
[b]State Key Laboratory of Chemical Resource Engineering, Beijing University of Chemical Technology, Beijing, 100029, China
li.sun@manchester.ac.uk

Plate heat exchangers (PHEs) have been getting popularity in industries due to their low cost, high heat transfer efficiency and operational flexibility. Heat transfer enhancement could be achieved by using the PHE with corrugated plate configuration, which provides additional heat transfer area and increased turbulence in fluid flow. This work explored how complex corrugated plates with different chevron angles, channel depth and pitch in multi-segmented configuration could further improve thermal-hydraulic performance of the PHE. Water was used as the heat transfer fluid. Key geometrical parameters were first identified as different chevron angles (β_{high} and β_{low}), corrugation aspect ratio (γ) and number of plate segments (N_S). Then, thermal-hydraulic models for the PHE with a wide range of corrugation geometries have been proposed and validated. These models could accurately estimate heat transfer and flow friction loss of the PHE with different plate corrugation structures and provide deep insight into the influence of the corrugation geometries. They could be applied as a guide in PHE design, operational optimization and heat transfer network retrofit in industries.

1. Introduction

Corrugated surface of the PHE provides significantly higher overall heat transfer coefficient compared to shell and tube heat exchangers (Tovazhnyanskyy et al., 2016) and could offer 70 % and 80 % of weight and volume saving, respectively, for the same effective heat transfer area (Wang et al., 2007). Thermal performance of PHE could be further improved by dividing the plate into four or more number of segments (N_S) as shown in Figure 1 (Wang et al., 2007) Figure 1(a), Figure1(b), and Figure(c) showed two-segmented plate with single β, four-segmented plate with two different angles β_{high} and β_{low}, and eight-segmented plate with mixed-β. Figure 1(d) presented basic geometrical parameters of a plate that consisted of chevron angle (β), corrugation depth (H_i) and corrugation pitch (P). Heat transfer rate was enhanced when β increased due to the formation of criss-crossing streams that induced secondary swirling motion along the furrows (Muley & Manglik, 1999). The ratio of H_i to P determined dominating effects of furrow and longitudinal flow components, hence affecting rate of heat transfer along the plates (Gaiser & Kottke, 1998).

Enhanced thermal performance however, came with a high pressure drop penalty due to increased turbulent flow (Focke et al., 1985). To reduce the flow friction, mixed-β configurations were introduced in 1970s where β_{high} and β_{low} plates were combined into a single PHE. β_{high} referred to chevron angle greater than 45° while β_{low} was less than 45°. Computational fluid dynamics (CFD) results showed that low turbulence effects of β_{low} was compensated by β_{high} of the adjacent plates, allowing overall heat transfer coefficient to be higher than the PHE that only consisted of β_{low} plates (Ma, 2016). Meanwhile, pressure drop of a mixed-β plate was lower than β_{high} plate. Additional segments allowed the presence of zig-zag and criss-crossing flow along the furrow to improve heat transfer performance (Ma, 2016).

Thermal-hydraulic performance of PHE could be predicted based on experimental results, validated CFD simulation and mathematical models. Experiments were usually expensive and time consuming. CFD simulation could provide detail numerical analysis for arbitrary geometries performance but required long elapse time to process large amount of grid points (Wang et al., 2007). Mathematical models were typically expressed in Nusselt number (Nu) and Fanning Friction Factor (f) (Arsenyeva et al., 2011). Thermal-hydraulic models have

Please cite this article as: Tan W.Q., Sun L., Jia Z., Li J., 2018, Thermal-hydraulic performance analysis of corrugated plate heat exchanger , Chemical Engineering Transactions, 70, 1153-1158 DOI:10.3303/CET1870193

been proposed by Muley & Manglik (1999) to investigate the influence of *β*. However, the application of model was limited to specific geometrical parameters such as fixed *β*, H_i, *P* and N_S.

In this study, key geometrical parameters for complex corrugated plates were identified. The influence of different chevron angles in a multiple-segmented plate was also explored. Mathematical models for heat transfer and flow friction were developed for the PHE with single-*β* in two-segmented configurations and mixed-*β* in four-segmented configurations. The models were then validated based on the percentage errors of the fitted values from the input data.

