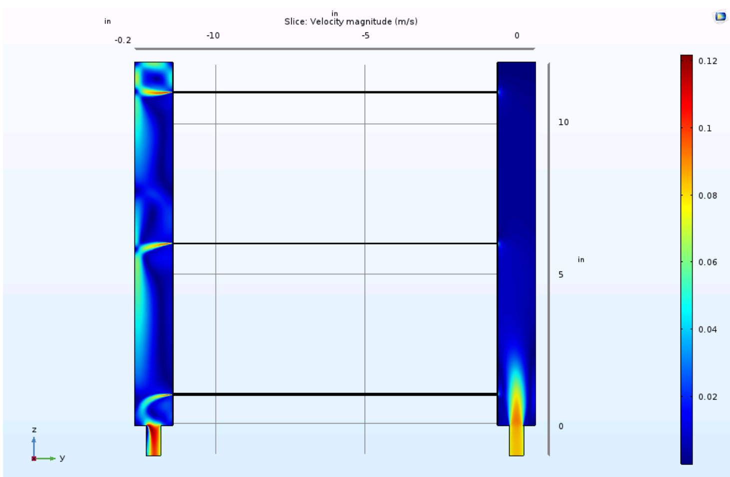
U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Integration of Piezoelectric Sensor-Actuators into Heat Exchanger Headers to Alleviate Flow Maldistribution in Real Time



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Project Summary

Timeline:

Start date: 10/01/2018

Planned end date: 09/30/2020

Key Milestones

1. Literature review, 12/31/2018 (complete)
2. Identification of refrigerant maldistribution indicators, 03/31/2019 (complete)
3. Heat exchanger (HX) flow distribution model, 06/30/2019 (on track)

Key Partners:

Multi-Scale Heat Transfer Laboratory, Worcester Polytechnic Institute (WPI)	Academic partner (subcontract) WPI

Budget:

Total Project $ to Date:

- DOE: $450k

Total Project $:

- DOE: $900k

Project Outcome:

- This project will use HX-integrated sensor-actuators to mitigate flow maldistribution in real time to improve the system's efficiency by up to 10%.
- Successful implementation in residential heating, ventilating, and air-conditioning (HVAC) HXs (for example) will have primary energy savings technical potential of 225 TBtu for the 2030 energy market in all climate zones.
- The project supports the 2030 Multi-Year Program Plan (MYPP) goal to develop cost-effective technologies capable of reducing a building's energy use per square foot by 45%, relative to 2010.
  - Aligns with strategy of funding early-stage R&D

Team

Oak Ridge National Laboratory | Building Technologies Research and Integration Center

Viral K. Patel, R&D Staff, Project PI
- Experimental development
- Thermodynamic system modeling
- Project management
- Research plan development

Ayyoub Momen, R&D Staff
- Wide range of ultrasonics expertise
- Two-phase flow simulation expertise

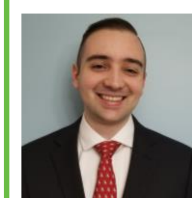
Kashif Nawaz, R&D Staff
- Heat exchanger design expertise
- Two-phase flow and boiling expertise

Ahmad Abu-Heiba, R&D Staff
- Heat pump system design expertise
- Sensors and data acquisition
- Controls expertise

Anthony Gehl, R&D Staff
- Experimental design
- Sensors and data acquisition
- Prototype fabrication expertise

WPI

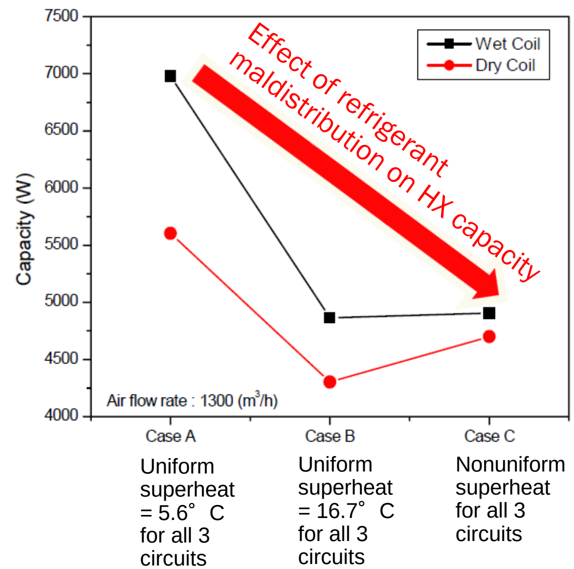
Jamal Yagoobi, Professor
- Two-phase flow expertise
- Electrically driven heat transport systems expertise



