Summary of Research on Shape Optimized Air-to-Refrigerant Heat Exchangers

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Introduction

• **Energy End Use**
  • Residential & commercial buildings accounted for ~40% of total U.S. energy consumption in 2021\(^1\)
  • HVAC&R accounts for ~55% of residential building & ~40% of commercial building energy use

• **System Energy Efficiency Standards**
  • IEA predicts that global stock of building A/C systems will increase to 5.6 billion by 2050\(^2\)
  • Starting in 2015, residential A/C & heat pump systems must have Seasonal Energy Efficiency Ratio ≥ 14.0\(^3\)

• **Refrigerants**
  • Kigali Amendment calls for significant reduction in HFC usage\(^4\), increased demand for systems utilizing HCs, HFOs, & other natural refrigerants (e.g., CO\(_2\), NH\(_3\), H\(_2\)O, C\(_3\)H\(_8\), etc.)
  • Reducing refrigerant charge can lead to lower leakage
    • Less environmental impact (Ozone depletion, global warming, etc.)
Air-To-Refrigerant Heat Exchangers

• Air-to-refrigerant heat exchangers (HXs) are critical HVAC&R components
  • Compact HXs have potential to increase energy efficiency & reduce environmental impact
    • Doubling condenser heat transfer coefficient can reduce cycle energy consumption by ~10-15%[2]
    • Finless HXs with small diameter tubes (<5.0mm) are more compact, utilize less refrigerant, and can outperform finned HXs[1-8]
  • HX Modeling and Optimization[9]
    • Investigate novel HX geometries prior to prototyping & experimentation
• Enabling Technologies
  • Computational: CFD / FEA, Multi-Objective Genetic Algorithm (MOGA), Approximation-Assisted Optimization (AAO)
  • Manufacturing techniques: Additive Manufacturing (AM), Hybrid manufacturing

Microchannel HX
Tube-fin A-Coil HX
Shape-optimized HX[5]
Bifurcating bare tube HX[6]
Challenges in Heat Exchanger Commercialization

- **Novelty challenges**
  - Novel designs must be at least 20% better with significant reductions in refrigerant charge
  - Novel design tools require expertise and significant time investment in advanced computing and fluid & structural analyses
  - Lack of heat transfer and fluid flow fundamentals & correlations for novel tube designs

- **Manufacturing challenges**
  - Component availability
  - Joining / manufacturing techniques
  - Product qualification

- **Operational challenges**
  - Flow maldistribution
  - Fouling and wetting
  - Noise and vibration
Goal: Next Generation Heat Exchangers

Investigations

• Shape optimized air-to-refrigerant heat exchangers
• Compare optimal designs for various current and lower-GWP refrigerants for residential AC systems
HX Optimization Framework

Concept Heat Exchanger — Parameterize Geometry — Manufacturing Constraints — Optimization - MOGA

- Current Technology
- Manufacturable Designs
- Best Designs

Optimized HX

Air ΔP, Volume, Mat’l, Heat Load, Max Stress, …

PPFSA = Parallel Parameterized Fluid & Structural Analysis | MOGA = Multi-Objective Genetic Algorithm
R410A / R32 / R454B Condenser

Background:
- Application: Nominal 5.28 kW air-to-R410A condenser
- Refrigerants: R410A, R32, R454B
- Baseline HX\(^{[11]}\): Tube-fin HX; Cu Tube + Al Fin
- Optimized Tube Shape: NTHX1\(^{[9]}\)
- Two fluid passes (60% / 40%)

\[
\begin{align*}
\min \Delta P_{\text{air}} \text{, } \min V_{\text{HX}} \\
\text{s.t.} \\
\dot{Q}_{\text{BL}} \leq \dot{Q} \leq 1.1 \cdot \dot{Q}_{\text{BL}} \\
\Delta P_{\text{air}} \leq 2.0 \cdot \Delta P_{\text{air,BL}} \\
\Delta P_{\text{Ref}} \leq \Delta P_{\text{Ref,BL}} \\
V_{\text{HX}} \leq 0.8 \cdot V_{\text{HX,BL}} \\
FA \leq FA_{\text{BL}} \\
0.5 \leq \frac{H_{\text{HX}}}{L_{\text{HX}}} \leq 2.0
\end{align*}
\]

Key Findings:
- Middle R32 design: 45%↓ \(V_{\text{HX}}\); 37%↓ \(\Delta P_{\text{air}}\); 24%↓ FA; 0%↓ \(V_{\text{mat}}\); 38%↓ \(V_{\text{int}}\); 51%↓ \(M_{\text{ref}}\)
- Middle R454B design: 41%↓ \(V_{\text{HX}}\); 49%↓ \(\Delta P_{\text{air}}\); 17%↓ FA; 6%↑ \(V_{\text{mat}}\); 33%↓ \(V_{\text{int}}\); 44%↓ \(M_{\text{ref}}\)

Project Details: Internal Project.

