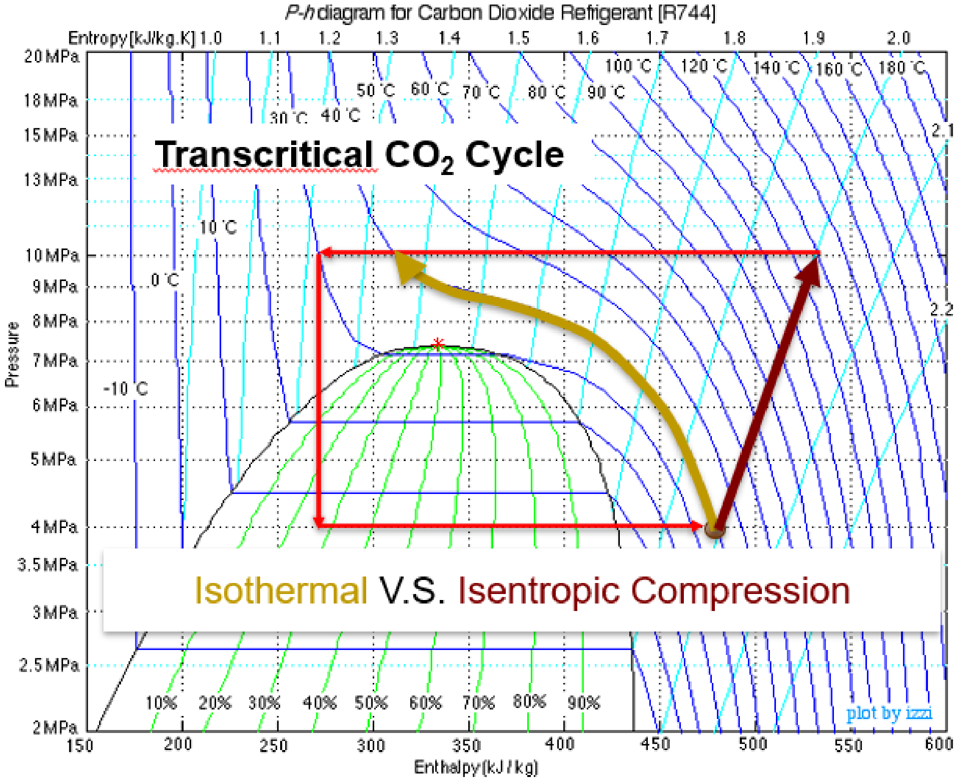
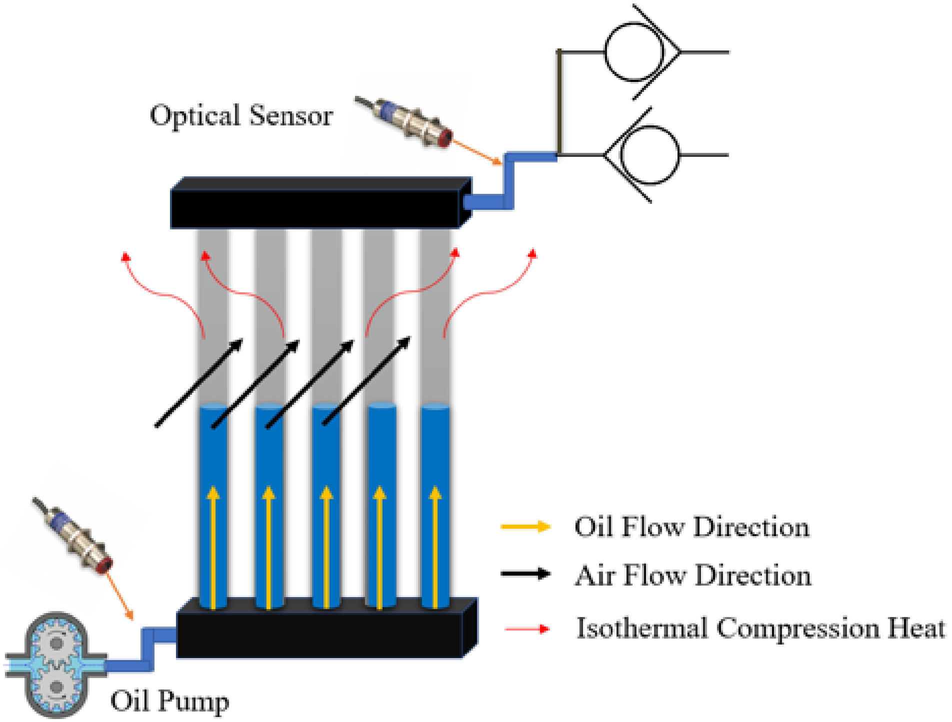
Enabling CO_2 Isothermal Compression Using Liquid Piston Within Integrated Gas Cooler