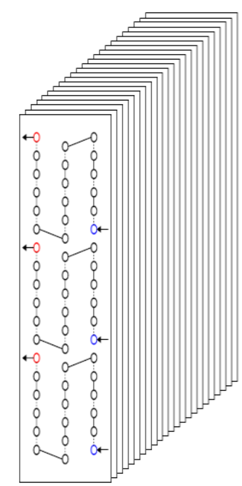
Nathaniel O'Connor, PhD Student
- Computational fluid dynamics simulation expertise
- Engineering system design and fabrication

Challenge

- **Maldistribution of refrigerant in heat exchangers is known to reduce their performance**
  - Nonuniform air-side and refrigerant-side flow leads to local high-temperature hot spots, increased refrigerant superheat, increased pressure drop, and increased compressor and blower work → *lower HX capacity and system coefficient of performance (COP)*
  - Air-conditioning, Heating & Refrigeration Institute (AHRI) five-year test data show estimated 70% of HXs underperform because of maldistribution
- **Current methods of addressing geometry-induced flow maldistribution in HXs involve a costly redesign process of headers and tubes**
  - These have limited impact for particular operating conditions
- **Few viable and cost-effective solutions exist for real-time mitigation of refrigerant maldistribution in HXs**

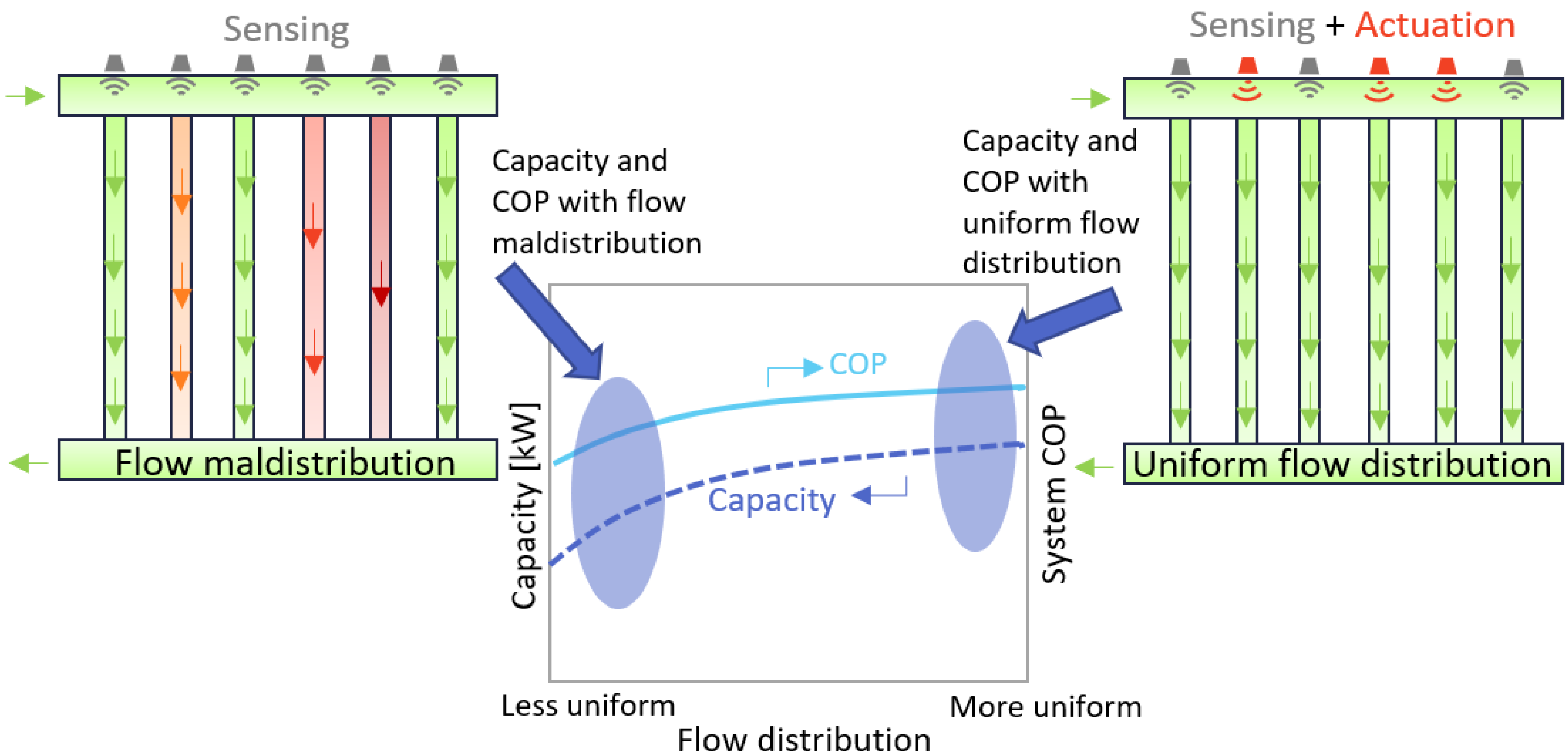


Choi et al. (2003)



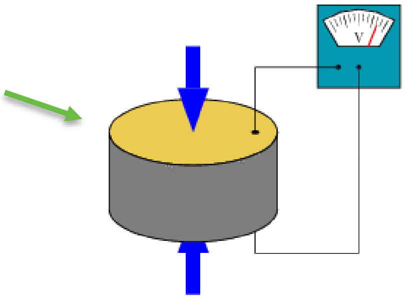
Proposed Solution

