Principles of Refrigerant Circuit Optimization in Single Row Microchannel Condensers

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Introduction

- MCHX condensers were first introduced in the automotive HVAC market more than 20 years back.
- HVAC&R OEMs have followed their lead in using MCHX condensers in residential and commercial cooling and heat pump applications.
- These residential/commercial applications began less than a decade back and their number has been increasing steadily.
MCHX Condenser: Basic construction
MCHX Building Blocks
<table>
<thead>
<tr>
<th>MCHX</th>
<th>RTPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>• All-Al construction</td>
<td>• Cu or Al round tubes with Al fins</td>
</tr>
<tr>
<td>• Flat tubes with many small ports</td>
<td>• Round tubes with various internal enhancements</td>
</tr>
<tr>
<td>• All-brazed construction</td>
<td>• Mechanically expanded tubes</td>
</tr>
</tbody>
</table>
MCHX benefits

- Equal or better heat duty and about 65% lower refrigerant ΔP. (Park and Hrnjak, 2008)
- Up to 10% lower refrigerant charge, due to smaller MCHX internal volume. (Park and Hrnjak, 2008)
- Compact design (about 2 to 3 times higher surface area-to-volume ratio). (Garimella, 2003)
- Hence, opportunities for weight and cost reduction.
- However, to achieve the best possible thermal performance, *it is essential to select the right refrigerant circuiting arrangement.*
Circuit optimization: background

- Complex, two-phase flows occur in MCHX condensers.
- Validated software that can accurately predict their performance is a very powerful and appropriate tool for designing the correct pass arrangement in MCHX condensers.
- These tools enable engineers to save significant time and expense, by minimizing the use of expensive test benches.
Circuit optimization: background

- Literature review reveals that an in-depth investigation into the trends and principles governing the selection of the appropriate pass arrangement for MCHX condensers has not been conducted.
- The influence of MCHX condenser tube length on the optimal pass arrangement has also not been addressed.
- A question commonly facing thermal system designers is the following:
Circuit optimization: background

- for a given MCHX condenser tube and louvered fin design,
- fixed number of tubes,
- pre-defined air velocity, refrigerant flow and operating conditions,
- should a 2-pass, 3-pass, or a 4-pass circuit arrangement be preferred?
- for the preferred arrangement, how should the microchannel tubes be proportioned among the various passes?
Circuit optimization: background

- Normally, an extensive experimental effort combined with simulation would be necessary to answer this question satisfactorily,
- which necessarily involves significant expenditure of time and resources.
- Here, the capabilities of CoilDesigner have been applied to explore the answers to these questions.
# MCHX condenser circuit optimization matrix

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube Length (m)</td>
<td>1.50 – 2.25</td>
</tr>
<tr>
<td>Total number of tubes</td>
<td>64</td>
</tr>
<tr>
<td>Tube depth, $D_t$ (m)</td>
<td>0.0255</td>
</tr>
<tr>
<td>Tube thickness, $t_t$ (m)</td>
<td>0.0021</td>
</tr>
<tr>
<td>Port Height $x$ Port Width, $H_p \times W_p$ (m x m)</td>
<td>0.0015 x 0.0015</td>
</tr>
<tr>
<td>Number of ports per tube</td>
<td>14</td>
</tr>
<tr>
<td>Number of passes</td>
<td>2, 3, and 4</td>
</tr>
<tr>
<td>Fin density, (fins per inch)</td>
<td>20</td>
</tr>
<tr>
<td>Louver length, $L_l$ (m)</td>
<td>0.00555</td>
</tr>
<tr>
<td>Louver angle, $\theta$ (deg.)</td>
<td>30</td>
</tr>
<tr>
<td>Louver pitch, $P_l$ (m)</td>
<td>0.0010</td>
</tr>
<tr>
<td>Fin height (m)</td>
<td>0.00590</td>
</tr>
<tr>
<td>Air face velocity (m/s)</td>
<td>2.0 m/s</td>
</tr>
<tr>
<td>Inlet air temperature ($^\circ$C)</td>
<td>35</td>
</tr>
<tr>
<td>R-410A inlet temperature ($^\circ$C)</td>
<td>45</td>
</tr>
<tr>
<td>R-410A inlet superheat ($^\circ$C)</td>
<td>20</td>
</tr>
<tr>
<td>R-410A mass flow rate (kg/s)</td>
<td>0.1000</td>
</tr>
</tbody>
</table>
## Correlations used