Performing Organization(s): University of Maryland, Emerson Climate Technologies
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DE-EE009685

Project Summary

DE-EE009685

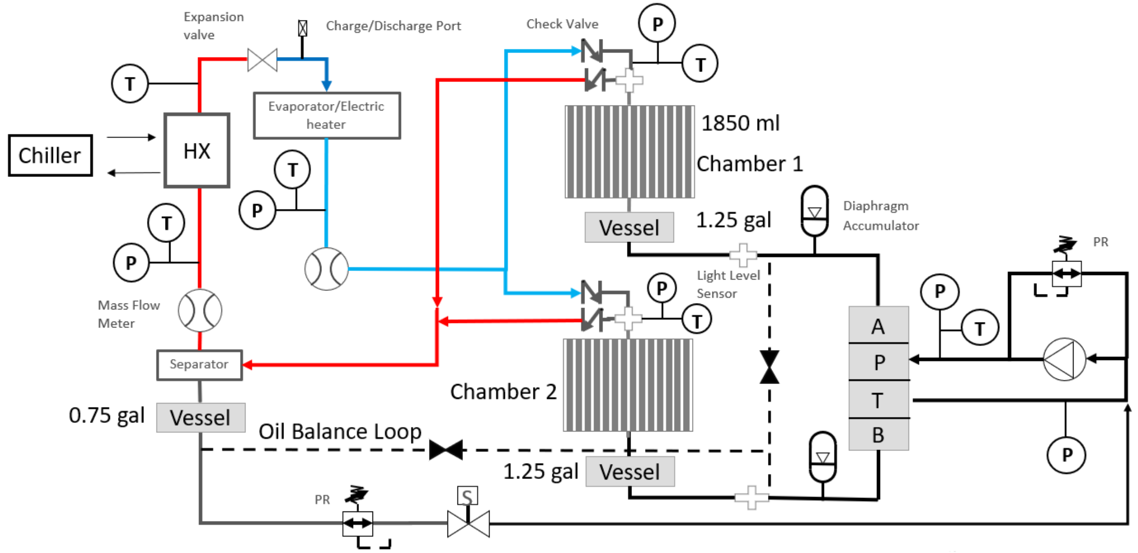
Objectives

1. Develop a novel isothermal compressor that reduces energy consumption by an average of 30% in refrigeration compared to isentropic compression.
2. Develop a transient isothermal compressor model that is capable of simulating CO_2 compression and heat rejection within the gas cooler.
3. Validate system model based on experimental data and then applied it into the field test.