- In the proposed technology, piezoelectric sensor-actuators are *integrated directly into the heat exchanger headers* to simultaneously sense maldistribution and actuate the flow in *real time* to *compensate for refrigerant maldistribution*
- This provides an effective solution with real-time response capability and can potentially be retrofitted into existing heat exchanger designs



Proposed Solution

- Piezoelectrics are ubiquitous devices used in medical applications, nondestructive testing, ultrasonic cleaning, etc.
- They rely on direct and inverse piezoelectric effects
- They include both sensors and actuators:



Ultrasonic flow sensor

Piezo micropump

Piezo valve (www.festo.com)

- For this project, we will consider combining both sensors and actuators into a single, compact package for integration into an HX header
- Dual functionality might be achieved simply by adjusting the frequency
- Operation frequencies will be such that they will not introduce additional sources of vibration to affect HX or tube integrity

Approach

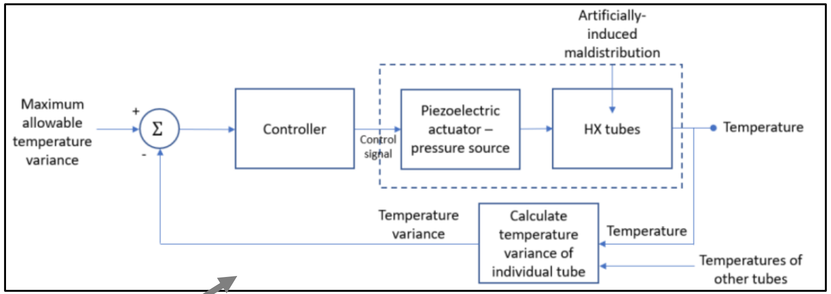
Year 1: HX flow distribution model

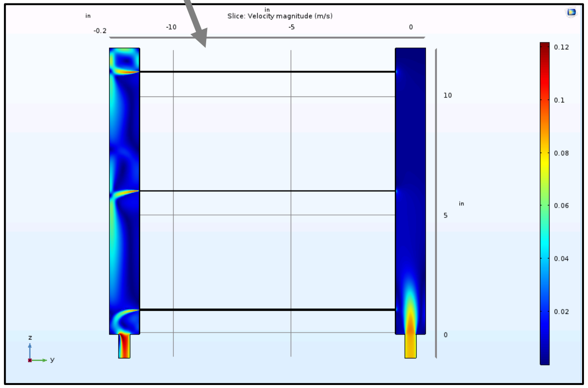
Single-phase flow-through header and parallel HX tubes—submodel