(a) Two segments (Wang et al., 2007) *(b) Four segments* *(c) Eight segments* *(d) Basic corrugation geometries (Kakạc et al., 2012)*

Figure 1: Multiple segments corrugated plate

2. Identification of key corrugation geometrical parameters

Sensitivity analysis was conducted to identify key plate corrugation geometrical parameters that had significant influence on heat transfer and pressure drop of the PHE.

Table 1 illustrated the influences of *β* and *γ* on thermal-hydraulic performance *of* two-segmented PHE (N_s = 2) at fixed fluid flow pattern (Reynold number). It was clear that *Nu* and *f* varied significantly with both *β* and *γ*. For instance, when *γ = 0.56, Nu* and *f* of the PHE with *β* = 60° were larger than *Nu* and *f* of the PHE with *β* = 30° by 72 % and 93 % respectively. While *γ = 1.0*, *Nu* and *f* increased by 62 % and 980 % respectively when *β* was changed from 30° to 60°.

Table 1: Effects of chevron angle (β) and corrugation aspect ratio (γ) on Nu and f

Literature	*β* (°)	*γ*	*Nu*	*f*
Gaiser & Kottke (1998)	30	0.28	31.6	0.200
	45	0.28	42.4	0.700
	60	0.28	39.9	1.00
Muley & Manglik (1999)	30	0.56	38.2	0.285
	45	0.56	50.4	0.390
	60	0.56	65.7	0.550
Focke et al. (1985)	30	1.00	94.7	0.500
	45	1.00	128	1.60
	60	1.00	153	5.40

Reynold number (*Re*) = 2000

Ma (2016) explored the thermal-hydraulic influences of multiple segmented plates. For example, the overall heat transfer coefficient of four-segmented plates (N_s =4) was 1.1 times higher than two-segmented plates (N_s =2) with the same mixed-*β.* Pressure drop of fluid across the four-segmented plates was 1.4 times greater than the two-segmented plates.

Thus, the influence of key corrugation geometrical parameters *β*, *γ* and N_S would be included in the thermal-hydraulic model for PHEs with wide range of corrugation configurations.

3. Thermal model development

Thermal performance for fully developed liquid flow in a multi-segmented PHE could be expressed in empirical model of *Nu* as shown in Eq(1):

$$Nu = C_1\, C_2\,(\beta)\, C_3\,(\gamma)\, Re^{C_4(\beta)}\, Pr^{1/3} \qquad (1)$$

where C_1 was an enhancement factor due to additional plate segments. Both C_2 and C_4 were determined by β. C_3 was determined by γ. A two-segmented plate had single β while a four-segmented plate had mixed-β. In the mixed-β configuration, β would be expressed as β_{mixed}, implying different weighting of β_{low} and β_{high}.

3.1 Regressed PHE thermal models

Statistical analysis software, R computing and non-linear least square (nls) function were used to develop the regressed model. The coefficients for C_1 to C_4 were presented in Table 2. The linear relationship between β_{mixed} and real angles of β_{high} and β_{low} of the corrugation configuration was obtained based on Ma (2016) results.

Table 2: Coefficients regression in thermal model

	Two-segmented plate	Four-segmented plate	Validation range
β	β	$\beta_{mixed} = 0.575\ \beta_{high} + 0.164\ \beta_{low}$	$0°\leq\beta\leq90°$
C_1	1.0	1.1	$45°<\beta_{high}<75°$ $25°<\beta_{low}\leq45°$
C_2	$-8.53\times10^{-7}\ \beta^3 + 1.84\times10^{-2}\ \beta + 0.158$		$0.3\leq\gamma\leq1.0$
C_3	$\gamma^2 - 0.370\ \gamma + 0.302$		$500\leq Re\leq5000$
C_4	$0.608 + 1.06\times10^{-2}\sin(\pi\beta/45 - 7.09)$		

For the four-segmented PHE with two angles β_{high} and β_{low} in the plate configuration, the weighting of β_{high} on β_{mixed} was about 3.5 times of β_{low} based on the expression of β_{mixed} shown in Table 2. This indicated that increasing β_{high} instead of β_{low} would be more effective at increasing thermal performance.