Team and Partners

University of Maryland

Emerson Climate Technologies



Stats

Performance Period: October 2021 ~ September 2024

DOE Budget: $1,200 k, Cost Share: $300 k

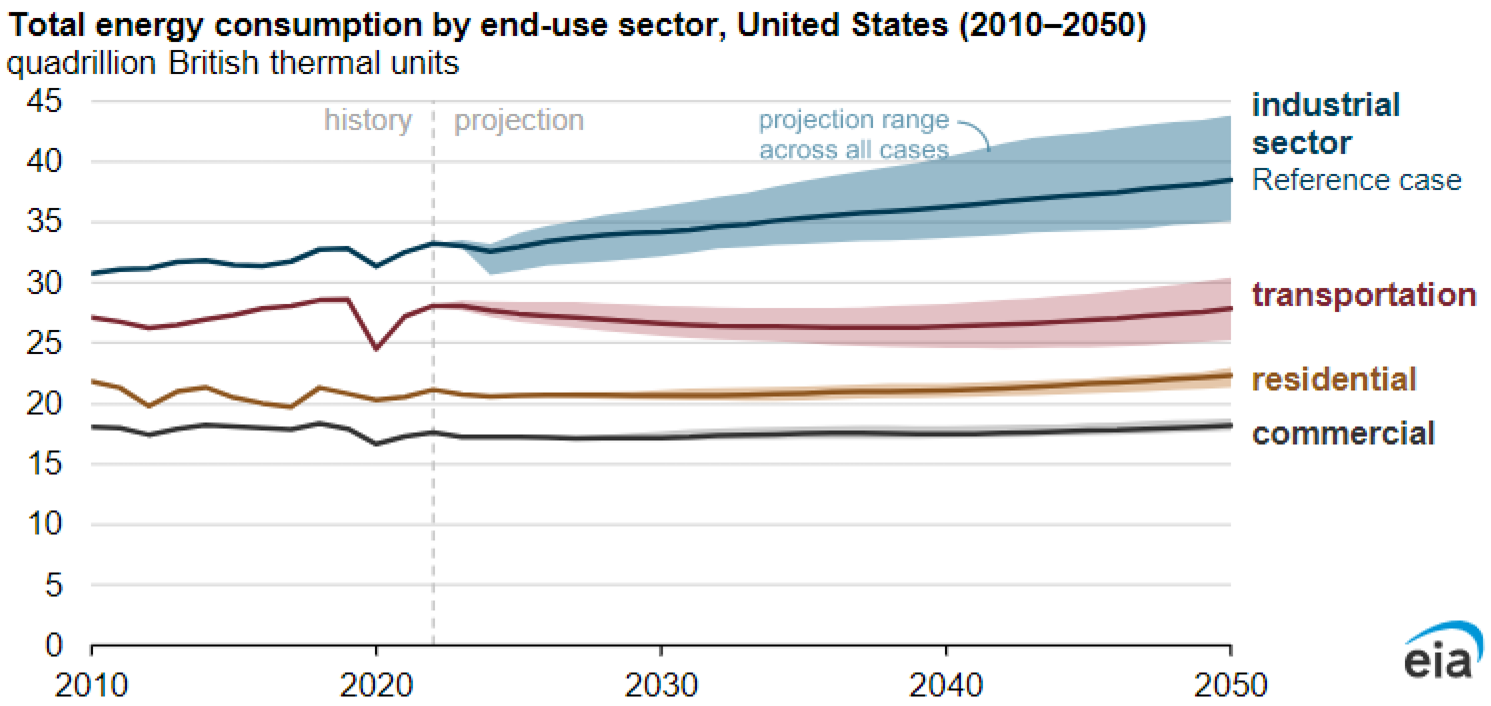
Milestone 1: Develop a proof-of-concept compressor and a simulation tool

Milestone 2: Construct a 1-ton capacity testing facility and improved simulation tool

Milestone 3: Perform field test in partner's supermarket

Problem

- Total energy consumption projection increases by as much as **15%** from 2022 to 2050. Households in the U.S. residential sector reached 5.1 Quads in 2022 and may reach between 5.9 Quads and 6.3 Quads from 2022 to 2050 based on the projections[1] .
- European Parliament adopted the revised F-Gas regulation banning HFCs and HFOs in multiple applications and phasing out HFCs by 2050
- The compressor is the major energy consumption component in an HVAC system. Study and research on compressor benefits in achieving carbon reduction.