R410A / R32 / R454B Condenser Design Insights

- The optimizer tends towards very similar airside tube layouts regardless of refrigerant choice
  - All HXs have similar tube pitches and number of tube banks
    - All R410A & R454B designs have 4 tube banks
    - Most R32 HXs have 5 tube banks (remainder have 4)
  - Fixed inlet air state & similar airside tube layout results in similar airside performance
    - Best airside performance is independent of refrigerant choice

- On average, the R32 HXs had the fewest tubes per bank
  - Likely results from R32 HXs having more tube banks
    - Tubes essentially moved from the face area to the depth-wise direction
  - Fixed air volume flow rate & smaller face area results in higher inlet air velocity
    - Can lead to undesirable fan noise / tube aeroacoustics challenges

- Additional performance improvement may be achieved by considering the (strictly-converging) pass configuration as a design variable
Air-to-R290 Condenser

Background:
- Application: Nominal 2.4 kW air-to-R290 condenser
- Baseline HX\cite{8}: Tube-fin HX, 5.0 mm OD copper tubes
- Optimized Tube Shape: NTHX1\cite{9}
- Two fluid passes

\[
\begin{align*}
\text{min } & \Delta P_{\text{air}}; \text{min } V_{\text{HX}} \\
\text{s.t. } & \dot{Q}_{\text{BL}} \leq \dot{Q} \leq 1.1 \cdot \dot{Q}_{\text{BL}} \\
& \Delta P_{\text{air}} \leq 2.0 \cdot \Delta P_{\text{air,BL}} \\
& \Delta P_{\text{Ref}} \leq \Delta P_{\text{Ref,BL}} \\
& V_{\text{HX}} \leq 0.8 \cdot V_{\text{HX,BL}} \\
& FA \leq FA_{\text{BL}} \\
& 0.5 \leq \frac{H_{\text{HX}}}{L_{\text{HX}}} \leq 2.0
\end{align*}
\]

Key Findings:
- Max $V_{\text{HX}}$ reduction: 69%↓ $V_{\text{HX}}$; 0%↓ $\Delta P_{\text{air}}$; 14%↓ FA;
  30%↓ $V_{\text{mat}}$; 49%↓ $V_{\text{int}}$; 48%↓ $M_{\text{ref}}$
- Max $\Delta P_{\text{air}}$ reduction: 44%↓ $V_{\text{HX}}$; 43%↓ $\Delta P_{\text{air}}$; 0%↓ FA;
  13%↓ $V_{\text{mat}}$; 37%↓ $V_{\text{int}}$; 38%↓ $M_{\text{ref}}$

Project Details: Internal Project.
### Summary of Completed HX Optimization Studies

<table>
<thead>
<tr>
<th>Optimization Study</th>
<th>Application</th>
<th>Tube Shape</th>
<th>Best Case Improvement (Air ΔP)</th>
<th>Best Case Improvement (HX Core Volume)</th>
<th>Best Case Improvement (Face Area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R290 Condenser</td>
<td>Nominal 2.4 kW A/C system</td>
<td>NTHX1</td>
<td>43%↓</td>
<td>69%↓</td>
<td>14%↓</td>
</tr>
<tr>
<td>R410A Condenser (A)</td>
<td>Nominal 5.28 kW A/C system</td>
<td>NTHX1</td>
<td>74%↓</td>
<td>49%↓</td>
<td>39%↓</td>
</tr>
<tr>
<td>R410A Condenser (B)</td>
<td>Nominal 5.28 kW A/C system</td>
<td>Full shape opt.</td>
<td>79%↓</td>
<td>69%↓</td>
<td>24%↓</td>
</tr>
<tr>
<td>R410a Condenser (C)</td>
<td>Nominal 5.28 kW A/C system</td>
<td>NTHX1</td>
<td>62%↓</td>
<td>53%↓</td>
<td>34%↓</td>
</tr>
<tr>
<td>R32 Condenser</td>
<td>Nominal 5.28 kW A/C system</td>
<td>NTHX1</td>
<td>47%↓</td>
<td>57%↓</td>
<td>50%↓</td>
</tr>
<tr>
<td>R454B Condenser</td>
<td>Nominal 5.28 kW A/C system</td>
<td>NTHX1</td>
<td>63%↓</td>
<td>47%↓</td>
<td>34%↓</td>
</tr>
<tr>
<td>R410A Evaporator</td>
<td>Nominal 5.28 kW A/C system</td>
<td>NTHX1</td>
<td>82%</td>
<td>68%↓</td>
<td>15%↓</td>
</tr>
<tr>
<td>R410A Evaporator</td>
<td>Heat pump system</td>
<td>NTHX1</td>
<td>62%↓</td>
<td>N/A</td>
<td>40%↓</td>
</tr>
<tr>
<td>R410A Evaporator</td>
<td>Heat pump system</td>
<td>Full shape opt.</td>
<td>77%↓</td>
<td>N/A</td>
<td>37%↓</td>
</tr>
<tr>
<td>sCO₂ Gas Cooler (A)</td>
<td>FTHX Baseline</td>
<td>Full shape opt.</td>
<td>N/A</td>
<td>74%↓</td>
<td>7%↓</td>
</tr>
<tr>
<td>sCO₂ Gas Cooler (B)</td>
<td>MCHX Baseline</td>
<td>Full shape opt.</td>
<td>79%↓</td>
<td>85%↓</td>
<td>133%↑</td>
</tr>
</tbody>
</table>
Prototype C1 Experimental Validation[^15]