3.2 Thermal performance for PHE with corrugated configurations

Figure 2 presented the effects of γ and *Re* on the thermal performance for the two-segmented PHE.

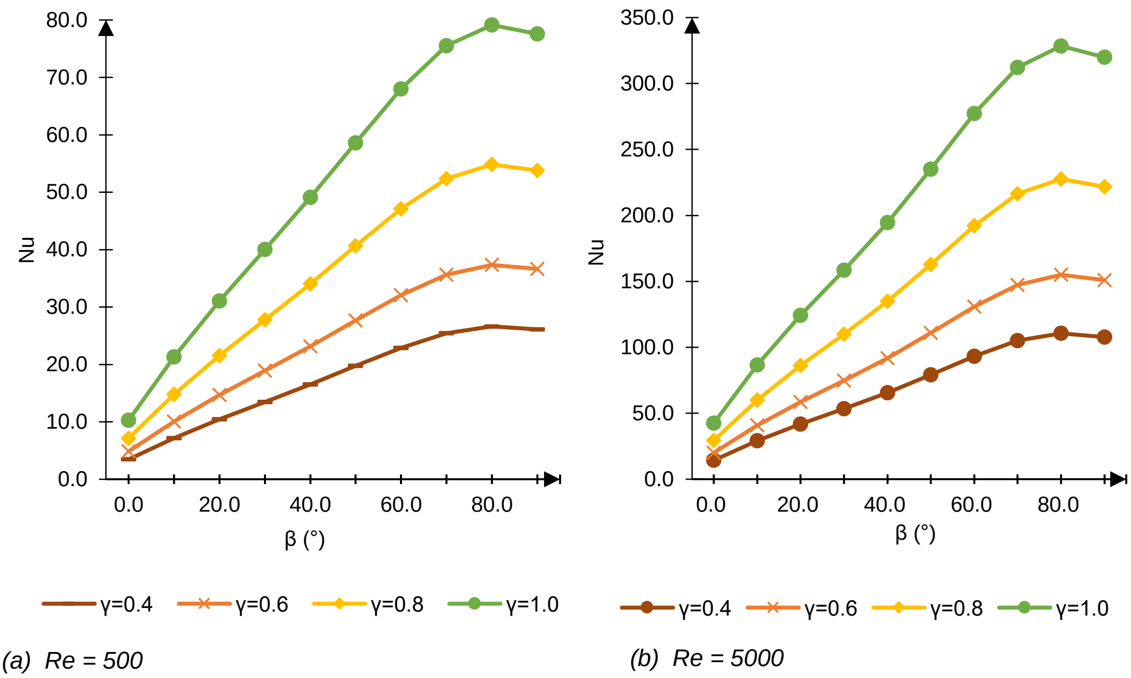


Figure 2: The effect of chevron angle (β) and corrugation aspect ratio (γ) on heat transfer

For the PHE with two-segmented configuration, its thermal performance was improved at larger *Re* and γ. Higher *Re* promoted better fluid mixing in the furrow. Large γ implied more effective heat transfer area. In Figures 2(a) and 2(b), heat transfer was enhanced at large β till β=80.0° due to the secondary swirling motion in the furrow. *Nu* then decreased when β was greater than 80.0° due to separated flow region in the furrow. It could be deduced that the corrugated plate designed at β smaller than 80.0° is beneficial for heat transfer.
For the four-segmented PHE with two angles β_{high} and β_{low} in the plate configuration, the weighting of β_{high} on β_{mixed} was about 4.2 times of β_{low} based on the expression of β_{mixed} shown in Table 2. While β_{low} was fixed at 25° and β_{high} was increased from 55° to 75°, *Nu* increased at a rate of 1.05; when β_{low} was increased from 25° to 45°, *Nu* increased at a less rate of 1.01 at fixed β_{high} = 55°. β_{high} had a greater effect on *Nu* than β_{low}.

