Thermal-hydraulic Performance Analysis of Corrugated Plate Heat Exchanger

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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 (\(\beta_{\text{high}}\) and \(\beta_{\text{low}}\)), corrugation aspect ratio (\(\gamma\)) and number of plate segments (\(N_{\text{s}}\)). 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 (Tovazhnyansky 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 (\(N_{\text{s}}\)) as shown in Figure 1 (Wang et al., 2007) Figure 1(a), Figure 1(b), and Figure 1(c) showed two-segmented plate with single \(\beta\), four-segmented plate with two different angles \(\beta_{\text{high}}\) and \(\beta_{\text{low}}\), and eight-segmented plate with mixed-\(\beta\). Figure 1(d) presented basic geometrical parameters of a plate that consisted of chevron angle (\(\beta\)), corrugation depth (\(H\)) and corrugation pitch (\(P\)). Heat transfer rate was enhanced when \(\beta\) increased due to the formation of criss-crossing streams that induced secondary swirling motion along the furrows (Muley & Manglik, 1999). The ratio of \(H\) 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-\(\beta\) configurations were introduced in 1970s where \(\beta_{\text{high}}\) and \(\beta_{\text{low}}\) plates were combined into a single PHE. \(\beta_{\text{high}}\) referred to chevron angle greater than 45\(^\circ\) while \(\beta_{\text{low}}\) was less than 45\(^\circ\). Computational fluid dynamics (CFD) results showed that low turbulence effects of \(\beta_{\text{low}}\) was compensated by \(\beta_{\text{high}}\) of the adjacent plates, allowing overall heat transfer coefficient to be higher than the PHE that only consisted of \(\beta_{\text{low}}\) plates (Ma, 2016). Meanwhile, pressure drop of a mixed-\(\beta\) plate was lower than \(\beta_{\text{high}}\) 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 detailed 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
been proposed by Muley & Manglik (1999) to investigate the influence of $\beta$. However, the application of model was limited to specific geometrical parameters such as fixed $\beta$, $H$, $P$ 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-$\beta$ in two-segmented configurations and mixed-$\beta$ in four-segmented configurations. The models were then validated based on the percentage errors of the fitted values from the input data.

![Images of corrugated plates with different segmentations]

(a) Two segments  (Wang et al., 2007)  (b) Four segments  (c) Eight segments  (d) Basic corrugation geometries  (Kakgc 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 $\beta$ and $\gamma$ 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 $\beta$ and $\gamma$. For instance, when $\gamma = 0.56$, $Nu$ and $f$ of the PHE with $\beta = 60^\circ$ were larger than $Nu$ and $f$ of the PHE with $\beta = 30^\circ$ by 72% and 93% respectively. While $\gamma = 1.0$, $Nu$ and $f$ increased by 62% and 980% respectively when $\beta$ was changed from $30^\circ$ to $60^\circ$.

<table>
<thead>
<tr>
<th>Literature</th>
<th>$\beta$ ($^\circ$)</th>
<th>$\gamma$</th>
<th>$Nu$</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaiser &amp; Kottke (1998)</td>
<td>30</td>
<td>0.28</td>
<td>31.6</td>
<td>0.200</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>0.28</td>
<td>42.4</td>
<td>0.700</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.28</td>
<td>39.9</td>
<td>1.00</td>
</tr>
<tr>
<td>Muley &amp; Manglik (1999)</td>
<td>30</td>
<td>0.56</td>
<td>38.2</td>
<td>0.285</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>0.56</td>
<td>50.4</td>
<td>0.390</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.56</td>
<td>65.7</td>
<td>0.550</td>
</tr>
<tr>
<td>Focke et al. (1985)</td>
<td>30</td>
<td>1.00</td>
<td>94.7</td>
<td>0.500</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>1.00</td>
<td>128</td>
<td>1.60</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>1.00</td>
<td>153</td>
<td>5.40</td>
</tr>
</tbody>
</table>

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-$\beta$. 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 $\beta$, $\gamma$ 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):

\[
Nu = C_1 C_2 (\beta) C_3 (\gamma) Re^{C_4(\beta)} Pr^{1/3}
\]

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

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 \( \beta_{\text{mixed}} \) and real angles of \( \beta_{\text{high}} \) and \( \beta_{\text{low}} \) of the corrugation configuration was obtained based on Ma (2016) results.