Data source: U.S. Energy Information Administration, Annual Energy Outlook 2023

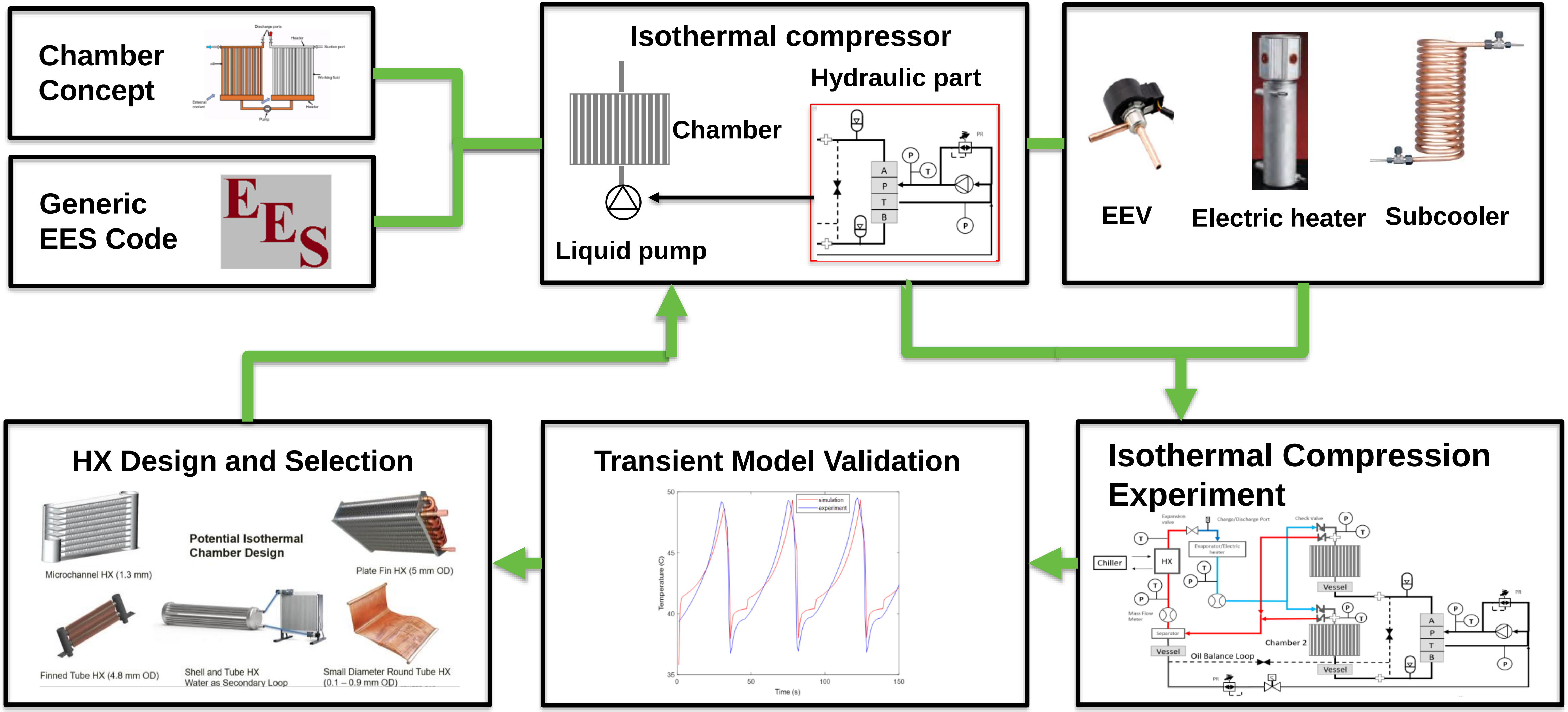
[1] - U.S. Energy Information Administration, Annual Energy Outlook 2023
[2] - IEA (2022), Energy Efficiency, IEA, Paris https://www.iea.org/reports/energy-efficiency, License: CC BY 4.0

Alignment and Impact

- **Advancement of Compressor Technology**
  - Realize the near-isothermal compression in air conditioning and refrigeration application
  - Integration mechanism of compressor chamber and gas cooler
  - 30% less compression work than the isentropic compression
- **Air Conditioning and Refrigeration Industry Impact**
  - Replacing HFCs with natural refrigerants like CO_2 has the potential to avoid emissions of up to 5.6 Gt CO_2 eq per year by 2050[3]
- **Acceleration of Energy Intensity Improvement toward NZB by 2050**
  - In 2022, the energy consumption for the residential and commercial sectors was 33 quads[4]
  - Space cooling and refrigeration account for 20% (6.6 quads)
  - If deployed the technology to both sectors with 30% energy consumption reduction, the yearly energy savings will be 2.0 quads

[3] - United Nations Environment Programme. (2014). HFCs: A Critical Link in Protecting Climate and the Ozone Layer. Retrieved from https://wedocs.unep.org/handle/20.500.11822/9417
[4] - U.S. Energy Information Administration, Monthly Energy Review – Table 2.1

Approach - Framework



Approach- Tasks and Milestones

Year-1: Develop the Proof-of-Concept Isothermal Compressor and a Transient Model (completed)

- Extensive literature review on nearly isothermal compression technology
- Develop a transient-based isothermal compressor model
- Fabricate the proof-of-concept isothermal compressor
- Successfully compress CO_2 above critical point and generate enough mass flow rate for a half-ton refrigeration cooling

Year-2: Improve the proof-of-concept compressor; Fabricate and test 1-ton refrigeration system

- Collect feedback from Y1 and determine necessary modifications to the proof of concept compressor
- Conduct system-level transient simulations to improve the isothermal compressor
- Select refrigeration cycle components based on the Y1 tests
- Conduct system-level refrigeration cycle tests with the isothermal compressor