4. Hydraulic model development

For a plate with multi-segmented configuration, flow friction *f* was expressed in empirical Equation (2):

$$f = C_5\, C_6(\beta)\, C_7(\gamma)\, Re^{C8(\beta)} \qquad (2)$$

Similarly, C_5 was an enhancement factor. Both C_6 and C_8 were determined by β. C_7 was determined by γ. C_5 to C_8 were shown in Table 3. In a four-segmented plate, β was expressed as β_{mixed}.

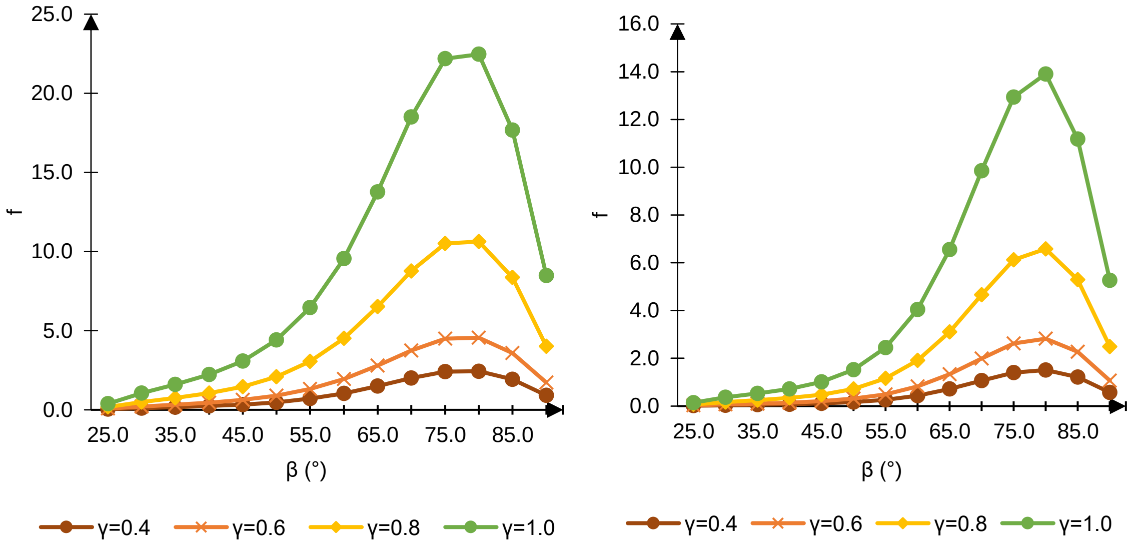
Table 3: Coefficients regression in hydraulic model

	Two-segmented plate	Four-segmented plate	Validation range
β	β	β_{mixed} = 0.714 β_{high} + 0.119 β_{low}	25°≤β≤90°
C_5	1.0	1.4	45°<β_{high}<75°
C_6	$-2.13 \times 10^{-3}\, \beta^3 + 0.249\, \beta^2 - 4.54\, \beta$		25°<β_{low}≤45°
C_7	$\gamma^3 - 0.477\, \gamma^2 + 7.76 \times 10^{-2}$		0.3≤γ≤1.0
C_8	$0.346 - 0.147 \sin(\pi\beta/45 + 1.91)$		500≤*Re*≤5000

The expression of β_{mixed} in Table 3 implied heavy weighting of β_{high} on β_{mixed}, which was 6 times of β_{low}. Similar as the effect of β_{high} on thermal performance, increasing β_{high} instead of β_{low} would have a greater impact on flow friction, which is a trade-off for the thermal enhancement.

4.1 Hydraulic performance for PHE with corrugated configurations

The relationship between *f* and β at different γ and *Re* were shown in Figure 3.



