Longitudinal Heat Conduction in Finned-Tube Evaporators

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Source publications
Questions:

How significant are longitudinal heat conduction effects?

Can they be neglected?
Literature Review

- **Kays and London (1984)**
  Longitudinal tube heat conduction
  \[ \lambda = \frac{kA_w}{LC_{\text{min}}} \]
  \[ \frac{C_{\text{min}}}{C_{\text{max}}} \]
  NTU (\( \varepsilon > 0.9 \))

- **Ranganayakulu et al. (1996)**
  Finite element simulation study; longitudinal tube heat conduction
  \[ \tau = \frac{\varepsilon_{\text{NC}} - \varepsilon_{\text{WC}}}{\varepsilon_{\text{NC}}} = f(\varepsilon_{\text{NC}}, \lambda, \frac{C_{\text{min}}}{C_{\text{max}}}, \text{NTU}) \] (\( \varepsilon > 0.8 \))

- **Heun and Crawford (1994)**
  Analytical study; multipass, cross-counterflow, single-depth-row hx, fin conduction
  Capacity degradation \( \uparrow \)  Fin conductance \( \uparrow \)
  \[ \frac{A_a h_a}{\dot{m} c_{pa}} \] \( \uparrow \)
Literature Review (cont.)

• **Romero-Mendez et al. (1997)**
  Analytical study; single-row finned-tube heat exchanger; fin conduction
  Capacity degradation as high as 20 %

• **Asinari et al. (2004)**
  Hybrid finite-volume and finite-element study, CO₂ microchannel gas cooler
  Longitudinal conduction in fins, transverse and longitudinal conduction in tubes give negligible effect on the total heat flow
  Capacity degradation is negligible (1.1 %)

• **Park and Hrnjak (2007)**
  Experimental and simulation study; CO₂ microchannel gas cooler
  Capacity improvement 1.9 % - 3.9 % by cutting some fins.
  The authors emphasize the importance of circuitry design

• **Other papers by Prasad, Shah, Chiou, Chinese researchers**
Heat Exchangers Tested

Common design features:
- 3 depth rows with 18 tubes per row
- 9.5 mm outside diameter
- 457 mm long round copper tubes
- 25.4 mm tube spacing in a row
- 3 parallel refrigerant circuits
- 0.1 mm thick aluminum fins

Design differences:
HX-wavy: used wavy fins
HX-slit: used slit fins
HX-slit-cut: depth rows separated by a cut in fins; slit fins
Three Refrigerant Circuits
Cross-counter flow configuration

Outlet
Inlet
Air
Test Conditions

**Air:**
Dry bulb: \textbf{26.7 °C ± 0.3 °C} \hspace{1cm} Dew point: \textbf{15.8 ± 0.3 °C}

**Refrigerant**

**Condenser exit**

\begin{itemize}
  \item $T_{\text{sat}}$: \textbf{48.9 °C ± 1.4 °C}
  \item $T_{\text{subcooling}}$: \textbf{8.3 °C ± 1.4 °C}
\end{itemize}

**Evaporator exit**

\begin{itemize}
  \item $T_{\text{sat}}$: \textbf{7.2 °C ± 0.3 °C}
  \item $T_{\text{superheat}}$: \textbf{5.6 °C or 16.7 °C ± 1.4 °C}
\end{itemize}

<table>
<thead>
<tr>
<th>Test</th>
<th>Air Volumetric Flowrate (m³/h)</th>
<th>Overall Exit Superheat (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Superheat in Individual Three Circuits (°C)</td>
</tr>
<tr>
<td></td>
<td>1300</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>1700</td>
<td>5.6/5.6/5.6</td>
</tr>
<tr>
<td>1</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>3</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>
Experimental Setup

(1) Refrigerant Flow Loop
(2) Water Flow Loop
(3) Air Flow Loop

- Mass flow meter
- Filter drier
- Chiller
- Variable speed compressor
- Liquid-cooled subcooler
- Water-Cooled Shell and Tube Condenser
- Test evaporator
- Turbine flow meter
- Needle valve
- Pressure regulator
- Flow straightener
- Flow sensor
- Thermocouple grid
- Dew point sensor
- Thermocouple grid
- Blower
Experimental Setup
Measurement Uncertainties
(95 % confidence level)

Evaporator capacities: within ± 5 %
All air-side and refrigerant-side capacities were within 5 %.

