The influence of plate corrugations geometry on Plate Heat Exchanger performance in specified process conditions

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• When integrating renewables, polygeneration and CHP units with traditional energy sources in process industries, more sophisticated challenges arise.

• Plate Heat Exchanger (PHE) is one of advanced modern types of heat recuperation equipment. Its application as an elements of a heat exchange networks gives efficient solutions.
The design and operation principles of PHEs

1 – heating heat carrier (hot side); 2 – heated heat carrier (cold side)
The PHE plate

1 – heat carrier inlet and outlet;
2, 5 – zones for flow distribution;
3 – rubber gasket;
4 – main corrugated field
Geometries of plates with different corrugation types

- 1, 2 – the intersection of the adjacent plates;
Geometries of plates with different corrugation types

- 3 – channel cross sections for the sinusoidal form of corrugations;
- 4 – channel cross sections for the triangular form of corrugations
The problem

- To find
  - the maximum overall heat transfer coefficients and
  - minimal heat transfer area

for the fixed corrugations parameters of plate
at given conditions due to full utilization of
pressure drop.

- To determine the influence of plate
corrugations geometrical parameters on ability
of PHE to satisfy specific process conditions
with minimal required heat transfer area.
Mathematical model for prediction of heat transfer and pressure drop
Assumptions

- The plate’s surface of industrial plate-and-frame PHE is under consideration.
- The inter-plate channel consists of
  - its main corrugated field and
  - distribution zone
The empirical equation for calculation of friction factor $\zeta$ in criss-cross flow channels

$$\zeta = 8 \cdot \left[ \left( \frac{12 + p2}{Re} \right)^{12} + \left( A + B \right)^{\frac{3}{2}} \right]^{\frac{1}{12}}$$

$$A = \left[ p4 \cdot \ln \left( \frac{p5}{\left( \frac{7 \cdot p3}{Re} \right)^{0.9} + 0.27 \cdot 10^{-5}} \right) \right]^{16}$$

$$B = \left( \frac{37530 \cdot p1}{Re} \right)^{16}$$
The mentioned parameters defined by channel corrugation form

\[ p_1 = \exp(-0.15705 \cdot \beta) \]

\[ p_2 = \frac{\pi \cdot \beta \cdot \gamma^2}{3} \]

\[ p_3 = \exp\left(-\pi \cdot \frac{\beta}{180} \cdot \frac{1}{\gamma^2}\right) \]

\[ p_4 = \left(0.061 + \left(0.69 + \tan\left(\frac{\beta \cdot \pi}{180}\right)\right)^{-2.63}\right) \cdot \left(1 + (1 - \gamma) \cdot 0.9 \cdot \beta^{0.01}\right) \]

\[ p_5 = 1 + \frac{\beta}{10} \]
Accounting for the pressure losses in distribution zones

- $\zeta_{DZ}$ is the coefficient of local hydraulic resistance in distribution zones, $\zeta_{DZ} = 38^1$
- The total pressure loss in a PHE channel:

$$\Delta p = \zeta \cdot \frac{L_F}{d_E} \cdot \frac{\rho \cdot w^2}{2} + \zeta_{DZ} \cdot \rho \cdot w^2$$

- $\rho$ is the fluid density, kg/m$^3$; $L_F$ is the length of corrugated field, m; $d_E = 2 \cdot b$ is the equivalent diameter of the channel, m; $w$ is the average velocity of stream at the main corrugated field.

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The comparison of calculated pressure losses with experimental data of paper

\[ \frac{\Delta P_c}{\Delta P_{exp}} = 38 \cdot \frac{\zeta_{65}(Re)}{\zeta_{65}(2700)} \]

\[ \zeta_{DZ} \]

\[ \beta = 30^\circ, 60^\circ \]

\[ \leq \pm 3\% \]

\[ \leq \pm 15\% \]

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The equation for calculation of film heat transfer coefficients in channels of PHEs

\[
Nu = 0.065 \cdot Re^{6/7} \cdot (\psi \cdot \zeta)^{3/7} \cdot Pr^{0.4} \cdot \left(\frac{\mu}{\mu_w}\right)^{0.14}
\]

- \(\mu\) and \(\mu_w\) are the dynamic viscosities at stream and at wall temperatures;
- \(\zeta\) – friction factor accounting for total pressure losses in channel;
- \(\psi\) – the share of pressure loss due to friction on the wall in total loss of pressure.
Equation’s parameters

- Pr - Prandtl number
- Nusselt number \( Nu = h \cdot d_e / \lambda \)
- Reynolds number \( Re = w \cdot d_e \cdot \rho / \mu \)
- The value of \( \psi \) can be estimated by the following Equation:

\[
\begin{align*}
\psi &= \left( \frac{Re}{A_1} \right)^{-0.15 \cdot \sin(\beta)} & \text{at } Re > A_1 \\
\psi &= 1 & \text{at } Re \leq A_1
\end{align*}
\]

\[ A_1 = 380 / \left[ \tan(\beta) \right]^{1.75} \]
Limits

- The corrugations inclination angle $\beta$ varies from 14° to 72°.