Two-phase flow-through parallel HX tubes—submodel

Piezoelectric actuation—submodel

Closed-loop feedback control—submodel





Year 2: Benchtop experimental setup

Detailed experimental measurements

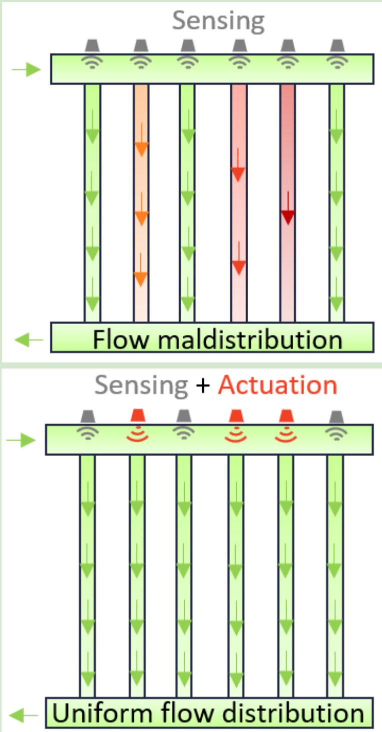
Transparent HX headers

Real-time flow visualization with piezoelectric actuation

Through a combination of modeling and experiments, demonstrate 15% increase in HX efficiency and project ≥10% increase in system efficiency

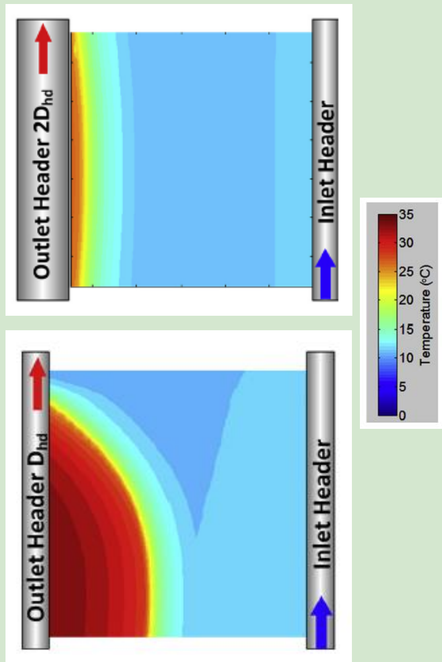
Advantages and Differentiation

Proposed technology



- ✓ Integration of piezos into HX headers is relatively simple with no moving parts
- ✓ Widely available piezoelectric technology has potential for lower cost
- ✓ Active technique
- ✓ Potentially compact solution incorporating sensing and actuation in one package

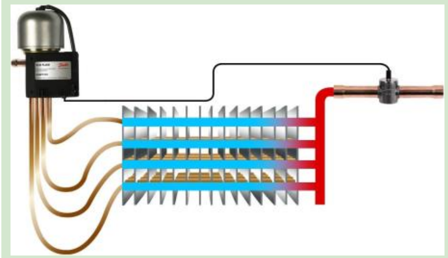
HX redesign approaches



Tuo & Hrnjak (2013)

- × Difficult optimization problem
- × Cost could be high
- × Passive technique that might only work for certain operating conditions
- × System might need to be oversized to accommodate worst case