Return bend temperatures: ± 0.5 ºC
Thermocouples were
- calibrated with the data acquisition system
- placed on return bends using a conductive paste and copper tape, attached with plastic “zip” ties
- thermally isolated from air using a foam insulating tape.
Return Bend Temperatures
HX-wavy, overall superheat 5.6 °C

Individual superheats: 5.6/5.6/5.6 °C

Test 1

Individual superheats: ?/16.7/16.7 °C

Test 3
Return Bend Temperatures

Uniform superheat: 5.6 °C,  Test 1
Return Bend Temperatures
Uniform superheat: 16.7 °C, Test 2

HX-slit

HX-slit-cut
Capacity: HX-slit and HX-slit-cut

Relative Capacity

<table>
<thead>
<tr>
<th>Uniform superheat:</th>
<th>5.6 ºC</th>
<th>16.7 ºC</th>
<th>5.6 ºC</th>
<th>16.7 ºC</th>
</tr>
</thead>
<tbody>
<tr>
<td>HX-slit</td>
<td>-0.2 %</td>
<td></td>
<td>-4.2 %</td>
<td></td>
</tr>
<tr>
<td>HX-slit-cut</td>
<td>-9.3 %</td>
<td>-18.4 %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Airflow = 1300 m³/h

Airflow = 1700 m³/h
Discussion

What is the contribution of the tube longitudinal conduction to capacity degradation?

4.9 kW evaporator

Evaluated tube # 15 using charts by Ranganayakulu et al. (1996):

\[
\lambda = \frac{kA_w}{L C_{\text{min}}} = 0.0011 \quad \frac{C_{\text{min}}}{C_{\text{max}}} = 0.411 \quad \text{NTU} = 0.368
\]

\[
\tau = \frac{\varepsilon_{\text{NC}} - \varepsilon_{\text{WC}}}{\varepsilon_{\text{NC}}} = 0.0005 \quad \varepsilon_{\text{NC}} = 0.29
\]
Capacity: Tests versus Simulations

EVAP-COND does not account for longitudinal heat conduction

[Graph showing capacity (kW) vs. uniform evaporator superheat (°C) for two different airflows: 1700 m³/h and 1300 m³/h.]
Capacity: Tests versus Simulations

EVAP-COND does not account for longitudinal heat conduction
(\(Q_{\text{fin}}\))_{i,j} \approx \frac{Wt_f k_f}{L} (T_{w,i} - T_{w,j})
Tube-to-Tube Heat Transfer

\[(Q_{\text{fin}})_{i,j} \approx \frac{Wt_f k_f}{L} (T_{w,i} - T_{w,j})\]
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\[(Q_{\text{fin}})_{i,j} \approx \frac{W t_f k_f}{L} (T_{w,i} - T_{w,j})\]
Capacity: Tests versus Simulations

△ □  Experiment

△ □  Simulations without internal heat transfer

Air flow rate: 1300 m³/h

Air flow rate: 1700 m³/h
Capacity: Tests versus Simulations

- Experiment
- Simulations without internal heat transfer
- Simulations with internal heat transfer

Air flow rate: 1300 m³/h

Air flow rate: 1700 m³/h
Capacity: Tests versus Simulations

- **Experiment**
- **Simulations without internal heat transfer**
- **Simulations with internal heat transfer**

Graphs showing capacity (kW) versus uniform evaporator superheat (°C) for air flow rates of 1300 and 1700 m³/h.
Conclusions

• Capacity measurements on HX-slit and HX-slit-cut evaporators are
  - very similar for 5.6 °C refrigerant exit superheat
  - different by as much as 18.4 % for 16.7 °C refrigerant exit superheat

• Air flow rate affects the difference in capacity between the HX-slit and HX-slit-cut

• Capacity measurements, pattern of measured return bend temperatures, and theoretical analysis indicate tube-to-tube heat transfer as the cause of capacity degradation

• It is desirable to account for tube-to-tube heat transfer in heat exchangers in which large differences in tube temperatures exist