<table>
<thead>
<tr>
<th></th>
<th>Air side</th>
<th>Refrigerant side</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Vapor</td>
<td>Two-Phase</td>
<td>Liquid</td>
<td></td>
</tr>
<tr>
<td>correlation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>correlation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Assumptions

1. Uniform air flow across the coil face.
2. Uniform refrigerant mass flow and vapor quality distribution among the tubes of any pass, as well as among the ports of any tube.
Types of pass arrangements

- Contracting pass arrangement

- Expanding pass arrangement

All possible contracting and expanding pass arrangements were automatically generated for the 2-, 3-, and 4-pass circuits using a self-developed code.

- 52 2-pass, 398 3-pass, and 1,064 4-pass arrangements were simulated using the parametric pass arrangement analysis capability of CoilDesigner.
Q vs. $\Delta P_r$, 1.50 m tube length

$0.16 < x_{out} < 0.30$
$Q$ vs. $\Delta P_r$, 1.75 m tube length

$0.01 < x_{out} < 0.20$
Q vs. $\Delta P_r$, 2.00 m tube length
Q vs. $\Delta P_r$, 2.25 m tube length
1. Within a given pass arrangement configuration, designs that result in a lower refrigerant $\Delta P$ lead to a higher heat duty.

- as the refrigerant $\Delta P$ through the condenser decreases, the average $\Delta T$ between the refrigerant and the air increases.

- Since it is this $\Delta T$ that drives the heat transfer, these trends are reasonable.
Conclusions

2. The 2-, 3-, and 4-pass expanding circuit arrangements span a much wider range of refrigerant $\Delta P$, and hence, heat duties, in comparison with the contracting pass arrangements.

● expanding pass configurations display a greater sensitivity to thermal performance changes than contracting pass configurations.
Conclusions

3. Practically most important, contracting pass configurations with the same number of passes yield comparable (in very few cases) or (mostly) higher heat duty for comparable refrigerant $\Delta P$ compared to the expanding pass configurations.
### Design guidelines

<table>
<thead>
<tr>
<th>Tube length (m)</th>
<th>Pass configuration</th>
<th>Pass arrangement (% tubes) for maximum heat duty</th>
<th>Maximum heat duty [W]</th>
<th>Corresponding refrigerant ΔP (kPa)</th>
<th>Pass arrangement for minimum heat duty</th>
<th>Minimum heat duty [W]</th>
<th>Corresponding refrigerant ΔP (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>4 contracting</td>
<td>38/31/20/11</td>
<td>19358</td>
<td>17.7</td>
<td>73/9/9/9</td>
<td>19057</td>
<td>43.1</td>
</tr>
<tr>
<td></td>
<td>3 contracting</td>
<td>42/41/17</td>
<td>19274</td>
<td>7.8</td>
<td>80/10/10</td>
<td>18944</td>
<td>23.3</td>
</tr>
<tr>
<td></td>
<td>4 expanding</td>
<td>23/25/25/27</td>
<td>19264</td>
<td>25.8</td>
<td>9/9/9/73</td>
<td>16709</td>
<td>140.7</td>
</tr>
<tr>
<td></td>
<td>3 expanding</td>
<td>32/34/34</td>
<td>19027</td>
<td>11.9</td>
<td>10/10/80</td>
<td>17649</td>
<td>87.5</td>
</tr>
<tr>
<td></td>
<td>2 contracting</td>
<td>67/33</td>
<td>18981</td>
<td>3.5</td>
<td>63/37</td>
<td>18700</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>2 expanding</td>
<td>47/53</td>
<td>18748</td>
<td>3.7</td>
<td>9/91</td>
<td>18309</td>
<td>37.5</td>
</tr>
</tbody>
</table>
4. Guidelines for selecting the optimal pass arrangement for MCHX condensers.