(a) Re = 500 *(b) Re = 5000*

Figure 3: The effect of chevron angle (β) and corrugation aspect ratio (γ) on friction loss

For the PHE with two-segmented configuration, at greater γ, the enhancement in heat transfer (shown in Figure 2) was accompanied by an increase in fluid friction, as larger *f* was observed in Figure 3. *f* was lower in higher

Re region. When *β* was greater than 80°, *f* decreased due to separated flow regions in the furrow. This was consistent with the observation of a decline in heat transfer performance when *β* was greater than 80°. In general, there was less friction in the PHE with smaller *β* (except when *β* > 80°) and lower γ.

For the four-segmented PHE with two angles β_{high} and β_{low} in the plate configuration, the expression of β_{mixed} in Table 4 implied heavy weighting of β_{high} on β_{mixed}, which was 5.20 times of β_{low}. When β_{low} was fixed at 25° and β_{high} was increased from 55.0° to 75.0°, *f* increased at a rate of 1.30 to 1.40; when β_{low} was increased from 25° to 45°, *f* only increased at a rate of 1.05 at fixed β_{high} = 55.0°. Again, β_{high} had a greater influence on hydraulic performance.

It should be noted that due to greater weighting of β_{high} in hydraulic model than in thermal model, large β_{high} would promote greater increase in *f* than in *Nu*. This trade-off must be considered when it comes to the selection of suitable *β* for plate design.

5. Model validation

The developed thermal model had been validated by comparing 128 PHE with corrugation PHEs with the geometrical range of 0°< β <90.0°, 0.28°< γ <1.00° and 500< Re <5,000. Figure 4 showed the error distribution of estimated *Nu* based on the proposed thermal model. The mean error for the proposed thermal model is 7.14 %. 74.2 % of estimated thermal performance lied in the zone with the error less than 10.0 %.

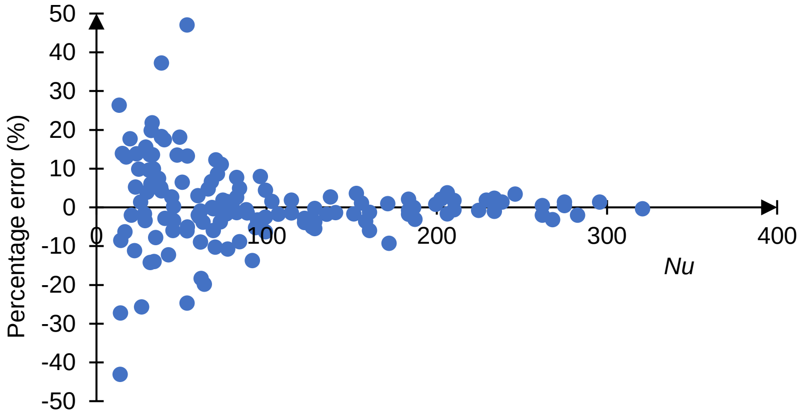


Figure 4: Corrugated PHE thermal model error distributions

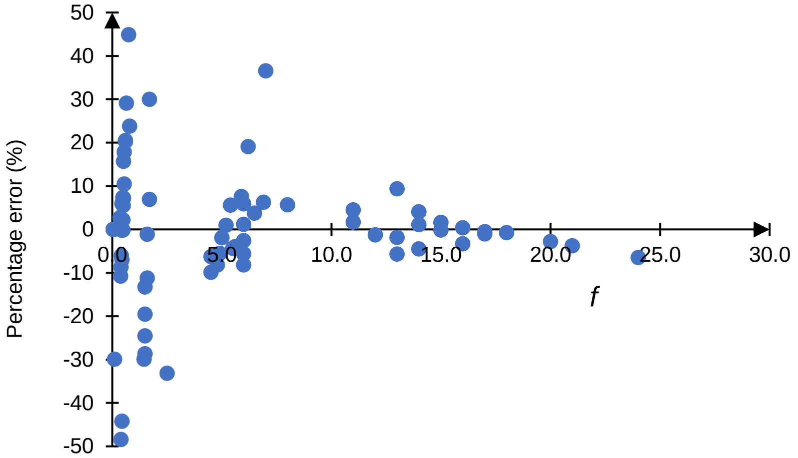


Figure 5: Corrugated PHE hydraulic model error distributions

The error distribution of estimated friction factor based on proposed hydraulic model comparing with 98 PHEs was shown in Figure 5. The mean error for the developed hydraulic model was 24.3 %, and over 50 % of estimated *f* lied within ± 15 % error zone.

