Performance Evaluation Criteria and Selection Utility Function for Compact Air-to-Refrigerant Heat Exchangers

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Objectives

Multiple Heat eXchanger (HX) surface alternatives: evaluate, compare and select

- Performance Evaluation Criteria (PEC):
  - Advantages and disadvantages
  - Meaning and the impact to the HX design

Decision-Making perspective:

- Why did the optimizer choose those designs?
- How to compare and select a design amongst two or more alternatives?
- Multi-Attribute Utility Function (MAUF)
Introduction

Heat Transfer Augmentation

- ↑ Compactness (Surface-to-Volume ratio)
- ↑ Thermal-Hydraulic performance
  - Subject to different interpretations and representations

Performance Evaluation Criteria (PEC)

- Energy-based
  - Premise: friction resistance is the sole responsible for the performance degradation

- Entropy-based
  - Characterize all degradation mechanisms
Literature Review

Area “goodness” factor (London, 1964)

\[
\frac{j}{f} = \left[ \frac{h}{\rho \mu_c c_p} \right] \left[ \frac{2A_c \Delta P}{A_o \rho u_c^2} \right] = K \frac{1}{A_c^2} \left( \frac{N_{tu}}{\Delta P} \right)
\]

\[\Delta P \propto u_c^m, \ m > 1.0; \quad h \propto u_c^n, \ 0.0 < n < 1.0; \quad A_c \propto u_c^{-1}\]

- Comparison issue: Face area vs. \(N_{tu}/\Delta P\)
- Design issue: \(\Delta P\), Face area, lastly \(N_{tu}\)

Volume “goodness” factor (London, 1964)

\[
\frac{h}{\dot{W}'''} = \frac{h}{\Delta P \cdot \dot{V} / A_o} = \left( \frac{c_p \mu}{2 \rho^2 D_h^3 \text{Pr}^{2/3}} \right) \left( \frac{f \text{Re}^3}{2 \rho \mu \text{Pr}^{2/3} \text{Re}^2} \right) = \frac{2 j \rho^2 c_p D_h^2}{f \mu^2 \text{Pr}^{2/3} \text{Re}^2}
\]

- Comparison and design issue: fixed \(D_h\)

Variations: \(Q/W, Q'''/W \cdot \Delta T\)
Entropy Generation Minimization (Bejan, 1977, 1996)

\[ N_S = \frac{\dot{S}_{gen}}{C_{min}} \]

Production cost vs. Irreversibility Cost (Bejan, 1977)
- Larger, “more expensive”, HX is more thermodynamically efficient (Bejan, 1977)

Better heat transfer \( \neq \) minimum entropy generation (Bejan & Pfister, 1980; Seculik & Herman, 1986)
Proposed HX Evaluation Criteria

Performance-Degradation Number
(Ogiso, 2003)

\[ \psi = \frac{N_{\text{tu}}}{N_s} \]

- Ideal gas

\[ \Delta s = \int \frac{\partial q}{T} + s_{\text{gen}} \rightarrow s_{\text{gen}} \approx c_p \ln \left( \frac{T_o}{T_i} \right) - q \frac{T}{T} - R \ln \left( \frac{P_o}{P_i} \right) \]

\[ N_s = N_{s,\Delta T} + N_{s,\Delta P}, \quad N_{s,\Delta T} = \frac{\dot{S}_{\text{gen},\Delta T}}{C} = \ln \left( \frac{T_o}{T_i} \right) - \frac{N_{\text{tu}} \Delta T_{ml}}{T}, \quad N_{s,\Delta P} = \frac{S_{\text{gen},\Delta P}}{R} = \ln \left( \frac{P_o + \Delta P}{P_o} \right) \]

\[ \psi = \frac{N_{\text{tu}}}{\ln \left( \frac{T_o (P_o + \Delta P)}{T_i P_o} \right) - \frac{N_{\text{tu}} \Delta T_{ml}}{T}} = \frac{N_{\text{tu}}}{\ln \left( \frac{T_o (P_o + \Delta P)}{T_i P_o} \right) - \varepsilon \Delta T_{\text{max}}/T} \]
Conventional Heat Transfer Surfaces

- Trade-off between size and low entropy generation
- Larger HX’s have larger heat transfer surfaces
- Novel shapes and smaller tube sizes result in higher heat transfer coefficients
  - Less need for surface area (~UA, ↑U)
  - Geometrical limitations might be different for these novel surfaces (face area, aspect ratio, etc.)
HX “Size”

- HX “size” is a broad term
- What aspect of the size is the most critical / important?
- How are two HX’s sizes comparable?

\[
\begin{align*}
\text{Face Area:} & \quad h_1l_1 < h_2l_2 \\
\text{Envelope Volume:} & \quad h_1l_1d_1 > h_2l_2d_2
\end{align*}
\]
Size Metrics

Compactness

- More meaningful than volume or surface area alone
- Independent to HX scale (surface characteristic)
- Surface hydraulic diameter
  \[ D_h = 4 \frac{A_c}{A_o} d = 4\sigma \frac{V}{A_o} \rightarrow A_o / V = 4\sigma / D_h \]

Face Area

- Smaller tubes compromise on friction resistance requiring smaller flow passage depths thus increasing face area
HX DESIGN AND OPTIMIZATION
## Problem Definition

