CFD-BASED CORRELATION DEVELOPMENT FOR AIR SIDE PERFORMANCE OF FINNED AND FINLESS TUBE HEAT EXCHANGERS WITH SMALL DIAMETER TUBES

Paper #2240

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- Objectives
- Geometries
- Methodology
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- Conclusions
- Future Work
Background and Motivation

- CEEE/DOE/ORNL Research Correlations/Tools
- Well investigated Micro/Mini-channel e.g., CoilDesigner™
- CEEE Research Correlation/Tools
- Well Investigated: Correlations/Tools e.g. CoilDesigner™
Objectives

- Present a comprehensive method for CFD-based correlation development

- Present a correlation for air side performance for small diameter tubes HX design and optimization
# Geometries

## Table 1: Heat exchangers design space.

<table>
<thead>
<tr>
<th>Design Variable</th>
<th>unit</th>
<th>Bare Tubes</th>
<th>Plain fin-and-tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_o$</td>
<td>mm</td>
<td>2.0 to 5.0</td>
<td>2.0 to 5.0</td>
</tr>
<tr>
<td>$P_t$ ratio ($D_o$)</td>
<td>-</td>
<td>1.5 to 3.0</td>
<td>1.5 to 3.0</td>
</tr>
<tr>
<td>$P_l$ ratio ($D_o$)</td>
<td>-</td>
<td>1.5 to 3.0</td>
<td>1.5 to 3.0</td>
</tr>
<tr>
<td>Tube Banks</td>
<td>-</td>
<td>2 to 20</td>
<td>2 to 10</td>
</tr>
<tr>
<td>FPI</td>
<td>in$^{-1}$</td>
<td>N/A</td>
<td>8 to 24</td>
</tr>
<tr>
<td>Air face velocity</td>
<td>m/s</td>
<td>0.5 to 7.0</td>
<td>0.5 to 7.0</td>
</tr>
<tr>
<td>Fin thickness</td>
<td>mm</td>
<td>N/A</td>
<td>0.115 (fixed) *</td>
</tr>
</tbody>
</table>

METHODOLOGY
Correlation Development

Design of Experiments (500) → Parallel Parameterized CFD (PPCFD\(^1\)) → Minimize SSRE (fgoalattain)

Automated CFD runs for a given parameterized geometry reducing the engineering time required to complete the CFD simulations and post-processing

\[
\begin{align*}
\min e_f &= \sum (f_{corr} - f_{CFD})^2 \\
\min e_j &= \sum (j_{corr} - j_{CFD})^2
\end{align*}
\]

5 dimensional design space projected onto a 2D plane

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## CFD Models

### Computational Domain
- **Bare Tube:** 2D
- **Plain Fin-and Tube:** 3D

### Mesh
- **Bare Tube:** Triangle
- **Plain Fin-and Tube:** Hexahedron

### Boundary Conditions
- **Bare Tube:**
  - Constant wall temperature: 338K
  - Uniform air inlet temperature: 308K

### Turb. Model
- **Bare Tube:** k-ε realizable (w/ enhanced wall functions)

### Density Model
- **Bare Tube:** Ideal-Gas

### Other properties
- \( k = 0.0272 \text{W/m.K}, \ c_p = 1006.4 \text{J/kg.K}, \ \mu = 0.00001945 \text{ Pa.s} \)

### Tolerances
- Momentum/Continuity: \( 10^{-5} \); Energy: \( 10^{-6} \); Turbulence: \( 10^{-3} \)

### Max. Iterations
- **Bare Tube:** 1750
- **Plain Fin-and Tube:** 2500
HX Data Reduction Method

\[ \dot{Q} = m c_p \left( T_{out} - T_{in} \right) \]

\[ NTU = \frac{UA}{C_{min}} \quad C^* = \frac{C_{min}}{C_{max}} = 0 \quad NTU = \ln \left( \frac{1}{1 - \varepsilon} \right) \]

\[ \frac{1}{UA} = \frac{1}{\eta_o h_{air} \cdot A_o} + \frac{1}{2} \ln \left( \frac{D_o}{D_i} \right) \frac{D_o}{k_w A_w} + \frac{1}{h_{ref} \cdot A_{ref}} \]

Plain fin-and-tube:
\[ \eta_o = 1 - \frac{A_f}{A_o} \left( 1 - \eta \right) \]

\[ \eta = \frac{\tanh \left( mr\phi \right)}{mr\phi} \]

\[ m = \left( \frac{2HTC_{air}}{k_f c_f} \right)^{0.5} \]

\[ \phi = \left( \frac{R_{eq}}{r} - 1 \right) \left[ 1 + 0.35 \ln \left( \frac{R_{eq}}{r} \right) \right] \]

\[ X_L = \frac{1}{2} \left( \frac{P_t^2}{4} + P_t^2 \right)^{0.5} \]

\[ X_M = \frac{P_t}{2} \]

\[ \frac{R_{eq}}{r} = 1.27 \frac{X_M}{r} \left( \frac{X_L}{X_M} - 0.3 \right)^{0.5} \]