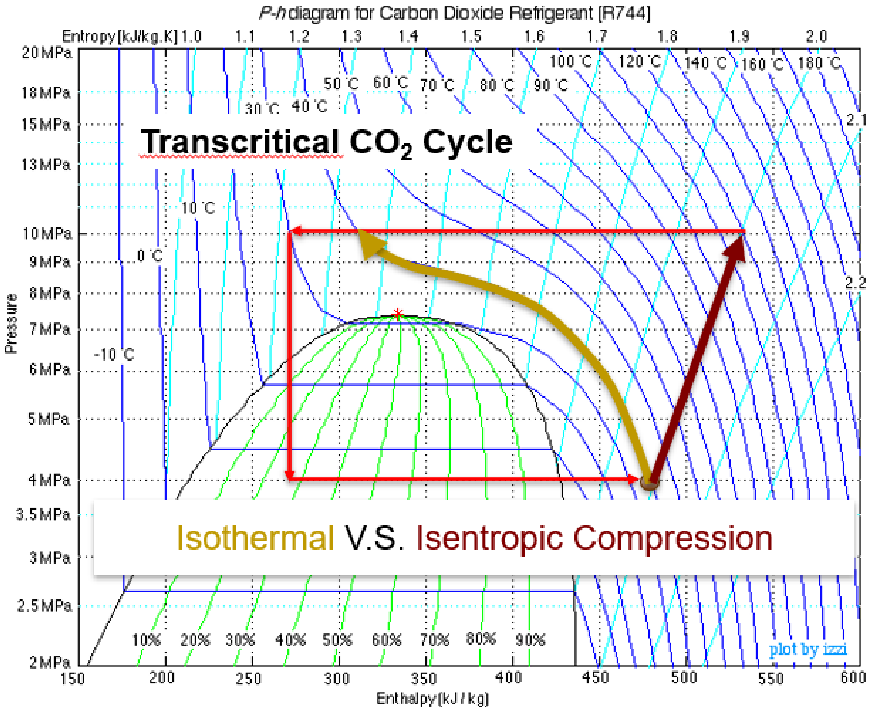
Year-3: Improve and scale up the compressor and conduct tests in a supermarket environment

- Collect feedback on the testing data and modify the compressor to perform field test
- Calibrate and improve the refrigeration system model
- Refrigeration system tests in the supermarket test facility
- Final documentation delivery

Progress – Compression Chamber

- Applied isothermal compressor using liquid piston integrated with gas cooler
  - Discharge compression work and internal energy simultaneously during compression
  - Up to 30% of work reduction
  - Manufacture and validate the proof-of-concept compression chamber in-house

Dimension	Unit	Value
Upper header	mm	10.9
Bottom header	mm	16.6
Tube ID	mm	6.2
Tube spacing	mm	19
Wall thickness	mm	1.65
Height	Inch	24
Width	inch	21.6