Smart refrigerant distributor

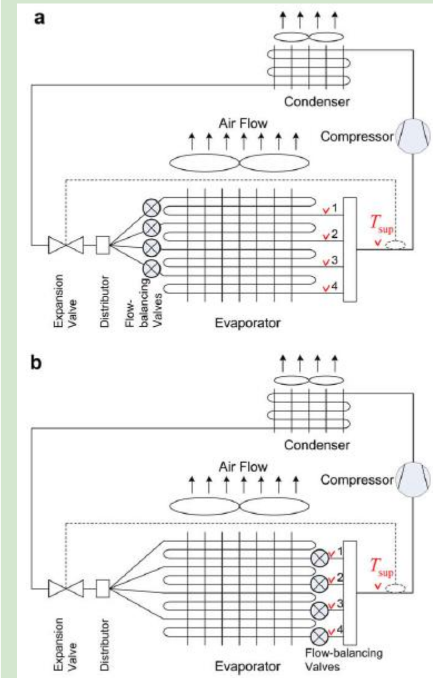


Misfeldt (2010)

Danfoss (2009)

- × Moving parts might affect reliability
- × Cost might be high
- × Not made for microchannel HXs
- ✓ Active technique

Individual circuit control



Kim et al. (2009)

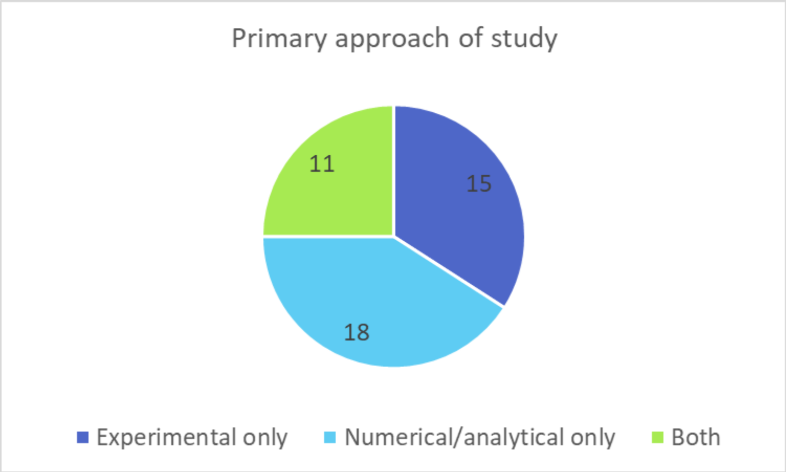
- × Individual electromechanical valves per tube—system complexity is high
- × Moving parts might affect reliability
- × Cost might be high
- ✓ Active technique