- The 38%/31%/20%/11%, 42%/41%/17%, 23%/25%/25%/27%, 32%/34%/34%, 67%/33%, and 47%/53% configurations are the best performing pass arrangements, in that order.

- Between the best and the worst pass arrangements, the heat duty differs by more than 3%.
Conclusions

- An even distribution of tubes among the four passes of an expanding arrangement tends to maximize its heat duty.
  - However, the $\Delta P$ for such a configuration may be excessively large for practical applications, and hence, is not preferred.

- An uneven 4-pass expanding pass arrangement will cause about 13% penalty in heat duty compared to the best pass arrangement in the same class.
  - due to non-optimal utilization of heat transfer surface area, and excessive vapor refrigerant pressure drop in the first and second passes.
Conclusions

- The 3-pass contracting pass arrangement may also be used with minimal loss of heat duty compared to the best contracting 4-pass circuit arrangement.

- However, in practice, considerations of inlet and outlet plumbing often dictate the choice of the pass arrangement.

- In real cases, the 4-pass contracting arrangement will be preferred, since, in addition to its superior heat duty and moderate refrigerant $\Delta P$, its inlet and outlet pipes will be on the same side of the coil, offering convenience and compact packaging.
Conclusions

- 2-pass contracting and expanding configurations will lead to up to 3% loss in heat duty, and hence, should not be used.

- Overall, the 38%/31%/20%/11%, configuration, with its optimal heat duty-refrigerant $\Delta P$ characteristics will be the preferred pass arrangement.
Future work

- In future development of this work, we plan to explore
  - the influence of air side and refrigerant side flow maldistribution on the optimal circuit arrangements.
  - fixed outlet subcooling instead of fixed refrigerant mass flow rate.
BACKUP
CoilDesigner™, version 3.9.20141.203 (Jiang et al., 2006), incorporates a network strategy for conveniently designing and analyzing coil circuiting.

- A segment-by-segment approach has been implemented within each tube,
- allows non-uniform air flow distribution across the coil face.
- The model captures the significant change of refrigerant properties between vapor, two-phase, and liquid regimes.
The software also provides a user-friendly graphical interface, and offers the user the choice of a wide variety of working fluids and heat transfer and pressure drop correlations.
CoilDesigner validation

● Schwentker et al. (2005) verified the prediction of CoilDesigner against experimentally measured data for eight MCHX condensers with R-134a as the working fluid.

● CoilDesigner was able to predict the condenser heat load within 2.25% for 80% of 35 experimental data points.

● The average error, average absolute error, and maximum error in the heat load prediction were 0.84%, 1.6%, and 4.6%, respectively.
In one of the most comprehensive MCHX condenser and gas cooler performance validation efforts, Huang et al. (2014) validated CoilDesigner against 227 experimental data points for:

- eight different working fluids including R410A
- eighteen MCHX heat exchanger geometries from
- seven different sources of data.

The average absolute deviation between the predicted and measured heat duty and the refrigerant pressure drop was found to be 2.7% and 28%, respectively.
Assumptions

1. Uniform air flow across the coil face.

   - Air flow non-uniformities in practical applications arise from condenser-fan configuration, duct design, and other similar factors which are beyond the scope of this work.
Assumptions

2. Uniform refrigerant mass flow and vapor quality distribution among the tubes of any pass, as well as among the ports of any tube.

- In actual MCHX designs, header $\Delta P$ will be influenced by
- header diameter and length,
- turning losses, inlet/exit losses, and the offsetting effects of friction and deceleration, as refrigerant enters each successive tube in the circuit and the mass flux in the remainder of the header decreases.
Assumptions

- Refrigerant headers can be designed such that flow maldistribution could be minimized in condensers having exterior package dimensions typical of those in use today.

- Here, we assumed that the refrigerant mass flux in the headers is neither too low (tends to cause gravity-induced liquid–vapor stratification), nor too high (since this would cause variable pressure drop across the tubes of a given pass).