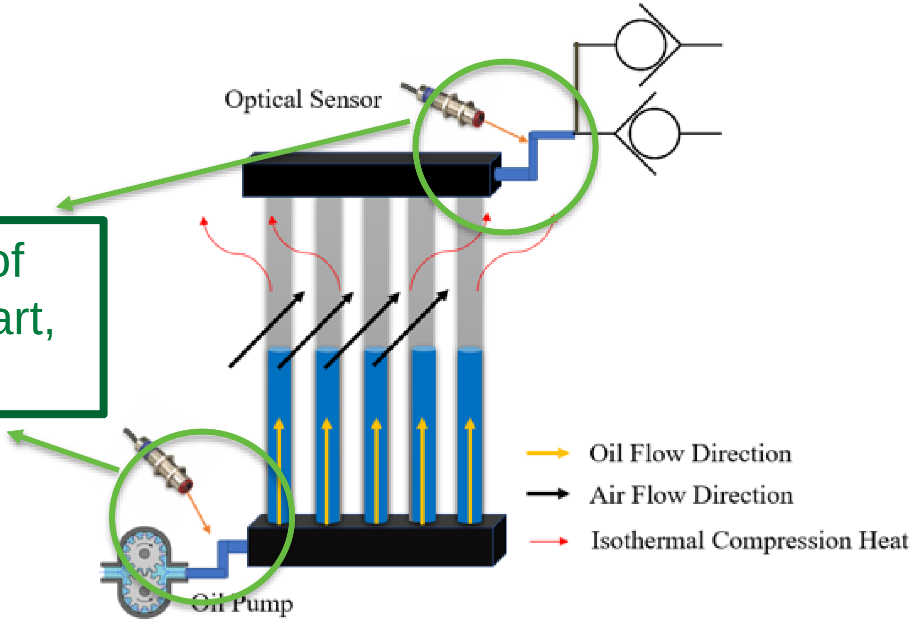


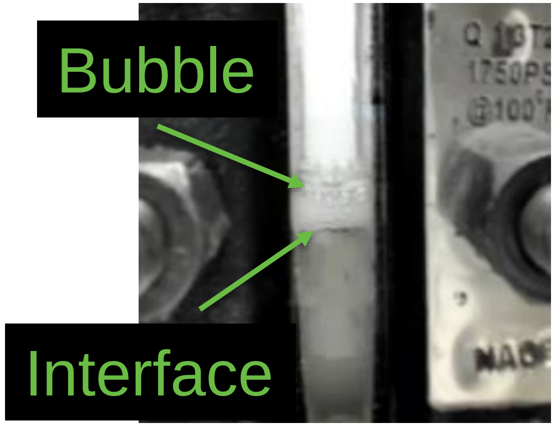
CO_2 P-h Diagram

Progress – Liquid Level Sensor

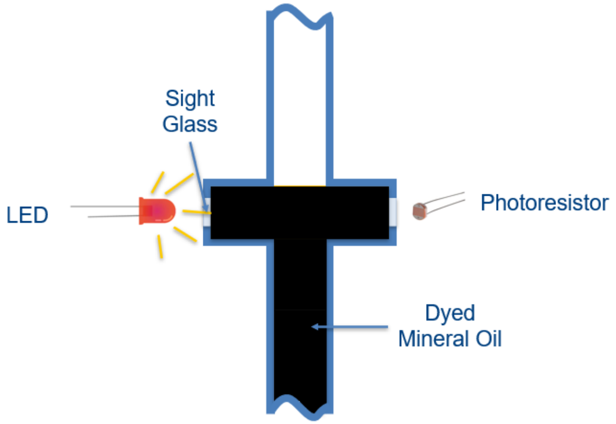
- The liquid level sensor determination and experiments
  - Visualization of CO_2 bubble formation when decompressed
  - Create a mind map for potential liquid-level sensor options
  - Test and validate the candidate sensors on the proof-of-concept prototype
- Required characteristics of the candidate sensors
  - Fast response, reliable, high-pressure proof, low-cost
- The optical sensor and thermal sensor fit the application most.

