Potential Benefits of Shape Optimized Air-to-Refrigerant Heat Exchangers for New Lower-GWP Refrigerants

Session: Heat Pumping Technologies for Residential, Commercial, and Industrial Applications
IEA HPT TCP: Annex 54 Heat Pump Systems with Low GWP Refrigerants

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• Next Gen HX Project Team (since 2005)
  • Team at University of Maryland
  • Industry Partners (OEMs, suppliers, AM expertise)
• Collaborators
  • Oak Ridge National Laboratory: Computational heat transfer
  • Heat Transfer Technologies: Novel mfg. process development
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• Conclusions
Motivation

- HVAC&R consumes 67% of US building energy and 14% of total US energy usage\(^1\)
  - AC, Heat Pumps, DHW, Refrigeration…
- IEA Estimate: 2B Air-conditioners today, 5B+ by 2050
- Equipment efficiency improvement is a key enabler for decarbonization of buildings
- Heat eXchangers (HX) are key components in thermal systems
  - Account for 20%+ losses
  - Generally 2 or more in each system
  - Cross-cutting technology across domains
- Improved HXs lead to:
  - Lower refrigerant charge, environmental impact
  - Size/weight reduction, lower costs
  - Lower energy consumption, emissions

\(^1\) Reference: [IEA Estimate]
Air-to-Refrigerant Heat Exchangers

- Tube-Fin (Dh: 4-12+ mm), Microchannels (Dh: 0.6-3mm)
- Extended Surfaces
  - Plain/enhanced fins
  - Bare tubes
- Refrigerant side
  - Fluid Classes: R410A, NH3, CO2, Water, HCs
  - Mass flux: 100 – 1500 kg/s.m²
  - HTC: 500-10,000+ W/m²K
- Air side
  - Face velocity: 0 – 5 m/s
  - HTC: 10 – 150+ W/m²K
- Air-side is the dominant resistance!
Goal: Next Generation Heat Exchangers

Performance Targets
• 20% Smaller, 20% Lighter, 20% more effective; 25% reduction in charge
• Manufacturable within 5 years, with “minimal” additional costs
Leverage advances in CFD, Machine Learning, etc.
Other Challenges

• Novelty
  • Novel designs must be at least 20% better with significant reductions in refrigerant charge
  • Lack of thermohydraulic characterization and reliable design tools
  • Design modularity

• Manufacturing aspects
  • Component availability
  • Joining / manufacturing techniques
  • Process scalability

• Operational aspects
  • Fouling, Wetting, and Frosting
  • Flow maldistribution
  • Noise and vibration, “abuse”

• Integration of Storage
• Costs / ROI / Markets & Regulations
HX Optimization Framework\textsuperscript{[1,4,5]}

- **Concept Heat Exchanger**
- **Optimized HX**
- **Parameterize Geometry**
- **ML Models**
  - DOE
  - PPFSA
- **Reusable Models**
  - Optimizer
  - New Design
  - HX FV Modeling & Simulation
  - Air $\Delta P$, Volume, Matl', Heat Load, Max Stress, ...

- **Current Technology**
- **Manufacturable Designs**
- **Best Designs**
- **HX Volume**
- **Air $\Delta P$**

PPFSA = Parallel Parameterized Fluid & Structural Analysis; MOGA = Multi-Objective Genetic Algorithm; FV: Finite Volume

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\textsuperscript{IEA Annex-54 Update at Chillventa 2022}

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Path configuration and system level optimization can be conducted simultaneously or sequentially.
Framework Details

• Shape representation
  • NURBS
• Design of Experiments
  • All at once, sequential/adaptive
• PPFSA
  • Parallel Parameterized Fluids & Structural Analysis
  • Analyze geometries generated on the fly, with simultaneous shape & topology change
  • Automated GCI Analysis
• Machine Learning Methods
  • Kriging/NN/SVM; Typical MAS: 90%+
  • (Nested) MOGAs
    • HX Design Optimization
    • Custom codes for flow path optimization
• Systems/buildings analysis

MAS: Metamodel Acceptability Score, based on a random sample
MOGA: Multi-Objective Genetic Algorithms
GCI: Grid Convergence Index (ASME Standard VV 20)
Lower-GWP Nominal 5.28 kW Condenser Optimization