- The corrugation double height to pitch ratio $\gamma = 2 \cdot \frac{b}{S}$ is from 0.52 to 1.02.

- The range of Reynolds numbers is from 5 to 25,000.

- The range of Prandtl number is from 1 to 15.
The presented mathematical model enables

- To predict the friction factor and film heat transfer coefficients in PHE channels on a data of their corrugations geometrical parameters, such as
  - corrugation angle $\beta$,
  - aspect ratio $\gamma$ and
  - coefficient of surface area enlargement $F_x$.

- To investigate the influence of these parameters, as well as corrugations height, equal to inter-plate spacing, and size of the plate on PHE performance in specific process conditions.
The best geometry of plate for specific process
The specified conditions of heat transfer process in PHE

\[ G_1, \text{kg/s} \]

\[ G_2, \text{kg/s} \]

\[ \Delta P_1^\circ, \text{Pa} \]

\[ \Delta P_2^\circ, \text{Pa} \]

\[ t_{11}, ^\circ\text{C} \]

\[ t_{12}, ^\circ\text{C} \]

\[ t_{21}, ^\circ\text{C} \]

\[ t_{22}, ^\circ\text{C} \]
Varied parameters of PHE construction

- Only internal parameters of PHE construction can be varied, like:
  - number
  - size of plates
  - corrugation pattern
  - streams passes numbers.

- It can lead to different:
  - channel geometries,
  - flow velocities and
  - wall temperatures inside the heat exchanger.
The basic relations

- When pressure drop condition for hot stream exactly satisfied the plate length is:

\[
\frac{L_F}{b} = \frac{4}{\zeta_1(w_1)} \cdot \left( \frac{\Delta P_1^o}{\rho_1 \cdot w_1^2} - \zeta_{DZ} \right)
\]

- The number of heat transfer units for hot stream in heat exchanger must be not less than

\[
NTU^0 = \frac{(t_{11} - t_{12})}{\Delta t_{in}}
\]

- The number of heat transfer units, which can be obtained in one PHE channel:

\[
NTU = \frac{2 \cdot U \cdot F_{pl}}{c_{p1} \cdot w_1 \cdot \rho_1 \cdot f_{ch}}
\]
The plate length that will fulfill the process conditions for NTU:

\[
\frac{L_F}{b} = \frac{NTU^0 \cdot 0.85 \cdot c_{p1} \cdot w_1 \cdot \rho_1}{2 \cdot U \cdot F_x}
\]

When satisfied both conditions, for heat load and pressure drop of hot stream, we have a system of two algebraic Equations with two unknown variables \(L_F\) and \(w_1\).

\[
\begin{align*}
\frac{L_F}{b} & = \frac{4}{\zeta_1(w_1)} \cdot \left( \frac{\Delta P^o}{\rho_1 \cdot w_1^2} - \zeta_{DZ} \right) \\
\frac{L_F}{b} & = \frac{NTU^0 \cdot 0.85 \cdot c_{p1} \cdot w_1 \cdot \rho_1}{2 \cdot U \cdot F_x}
\end{align*}
\]
The basic relations

- flow velocity of hot stream in PHE channels, m/s

\[ w_1 = \sqrt{\frac{\Delta P_1^0}{\rho_1}} \cdot \frac{1}{\zeta_{DZ}(w_1) + \zeta_1(w_1)} \cdot \frac{NTU^0 \cdot 0.85 \cdot c_p \cdot w_1 \cdot \rho_1}{8 \cdot U(w_1) \cdot F_x} \]

- the overall heat transfer coefficient

\[ \frac{1}{U} = \frac{1}{h_1} + \frac{1}{h_2} + \frac{\delta_w}{\lambda_w} + R_{foul} \]

- heat transfer area of one plate, m²

\[ F_{pl} = L_F \cdot W \cdot F_x / 0.85 \]

- W is the width of the channel, m
Case study
PHE application in District Heating (DH) system.