The determination of the compression start, and end is crucial





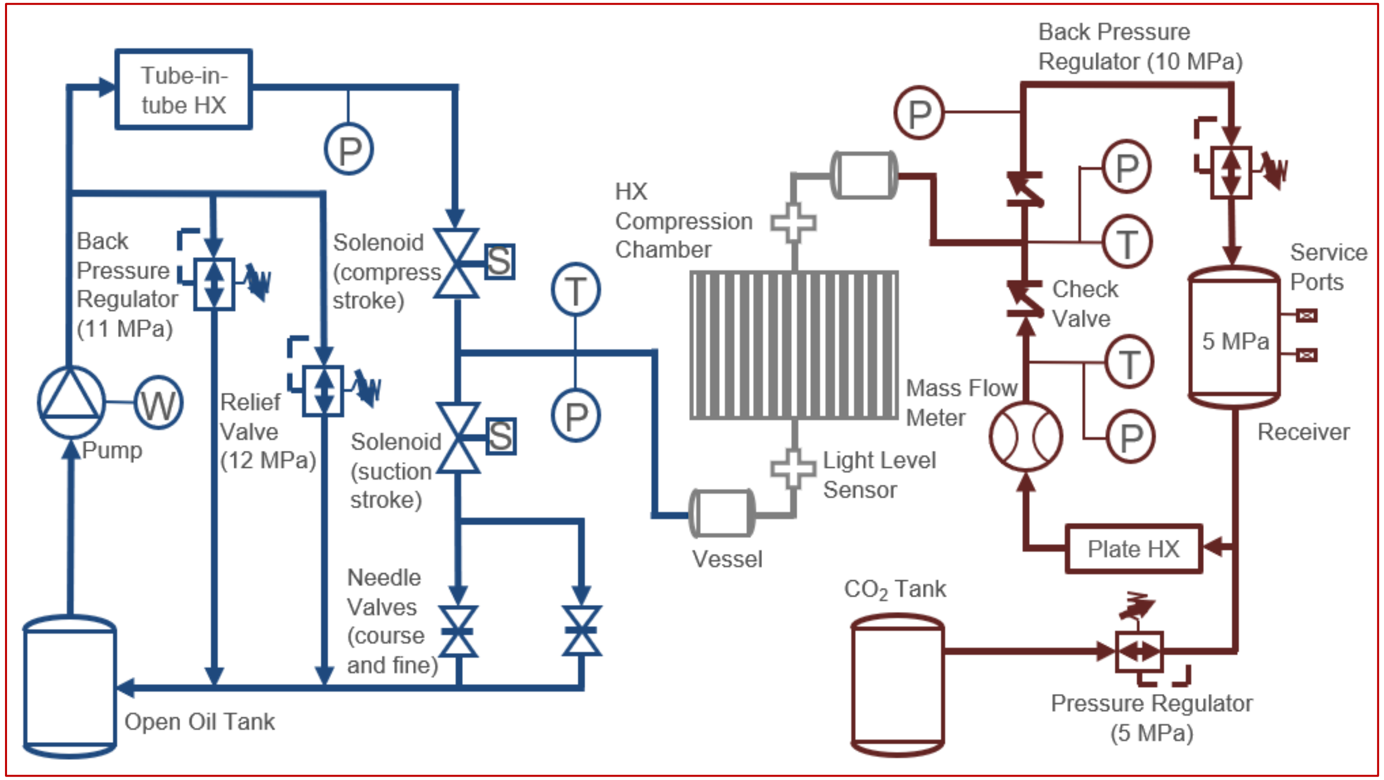
CO_2 Bubble Formation



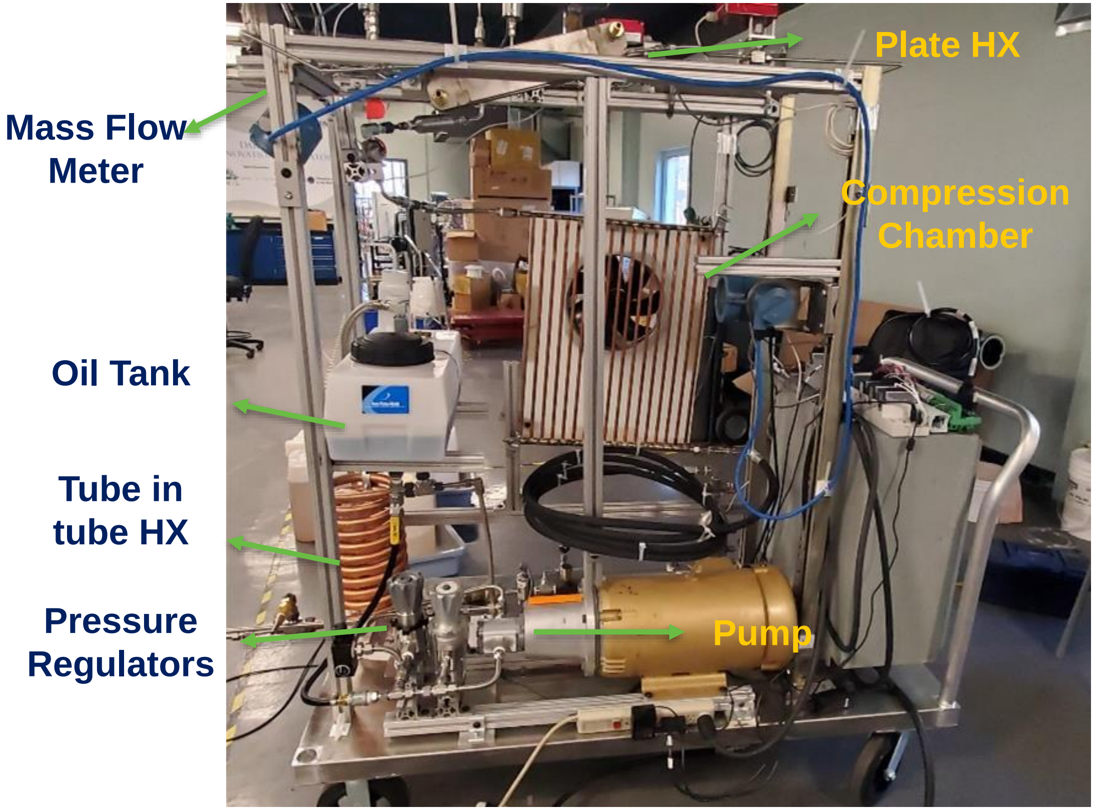
Optical Sensor

Progress – Proof of Concept Experiment Setup

- A proof-of-concept isothermal compressor prototype was built to examine the actual compression efficiency
  - The cooling capacity was estimated based on the refrigerant mass flow rate