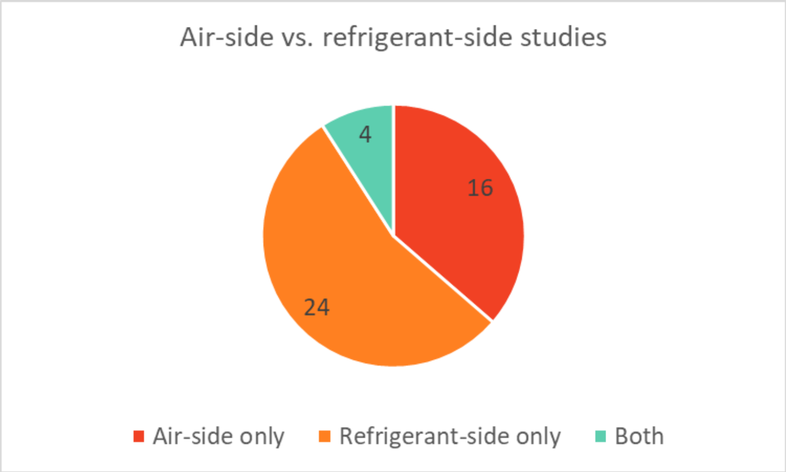
Impact

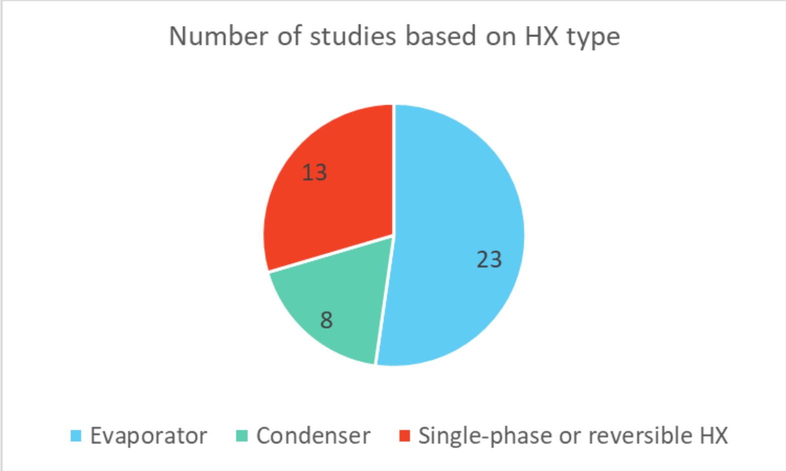
- **Literature shows that much work has been dedicated to understanding the underlying causes and effects of refrigerant maldistribution**
  - However, *few realizable solutions exist!*
- **This project will:**
  - Add to the knowledge base by providing a new fundamental understanding of electromechanically actuated flow distribution control in HXs
  - Address a challenging problem by providing real-time flow distribution control that could not be resolved by previous static solutions with limited applicability
  - Pave the way for further development of a new class of state-of-the-art HXs
- **If successfully implemented in HX designs currently used for residential HVAC (for example) with 10% improvement in system efficiency, primary energy savings technical potential will be 225 TBtu for 2030 energy market in all climate zones**
- **Target audience/customers:**
  - General HX R&D community, HX manufacturers, equipment manufacturers

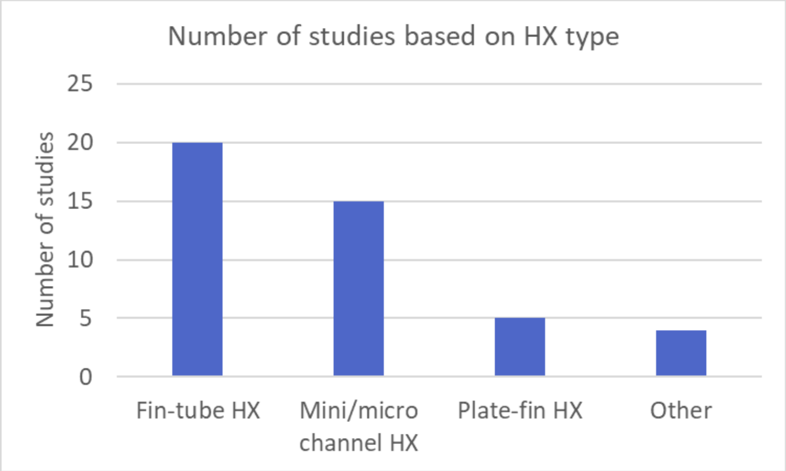
Progress — Literature Review

- General literature was compiled into a spreadsheet and organized into several categories: equipment type, HX type, general dimensions, nominal capacity, refrigerant pressure/flow rate, max HX capacity loss due to maldistribution