\[ Q_2 = 3000 \text{ kW} \]
\[ \Delta P_2^o = 70 \text{ kPa} \]

\[ Q_1 = 600 \text{ kW} \]
\[ \Delta P_1^o = 20 \text{ kPa} \]

\[ Q = (t_{11} - t_{12}) \cdot c_{p1} \cdot G_1 = (t_{22} - t_{21}) \cdot c_{p2} \cdot G_2 \]

\[ t_{21} = 70 ^\circ C \]
\[ t_{11} = 120 ^\circ C \]
\[ t_{22} = 95 ^\circ C \]
\[ t_{12} = 75 ^\circ C \]
Dependence of heat transfer area $F_a$ from the corrugations geometry

$Q = 3000$ kW
Dependence of plate length $L_F$ from the corrugations geometry

$Q = 3000 \text{ kW}$
The dependence of required plate length $L_F$ and PHE heat transfer area from corrugations angle $\beta$ at $b = 1.5$ mm.

**Graphical Representation:**
- $F_{a1}, m^2$
- $F_{a2}, m^2$
- $F_{a2} = 42.4 \ m^2$
- 115 plates

**Equations and Calculations:**
- $L_F = 710 \ mm$
- $L_F = 300 \ mm$
- $F_{a1} = 6.06 \ m^2$
- $F_{a1} = 0.066 \ m^2$
- $F_{pl1} = 0.37 \ m^2$
- $92 \ 460 \ \leq 120$

**Note:**
- $F_{pl1} = L_F^2 \cdot F_x / (2 \cdot 0.85)$
The dependence of required plate length $L_F$ and PHE heat transfer area from corrugations angle $\beta$ at $b = 2 \text{ mm}$

$F_{a1} = 6.43 \text{ m}^2$

$F_{a2} = 32.15 \text{ m}^2$

$F_{a2} = 38 \text{ m}^2$

$F_{pl1} = 0.35 \text{ m}^2$

109 plates

$\beta = 50^\circ$

$\beta = 65^\circ$

$L_F = 700 \text{ mm}$
The dependence of required plate length $L_F$ and PHE heat transfer area from corrugations angle $\beta$ at $b = 2.5$ mm

- $F_{a1} = 6.74 \text{ m}^2$
- $F_{a2} = 39.6 \text{ m}^2$
- $F_{a2} = 33.72 \text{ m}^2$
- $F_{pl1} = 0.61 \text{ m}^2$
- 65 plates

$F_{a1}(\beta)$

$F_{a2}(\beta)$

$L(\beta)$

$F_{pl1} = 0.61 \text{ m}^2$

$65$ plates

$L_F = 910 \text{ mm}$
Obtained data for corrugations inclination angle $\beta$ and for plate spacing $b$

<table>
<thead>
<tr>
<th>$b$</th>
<th>$\beta = 65^\circ$</th>
<th>$\beta = 37^\circ$</th>
<th>$\beta = 50^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 mm</td>
<td>$F_{a1} = 6.06 , m^2$</td>
<td>$L_F = 710 , mm$</td>
<td>$L_F = 700 , mm$</td>
</tr>
<tr>
<td></td>
<td>$F_{a2} = 30.28 , m^2$</td>
<td>$F_{pl1} = 0.37 , m^2$</td>
<td>$F_{pl1} = 0.35 , m^2$</td>
</tr>
<tr>
<td>2 mm</td>
<td>$F_{a1} = 6.43 , m^2$</td>
<td>$F_{a2} = 42.4 , m^2$</td>
<td>$F_{a2} = 38 , m^2$</td>
</tr>
<tr>
<td></td>
<td>$F_{a2} = 32.15 , m^2$</td>
<td>$\beta = 50^\circ$</td>
<td>109 plates</td>
</tr>
<tr>
<td>2.5 mm</td>
<td>$F_{a1} = 6.74 , m^2$</td>
<td>$L_F = 910 , mm$</td>
<td>$L_F = 910 , mm$</td>
</tr>
<tr>
<td></td>
<td>$F_{a2} = 33.72 , m^2$</td>
<td>$F_{pl1} = 0.61 , m^2$</td>
<td>$F_{a2} = 39.6 , m^2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>65 plates</td>
</tr>
</tbody>
</table>
Case study shows

- To satisfy process conditions with minimal heat transfer area there are required plates of different size with different geometrical parameters.
- To maintain full utilization of allowable pressure drop with exact satisfaction of heat load, it is possible
  1. by decreasing $\beta$ or
  2. by increasing plate spacing $b$. 
Conclusions

- The presented mathematical model enables to predict the influence of plate corrugation parameters on PHE performance.
- For the specified process conditions
  - pressure drop,
  - temperature program,
  - heat load and
  - streams physical properties
the geometrical parameters of plate and its corrugations enabling to make PHE with minimal heat transfer area can be found.
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THANK YOU