CFD Uncertainty Quantification

- Designs at the boundary of design space: $2^{n+1}$
  - Any design inside design space exhibits similar or lower uncertainty
- Determine Grid Convergence Index (GCI)

$$GCI^{21}_{fine} = \frac{F_s \cdot e^{21}_a}{r_2^{\hat{p}} - 1}$$

- $F_s = 1.25$
- $e^{21}_a = |\phi(h_{fine}) - \phi(h_{coarse})|$
- $r_2^{\hat{p}} = \frac{h_{coarse}}{h_{fine}}$
- $\hat{p} = \min \{\max[0.5, p], 2.0\}$

$$h = \sqrt{\frac{\sum \Delta A_i}{N}}(2D) \quad h = \sqrt[3]{\frac{\sum \Delta V_i}{N}}(3D)$$

Uncertainty Analysis

Heat Transfer Coefficient

Pressure Drop
Correlations

Bare Tubes:

\[ f = C_1 \text{Re}^{F_1}_{D_o} N_t^{F_2} \left( \frac{P_l}{D_o} \right)^{F_3} \left( \frac{P_t}{P_l} \right)^{F_4} \]

\[ j = C_1 \text{Re}^{J_1}_{D_o} N_t^{J_2} \left( \frac{P_l}{D_o} \right)^{J_3} \left( \frac{P_t}{P_l} \right)^{J_4} \]

\[ J_1 = C_3 + \frac{C_4 N_t}{\ln(\text{Re}_{D_o})} + C_5 \ln \left[ N_t \left( \frac{P_l}{D_o} \right)^{C_6} \right] \]

\[ J_2 = C_7 + \frac{C_8}{\ln(\text{Re}_{D_o})} \left( \frac{P_t}{D_o} \right)^{C_9} \]

\[ J_3 = C_{10} + \frac{C_{11} N_t}{\ln(\text{Re}_{D_o})} \]

\[ J_4 = C_{12} + C_{13} \ln \frac{\text{Re}_{D_o}}{N_t} \]

Plain Fin-and-Tube:

\[ f = C_1 \text{Re}^{F_1}_{D_o} N_t^{F_2} \left( \frac{F_p}{D_c} \right)^{F_3} \left( \frac{P_t}{P_l} \right)^{F_4} \]

\[ j = C_1 \text{Re}^{J_1}_{D_o} N_t^{J_2} \left( \frac{F_p}{D_c} \right)^{J_3} \left( \frac{P_t}{P_l} \right)^{J_4} \]

\[ J_1 = C_3 + \frac{C_4 N_t}{\ln(\text{Re}_{D_c})} + C_5 \ln \left[ N_t \left( \frac{F_p}{D_c} \right)^{C_6} \right] \]

\[ J_2 = C_7 + \frac{C_8}{\ln(\text{Re}_{D_c})} \left( \frac{P_t}{D_o} \right)^{C_9} \]

\[ J_3 = C_{10} + \frac{C_{11} N_t}{\ln(\text{Re}_{D_c})} \]

\[ J_4 = C_{12} + C_{13} \ln \frac{\text{Re}_{D_c}}{N_t} \]

RESULTS
## Correlations Coefficients

**Table 2:** Correlations coefficients.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Bare Tube $j$</th>
<th>Bare Tube $f$</th>
<th>Plain fin-and-tube $j$</th>
<th>Plain fin-and-tube $f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>0.31692086</td>
<td>0.37714526</td>
<td>0.14766977</td>
<td>1.71188871</td>
</tr>
<tr>
<td>$C_2$</td>
<td>0.34727050</td>
<td>0.26992253</td>
<td>-0.28005133</td>
<td>0.92946488</td>
</tr>
<tr>
<td>$C_3$</td>
<td>-0.51134999</td>
<td>-0.04481229</td>
<td>-0.38888827</td>
<td>-0.22854500</td>
</tr>
<tr>
<td>$C_4$</td>
<td>-0.00401654</td>
<td>0.01138922</td>
<td>-0.04370010</td>
<td>0.04029790</td>
</tr>
<tr>
<td>$C_5$</td>
<td>0.09334736</td>
<td>-0.04293416</td>
<td>0.28331915</td>
<td>-0.00430627</td>
</tr>
<tr>
<td>$C_6$</td>
<td>0.52999408</td>
<td>0.77274225</td>
<td>0.44735913</td>
<td>-4.91278551</td>
</tr>
<tr>
<td>$C_7$</td>
<td>-0.97703628</td>
<td>0.21709950</td>
<td>-2.52843969</td>
<td>-0.62616159</td>
</tr>
<tr>
<td>$C_8$</td>
<td>3.10160601</td>
<td>1.73124835</td>
<td>5.29660856</td>
<td>1.31700831</td>
</tr>
<tr>
<td>$C_9$</td>
<td>-0.30758351</td>
<td>-4.97083301</td>
<td>-0.22444323</td>
<td>0.27195519</td>
</tr>
<tr>
<td>$C_{10}$</td>
<td>-0.73451673</td>
<td>-0.18590460</td>
<td>-1.00067472</td>
<td>-2.42919816</td>
</tr>
<tr>
<td>$C_{11}$</td>
<td>0.002349867</td>
<td>-0.01814594</td>
<td>0.30250007</td>
<td>0.06332710</td>
</tr>
<tr>
<td>$C_{12}$</td>
<td>1.34217805</td>
<td>0.56056314</td>
<td>2.08539578</td>
<td>0.97021840</td>
</tr>
<tr>
<td>$C_{13}$</td>
<td>-0.07168253</td>
<td>0.04926124</td>
<td>-0.27444087</td>
<td>0.10375729</td>
</tr>
</tbody>
</table>
Bare Tubes