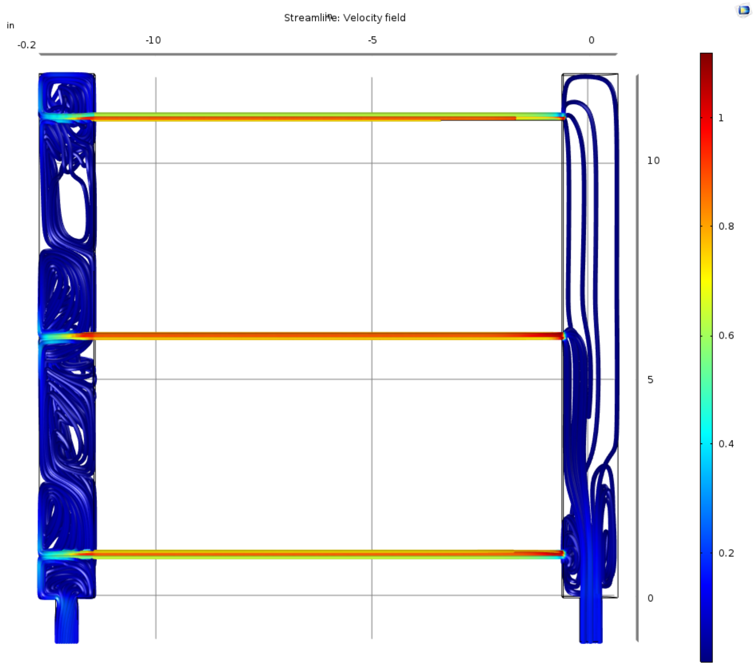


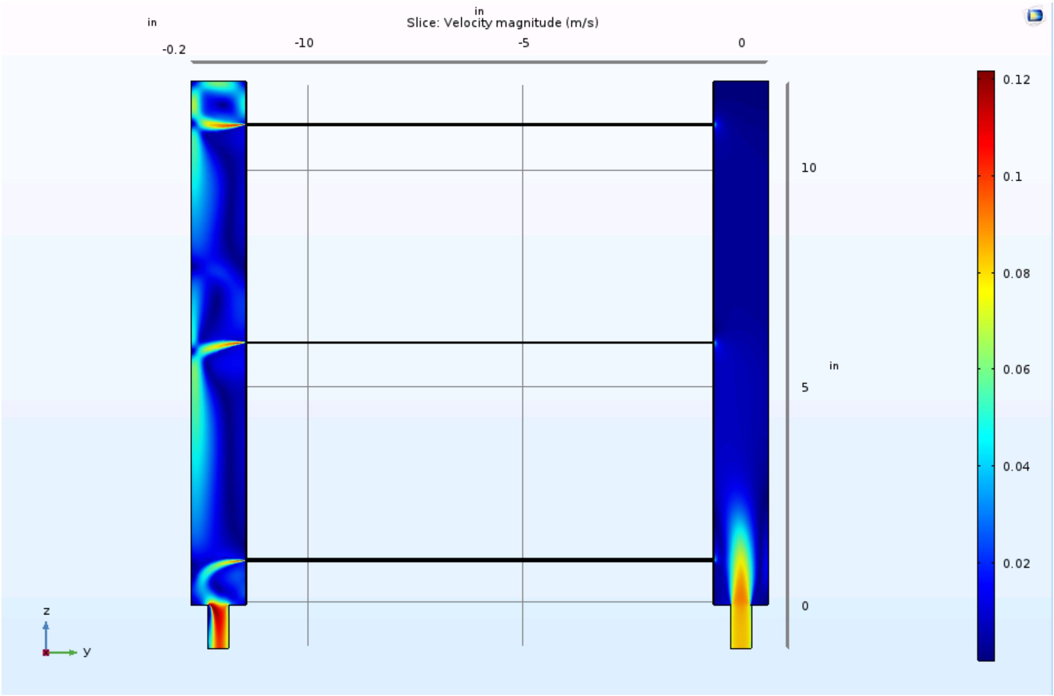
Progress — Major Findings from Literature

- Maldistribution mitigation in *evaporators* where refrigerant enters as a liquid-vapor mixture appears to be a more pressing need
- Large number of studies exist on fin-tube HXs with refrigerant distributors, but mini/microchannels are gaining wider adoption → *we plan to focus on these*:
  - They are compact, efficient, and have lower charge (important for adoption of new A2L refrigerants), but refrigerant maldistribution issues also tend to be more pronounced, especially in the headers
- From a cost and economics perspective, *we are targeting a heat pump type system in the 1–2 kW range*
- From an engineering perspective regarding the benchtop experimental setup, *we will use a low- to medium-pressure refrigerant, e.g., R-134a*
- The aforementioned selections have allowed us to pin down the *saturation temperature, pressure, and refrigerant flow rates* for the model
- The HX will have a *vertical header* with *horizontal parallel channels* to account for gravitational effects on maldistribution
- We will model a *minimum of three channels* to properly characterize the distribution, depending on computational power and time
- The header will reflect *practical design* in terms of length and microchannel-to-microchannel spacing