- **Optimization Problem Formulation**
  - Cross-flow HX with fixed inlet conditions\[^{30}\]
  - Fixed, non-round, conventionally-manufacturable NTHX1 tube shape\[^{6}\]
  - Baseline refrigerant: R410A
  - Lower-GWP alternatives: R32, R454B

\[
\begin{align*}
\text{min} \Delta P_{air}, V_{HX} \\
\text{s.t.} \quad \Delta P_{air} \leq 2.0 \cdot \Delta P_{air,BL} \quad V_{HX} \leq V_{HX,BL} \\
0.5 \leq \frac{H_{HX}}{L_{HX}} \leq 2.0 \quad A_f \leq A_{f,BL} \\
\Delta T_{SC,BL} -1.0 \leq \Delta T_{SC} \leq \Delta T_{SC,BL}
\end{align*}
\]

\[^{*}\text{Cu tube showed no deformation up to 20 MPa internal pressure}\[^{30}\]
\[^{**}\text{Al tube showed no deformation up to 7.5 MPa internal pressure}\[^{30}\]

<table>
<thead>
<tr>
<th>Variables</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube pitches (HS, VS)</td>
<td>Air inlet state (T, RH, ( \dot{V} ))</td>
</tr>
<tr>
<td># Tube Banks</td>
<td>Fluid inlet state (T, P, ( \dot{m} ))</td>
</tr>
<tr>
<td># Tubes per Bank</td>
<td>NTHX1 tube shape</td>
</tr>
<tr>
<td>Inlet Air Velocity</td>
<td>Two fluid passes (60% / 40%)</td>
</tr>
</tbody>
</table>
### Optimal HX Design Comparison for each Refrigerant

#### HX-Level Performance Metrics

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Line Style</th>
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<tbody>
<tr>
<td>R410A (BL)</td>
<td>[baseline]</td>
</tr>
<tr>
<td>R410A (Opt)</td>
<td>[optimized]</td>
</tr>
<tr>
<td>R32</td>
<td>[R32]</td>
</tr>
<tr>
<td>R454B</td>
<td>[R454B]</td>
</tr>
</tbody>
</table>

#### HX Face Area Bounding Box

*Baseline HX is square[^30]*  
**Images to scale**
Prototyping

1.5TR-E-11B: 1.5TR Nominal capacity evaporator with 11 rows
Conventional Materials: Copper, Aluminum; Additive Materials: Titanium, Plastics

NTHX-1, Ti (2016)

Additively Manufactured

Baffle Location Based on Flow Path Optimization

Tube Representative Cross Section

Conventionally Manufactured

~250 mm
1.5TR-3B-001 (2019)

~370 mm
~520 mm
~500 mm

ENTHX1, Ti (2019)

~780 mm

~210 mm
1.5TR-C-4B-002 (x2) (2021)

~500 mm
~470 mm

~480 mm
~780 mm
Experimental Validation

- Comprehensive validation across 11+ radiator, condenser, and evaporator prototypes\(^{[11-12]}\)
- Predictions within ±15% for capacity and pressure drop
- Successful independent lab validations
Prototype C1 Wet Evaporator Testing Water Bridging

Dry & Wet Conditions Airside Pressure Drop

- Wet Evap. Conditions
- Dry Evap Conditions

2.3x increase

Airside Pressure Drop [Pa]

Inlet Air Velocity [m/s]
Conclusions

• Advances in computational methods, computing hardware, and Machine Learning is transforming the way thermal systems are conceived, designed, optimized, and operated

• Systematic optimization required to optimize heat exchangers for different refrigerants and application – thus enabling the low-GWP transition

• Shape optimized flow channels have the potential to reduce size/weight of heat exchangers by 25%, and refrigerant charge by 30%

• (In general) Current modeling capabilities offer 15% accuracy – pretty good for novel designs

• Cost is still the primary consideration in introducing novel HX technologies to market
Progress Since Last Annex Update (Jun 2022)

• System level testing for performance validation
  • System donated by HVAC OEM Partner
  • Designed/optimized heat exchangers for system testing
  • Fabrication of heat exchangers in progress; lessons learned
  • Updated lab capabilities to instrument the test unit

• Modeling Updates
  • Final correlations for aero-acoustics/noise
  • Started comprehensive effort on modeling dehumidification characteristics for non-round shape-optimized tubes; promising initial results
  • Developing an automated tool to “generate” an equivalent optimal design for a given tube-fin or microchannel heat exchanger


3. ANSYS, Inc. (2018a) *Ansys® GAMBIT, Release 2.4.6, Fluent Release 19.3, Mechanical Release 18.0*


Questions?

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