<table>
<thead>
<tr>
<th>Heat Exchanger</th>
<th>Bare Tubes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air side performance metrics</strong></td>
<td><strong>h\text{air}</strong></td>
</tr>
<tr>
<td>10% absolute deviation</td>
<td>98.50%</td>
</tr>
<tr>
<td>15% absolute deviation</td>
<td>100.00%</td>
</tr>
<tr>
<td>20% absolute deviation</td>
<td>100.00%</td>
</tr>
<tr>
<td>30% absolute deviation</td>
<td>100.00%</td>
</tr>
<tr>
<td>Mean absolute relative deviation</td>
<td>3.60%</td>
</tr>
<tr>
<td>Mean GCI\textsuperscript{21}</td>
<td>1.60%</td>
</tr>
<tr>
<td>Coefficient of determination (R\textsuperscript{2})</td>
<td>99.60%</td>
</tr>
</tbody>
</table>
### Plain Fin-and-Tube

<table>
<thead>
<tr>
<th>Heat Exchanger</th>
<th>Fin and Tube</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air side performance metrics</strong></td>
<td><strong>h_{air}</strong></td>
</tr>
<tr>
<td>10% absolute deviation</td>
<td>63.58%</td>
</tr>
<tr>
<td>15% absolute deviation</td>
<td>82.49%</td>
</tr>
<tr>
<td>20% absolute deviation</td>
<td>91.55%</td>
</tr>
<tr>
<td>30% absolute deviation</td>
<td>96.98%</td>
</tr>
<tr>
<td>Mean absolute relative deviation</td>
<td>9.51%</td>
</tr>
<tr>
<td>Mean GCI^{21}</td>
<td>4.20%</td>
</tr>
<tr>
<td>Coefficient of determination (R^2)</td>
<td>95.67%</td>
</tr>
</tbody>
</table>
Conclusions

Total of 1392 cases simulated:

- PPCFD Engineering time:
  - Coding / debugging: 25 hours
- PPCFD Computational time:
  - Mesh generation and simulation: 40 min/case

Bare Tubes: 90% of the data points within 10% deviation

Plain Fin-and-Tube: more than 80% of the data points within 15% deviation

Correlations can be used for design and optimization of small diameter tubes HX in a finite volume HX design tool
Future Work

- Build prototypes, measure actual performance and modify correlations

- Investigate other geometries and develop new correlations
  - Fins: wavy, louver, slits
  - Tube diameter range: below 2.0mm
ACKNOWLEDGMENT
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Thank You!
References


References cont’d

\[ f = \frac{A_c}{A_o} \frac{\rho_m}{\rho_1} \left[ \frac{2 \Delta p \rho_1}{G_{\text{max}}^2} - \left(1 + \sigma^2\right) \left(\frac{\rho_1}{\rho_2} - 1\right) \right] \]
\[ \Delta P = f \frac{A_o}{A_c \rho_m} \frac{\rho_1}{2 \rho_1} G_{\text{max}}^2 \]

\[ \Delta P = \left[ f \frac{A_o}{A_c \rho_m} \rho_1 + (1 + \sigma^2) \left( \frac{\rho_1}{\rho_2} - 1 \right) \right] \frac{G_{\text{max}}^2}{2 \rho_1} \]
Fin pattern = plain.

$N = 1–6$.

$D_o = 6.35–12.7$ mm.

$F_p = 1.19–8.7$ mm.

$P_t = 17.7–31.75$ mm.

$P_l = 12.4–27.5$ mm.

Table 2
Comparison of the proposed correlation and other correlations

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$j$</td>
<td>$f$</td>
<td>$j$</td>
<td>$f$</td>
</tr>
<tr>
<td>± 10%</td>
<td>75.6</td>
<td>71.1</td>
<td>34.7</td>
<td>18.7</td>
</tr>
<tr>
<td>± 15%</td>
<td>88.6</td>
<td>85.1</td>
<td>46.7</td>
<td>25.8</td>
</tr>
<tr>
<td>± 20%</td>
<td>94.3</td>
<td>94.2</td>
<td>56.3</td>
<td>29.2</td>
</tr>
<tr>
<td>Average deviation$^b$ (%)</td>
<td>0.59</td>
<td>0.76</td>
<td>-20.4</td>
<td>-12.2</td>
</tr>
<tr>
<td>Mean deviation$^c$ (%)</td>
<td>7.51</td>
<td>8.31</td>
<td>34.4</td>
<td>40.6</td>
</tr>
</tbody>
</table>