Progress — CFD Simulation

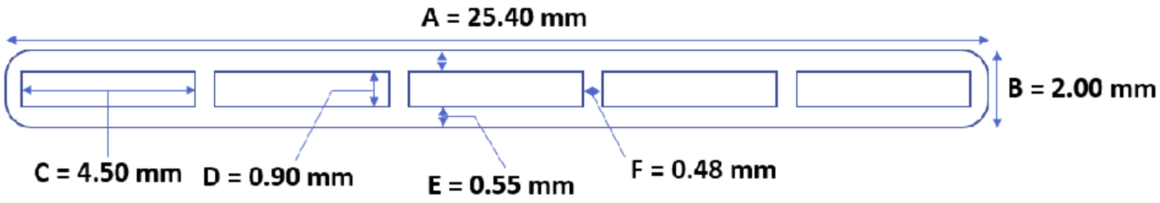
- **Single-phase flow model complete and running**
  - Water as working fluid, overall flow 0.01 kg/s
  - Parameters include tube insertion depth, flow rate, and header orientation



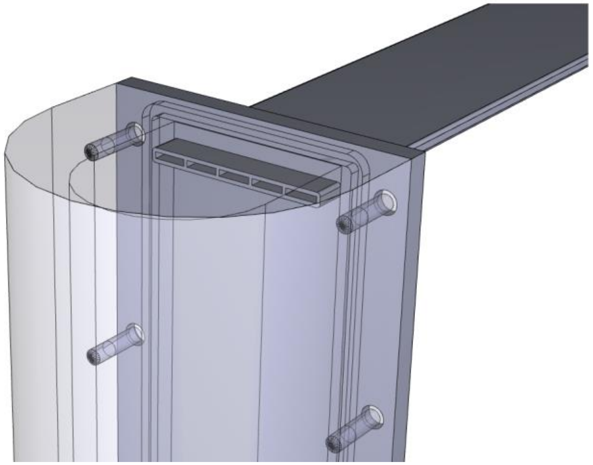


Progress — Benchtop Experimental Setup

- **Initial benchtop setup being fabricated with water as the working fluid**
  - Aluminum microchannels selected:



  - HX assembly fabricated with transparent polycarbonate headers:



Stakeholder Engagement

- **Direct engagement with HX and equipment manufacturers and Better Buildings partners → This is an explicit task in the technical work plan**
  - Task 5: Validate research and demonstrate relevance to a marketplace problem
    - Subtask 5.1: Engage with external stakeholders, share results so far and ensure market relevance for proposed technology
    - Milestone 5: In collaboration with stakeholders, verify that the research is technically sound, relevant to the market, satisfies an unmet market need, and if successful, will save energy in buildings
    - Deliverable 5: Report of research validation with stakeholder input
- **Publication of research in peer-reviewed journals, conference presentations, and publications**
- **Highlighting research in DOE BTO Success Stories**
- **Organizing industry visits**
- **Communicating with email and conference calls**
- **Other outreach through ORNL and ORNL Building Technologies Office websites**
- **Formation of related cooperative research and development agreements (CRADA) with industry partners to continue research**

Remaining Project Work

- **FY 2019**
  - HX flow distribution model–complete HX flow distribution model
  - Sensor-actuator requirements–use model results to determine piezoelectric sensor-actuator requirements
  - Validate research–in collaboration with stakeholders, verify that the research is technically sound, relevant to the market, etc.
- **FY 2020**
  - Piezoelectric sensor-actuator fabrication–assemble piezoelectric sensor-actuators and prepare for install
  - Benchtop experimental setup–complete transparent HX fabrication
  - Shakedown testing–complete shakedown testing and acquire preliminary data
  - Demonstrated performance-through a combination of experimental and modeling results, demonstrate increase in heat transfer efficiency by 15% and potential for increasing system efficiency by ≥10%

Thank You

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REFERENCE SLIDES

References

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Project Budget

Project Budget: $900K DOE
Variances: No variances
Cost to Date: $66K
Additional Funding: No additional funding

Budget History					
10/01/2018– FY 2018 (past)		FY 2019 (current)		FY 2020 – 09/30/2020 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
		$450k	$0	$450k	$0

Project Plan and Schedule