<table>
<thead>
<tr>
<th>Two-segmented plate</th>
<th>Four-segmented plate</th>
<th>Validation range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta )</td>
<td>( \beta_{\text{mixed}} = 0.575 \beta_{\text{high}} + 0.164 \beta_{\text{low}} )</td>
<td>( 0^\circ \leq \beta \leq 90^\circ )</td>
</tr>
<tr>
<td>( C_1 )</td>
<td>1.0</td>
<td>45^\circ &lt; \beta_{\text{high}} &lt; 75^\circ</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>25^\circ &lt; \beta_{\text{low}} \leq 45^\circ</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>(- 8.53 \times 10^{-7} \beta^3 + 1.84 \times 10^{-2} \beta + 0.158)</td>
<td>0.3 \leq \gamma \leq 1.0</td>
</tr>
<tr>
<td>( C_3 )</td>
<td>( \gamma^2 - 0.370 \gamma + 0.302 )</td>
<td>500 \leq Re \leq 5000</td>
</tr>
<tr>
<td>( C_4 )</td>
<td>( 0.608 + 1.06 \times 10^{-5} \sin(\pi \beta/45 - 7.09) )</td>
<td></td>
</tr>
</tbody>
</table>

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

3.2 Thermal performance for PHE with corrugated configurations

Figure 2 presented the effects of \( \gamma \) 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](image-url)
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 $β\approx80^\circ$ due to the secondary swirling motion in the furrow. $Nu$ then decreased when $β$ was greater than $80.0^\circ$ due to separated flow region in the furrow. It could be deduced that the corrugated plate designed at $β$ smaller than $80.0^\circ$ is beneficial for heat transfer.

For the four-segmented PHE with two angles $β_{\text{high}}$ and $β_{\text{low}}$ in the plate configuration, the weighting of $β_{\text{high}}$ on $β_{\text{mixed}}$ was about 4.2 times of $β_{\text{low}}$ based on the expression of $β_{\text{mixed}}$ shown in Table 2. While $β_{\text{low}}$ was fixed at $25^\circ$ and $β_{\text{high}}$ was increased from $55^\circ$ to $75^\circ$, $Nu$ increased at a rate of 1.05; when $β_{\text{low}}$ was increased from $25^\circ$ to $45^\circ$, $Nu$ increased at a less rate of 1.01 at fixed $β_{\text{high}} = 55^\circ$. $β_{\text{high}}$ had a greater effect on $Nu$ than $β_{\text{low}}$.

### 4. Hydraulic model development

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

$$f = C_5 C_6(β) C_7(γ) Re^{C_8(β)}$$

(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 $β_{\text{mixed}}$.

<table>
<thead>
<tr>
<th>Table 3: Coefficients regression in hydraulic model</th>
</tr>
</thead>
<tbody>
<tr>
<td>two-segmented plate</td>
</tr>
<tr>
<td>$β$</td>
</tr>
<tr>
<td>$C_5$</td>
</tr>
<tr>
<td>$C_6$</td>
</tr>
<tr>
<td>$C_7$</td>
</tr>
<tr>
<td>$C_8$</td>
</tr>
</tbody>
</table>

The expression of $β_{\text{mixed}}$ in Table 3 implied heavy weighting of $β_{\text{high}}$ on $β_{\text{mixed}}$, which was 6 times of $β_{\text{low}}$. Similar as the effect of $β_{\text{high}}$ on thermal performance, increasing $β_{\text{high}}$ instead of $β_{\text{low}}$ 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.

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

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...
region. When $\beta$ 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 $\beta$ was greater than 80°. In general, there was less friction in the PHE with smaller $\beta$ (except when $\beta > 80^\circ$) and lower $\gamma$.

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

It should be noted that due to greater weighting of $\beta_{\text{high}}$ in hydraulic model than in thermal model, large $\beta_{\text{high}}$ would promote greater increase in $f$ than in $Nu$. This trade-off must be considered when it comes to the selection of suitable $\beta$ 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 $0^\circ < \beta < 90.0^\circ$, $0.28^\circ < \gamma < 1.00^\circ$ 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](image)

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.

![Figure 5: Corrugated PHE hydraulic model error distributions](image)
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 (\(\beta\)), corrugation aspect ratio (\(\gamma\)) 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 \(\beta\), \(\gamma\) 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 \(\beta\) was increased from 0° to 80° and \(\gamma\) was increased from 0.3 to 1.0. The two-segmented plate with \(\beta\) 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-\(\beta\) configuration, \(\beta_{high}\) had strong influence on heat transfer compared to \(\beta_{low}\), therefore larger \(\beta_{high}\) 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


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.