<table>
<thead>
<tr>
<th>Optimization</th>
<th>OPT01</th>
<th>OPT02</th>
<th>OPT03</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Objectives</strong></td>
<td>Conventional PEC</td>
<td>Conventional PEC</td>
<td>Alternative PEC</td>
</tr>
<tr>
<td>min $A_f$</td>
<td>min $A_f$</td>
<td>min $A_f$</td>
<td></td>
</tr>
<tr>
<td>max $h/\Delta P$</td>
<td>max $j/f$</td>
<td>max $\psi$</td>
<td></td>
</tr>
<tr>
<td><strong>Constraints</strong></td>
<td>$1.0 &lt; Q &lt; 1.01kW$</td>
<td>$0.61 &lt; AR &lt; 1.61$</td>
<td></td>
</tr>
<tr>
<td>$V_{HX} \leq V_{HX, \text{baseline}}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta P_{\text{air}} \leq \Delta P_{\text{air, baseline}}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta P_{\text{water}} \leq \Delta P_{\text{water}}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td>$\dot{m}_{\text{air}} = \text{fixed}$</td>
<td>$\dot{m}_{\text{water}} = \text{fixed}$</td>
<td></td>
</tr>
<tr>
<td>$0.5 \leq U_{\text{air}} \leq 7.0 \text{m/s}$</td>
<td>$0.8 \Delta T_{\text{in, baseline}} \leq \Delta T_{\text{in}} \leq \Delta T_{\text{in, baseline}}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Results

OPT01: $h/\Delta P$
OPT02: $j/f$
OPT03: $\psi$

<table>
<thead>
<tr>
<th>PEC</th>
<th>$h/\Delta P$</th>
<th>$j/f$</th>
<th>$\psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compactness</td>
<td>↑</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Face Area</td>
<td>↓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Resistance</td>
<td>↓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Friction</td>
<td>↓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Entropy Generation</td>
<td>↓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
HX SELECTION
Multi-Attribute Utility Function

Weighted Lp-norm expression
(Scott and Antonsson, 2005), (Herrmann, 2015)

\[
U(\bar{x}) = \left( \frac{\sum w_i u(x_i)^p}{\sum w_i} \right)^{1/p}, \quad \text{if } p = 0 \quad \rightarrow \quad U(\bar{x}) = \left( \sum u(x_i)^{w_i} \right)^{1/\sum w_i}
\]

- Objective: Find the maximum aggregate utility (U(x))

Attributes (normalized): ψ, 4σ/D_h, 1/A_f
## HX Selection Results (1 Pareto)

### Pareto - WTHX

<table>
<thead>
<tr>
<th></th>
<th>HX001</th>
<th>HX002</th>
<th>HX003</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi$</td>
<td>0.980</td>
<td>0.982</td>
<td>1.000</td>
</tr>
<tr>
<td>$h/\Delta P$</td>
<td>0.269</td>
<td>0.269</td>
<td>0.288</td>
</tr>
<tr>
<td>$j/f$</td>
<td>0.978</td>
<td>0.977</td>
<td>0.998</td>
</tr>
<tr>
<td>$4\sigma/Dh$</td>
<td>0.883</td>
<td>0.883</td>
<td>0.883</td>
</tr>
<tr>
<td>$Af$</td>
<td>0.524</td>
<td>0.525</td>
<td>0.551</td>
</tr>
<tr>
<td>$U(x)$</td>
<td>0.997</td>
<td>1.000</td>
<td>0.999</td>
</tr>
</tbody>
</table>

### Diagram

- **Normalized $\psi$**
- **Normalized Face Area**
- **Pareto - WTHX**
- **Selected - WTHX**
HX Selection Results

![Diagram of HX selection results with dimensions and metrics]

<table>
<thead>
<tr>
<th>Norm. Metrics</th>
<th>RTHX</th>
<th>WTHX</th>
<th>Rel. diff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_f$</td>
<td>0.879</td>
<td>0.525</td>
<td>-40.2</td>
</tr>
<tr>
<td>$V_{HX}$</td>
<td>0.683</td>
<td>0.930</td>
<td>36.2</td>
</tr>
<tr>
<td>$4\sigma/D_h$</td>
<td>0.825</td>
<td>0.883</td>
<td>7.0</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>0.994</td>
<td>0.998</td>
<td>0.4</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>0.913</td>
<td>0.864</td>
<td>-5.4</td>
</tr>
<tr>
<td>$\psi$</td>
<td>0.817</td>
<td>0.982</td>
<td>20.3</td>
</tr>
<tr>
<td>$j/f$</td>
<td>0.317</td>
<td>0.977</td>
<td>207.7</td>
</tr>
<tr>
<td>$h/\Delta P$</td>
<td>0.375</td>
<td>0.269</td>
<td>-28.2</td>
</tr>
</tbody>
</table>
Conclusions

Impact of PEC on design, optimization and selection
- Mixed approach lead to better thermal performance and good compactness

MAUF is one way of decision-making

Introduction to a broader robust methodology that allows one to compare and select HX’s from multiple Pareto sets, including various surfaces types and sizes, on a fair basis
Acknowledgements

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THANK YOU!