6. Conclusions

This work explored the effects of corrugated plate geometries on the thermal-hydraulic performance of the PHEs. Both thermal and hydraulic performances of the corrugated PHEs vary significantly with respect to chevron angle (β), corrugation aspect ratio (γ) and plate segments (N_s).This paper developed mathematical models to quantitatively predict *Nu* for heat transfer and friction factor *f* for fluid flow loss in the PHEs over a wide range of β, γ and N_s, and the proposed models were considered as robust prediction tools for wide range of corrugation geometries.

Heat transfer and flow friction were found to increase when β was increased from 0° to 80° and γ was increased from 0.3 to 1.0. The two-segmented plate with β below 80° could prevent decline in thermal performance. Thermal performance of four-segmented plate could be enhanced by 10% compared to two-segmented plate with similar angles. In a four-segmented plate with mixed-β configuration, β_{high} had strong influence on heat transfer compared to β_{low}, therefore larger β_{high} would be more effective at improving heat transfer of the PHE. However, high thermal performance also came with higher pressure drop. The trade-off between heat transfer and pressure drop could be considered in the plate design.

Future work will explore how to design PHEs with multiple-segmented configurations to both enhance thermal and hydraulic performances performance simultaneously.

References

Arsenyeva O., Tovazhnyansky L., Kapustenko P., Khavin G., 2011, The generalized correlation for friction factor in crisscross flow channels of plate heat exchangers, Chemical Engineering Transactions, 25, 399-404.

Dović D., Palm B., Švaić S., 2009, Generalized correlations for predicting heat transfer and pressure drop in plate heat exchanger channels of arbitrary geometry, International Journal of Heat and Mass Transfer, 52(19-20), 4553-4563.

Focke W., Zachariades J., Olivier I., 1985, The effect of the corrugation inclination angle on the thermohydraulic performance of plate heat exchangers, International Journal of Heat and Mass Transfer, 28(8), 1469-1479.

Gaiser G., Kottke V., 1998, Effects of wavelength and inclination angle on the homogeneity of local heat transfer coefficients in plate heat exchangers, Heat Transfer, 6, 203-208.

Kakąc S., Liu H., Pramuanjaroenkij., 2012, Heat exchangers: selection, rating, and thermal design, CRC Press, Taylor & Francis Group, Florida, US.

Khan T. S., Khan M. S., Ayub Z. H., 2017, Single-Phase Flow Pressure Drop Analysis in a Plate Heat Exchanger, Heat Transfer Engineering, 38(2), 256-264.

Khan T. S., Khan M. S., Chyu M. C., Ayub Z. H., 2010, Experimental investigation of single phase convective heat transfer coefficient in a corrugated plate heat exchanger for multiple plate configurations, Applied Thermal Engineering, 30(8-9), 1058-1065.

Ma S. P., 2016, Numerical simulation study on the mechanics of the enhanced heat transfer in a plate heat exchanger with compound corrugation flow channels, MSc Dissertation, Beijing University of Chemical Technology, Beijing, China.

Muley A., Manglik R., 1999, Experimental Study of Turbulent Flow Heat Transfer and Pressure Drop in a Plate Heat Exchanger with Chevron Plates, Transactions of the ASME, Journal of Heat Transfer, 121, 110-117

Tovazhnyanskyy L.L., Kapustenko P.O., Perevertaylenko O.Y., Khavin G.L., Arsenyeva O.P., Arsenyev P.Y., Khusanov A.E., 2016, Heat Transfer and Pressure Drop in Cross-Flow Welded Plate Heat Exchanger for Ammonia Synthesis Column, Chemical Engineering Transactions, 52, 553-558.

Wang L., Sundén B., Manglik R. M., 2007, Plate Heat Exchangers: Design, Applications and Performance, WIT Press, Southampton, UK.