### Dry Evaporator Conditions[^16]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid</td>
<td>R410A</td>
</tr>
<tr>
<td>MFR</td>
<td>5.0 – 9.5 g/s</td>
</tr>
<tr>
<td>Evaporation Temp.</td>
<td>10°C</td>
</tr>
<tr>
<td>Inlet Quality [-]</td>
<td>0.20</td>
</tr>
<tr>
<td>Superheat</td>
<td>&gt; 8 K</td>
</tr>
<tr>
<td>Air Inlet Temp.</td>
<td>26.7°C</td>
</tr>
<tr>
<td>Air Inlet RH</td>
<td>10%</td>
</tr>
<tr>
<td>Air Inlet Velocity</td>
<td>1.0 – 2.5 m/s</td>
</tr>
<tr>
<td>Airside ΔP</td>
<td>6.3 – 24.6 Pa</td>
</tr>
<tr>
<td>Nominal Capacity</td>
<td>1250 – 2000 W</td>
</tr>
</tbody>
</table>

### Wet Evaporator Conditions[^16]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFR</td>
<td>7.0 – 11.5 g/s</td>
</tr>
<tr>
<td>Evaporation Temp.</td>
<td>10°C</td>
</tr>
<tr>
<td>Inlet Quality [-]</td>
<td>0.20</td>
</tr>
<tr>
<td>Superheat</td>
<td>&gt; 8 K</td>
</tr>
<tr>
<td>Air Inlet Temp.</td>
<td>26.7°C</td>
</tr>
<tr>
<td>Air Inlet RH</td>
<td>52%</td>
</tr>
<tr>
<td>Air Inlet Velocity</td>
<td>1.0 – 2.5 m/s</td>
</tr>
<tr>
<td>Airside ΔP</td>
<td>6.3 – 24.6 Pa</td>
</tr>
<tr>
<td>Nominal Capacity</td>
<td>1250 – 2000 W</td>
</tr>
<tr>
<td>Sensible Heat Ratio</td>
<td>0.70 – 0.76</td>
</tr>
</tbody>
</table>
Conclusion

• Developed an HX optimization framework featuring multi-scale & multi-physics analyses for the design of high performance, reduced charge air-to-refrigerant HXs with novel, non-round, shape-optimized tube shapes
  • Framework successfully exercised for radiator, condenser, evaporator, & gas cooler applications
  • New designs can be 20% smaller, 20% lighter, 15% more effective, & exhibit 25% reduction in internal volume compared to state-of-the-art baseline HXs

• Manufactured prototype tubes & HXs using conventional & additive techniques
  • Two (2) additively-manufactured prototype HXs (Material: Titanium)
  • Five (5) conventionally-manufactured prototype non-round tubes (Materials: Aluminum, Brass, & Copper)
  • Eight (8) conventionally-manufactured prototype HXs featuring (Al and Cu tubes)

• Conducted extensive experimental testing in a standardized wind-tunnel test facility to validate prototype performance and design framework efficacy
  • Independent validations at external labs
  • Modeled HX performance showed good agreement with prototype experimental performance
  • Tube blockages and wetting during dehumidification can have significant impact on HX performance
Thank you!

Questions / Feedback:
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References