  - Inlet condition: 40°C, 4,000 kPa;   Outlet condition:10,000 kPa



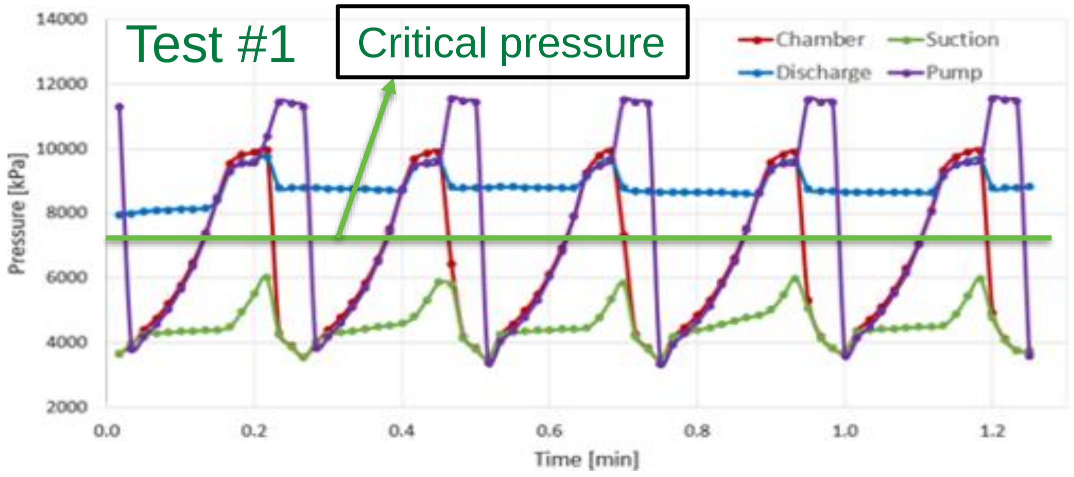
Test Facility



Test Facility and Components Pictures

Progress – Proof of Concept Testing Results

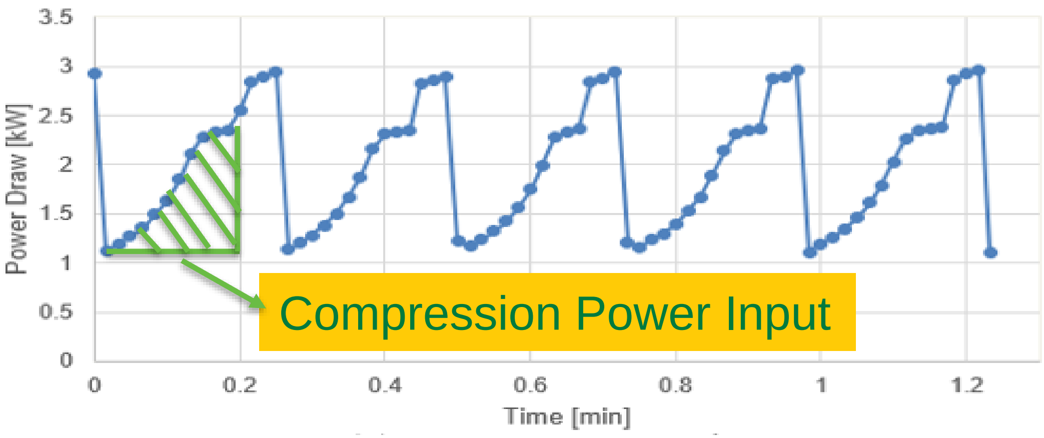
- 60% of isothermal efficiency was achieved in the 0.5-ton capacity testing condition
  - Successfully compressed CO_2 over the critical point (7,385 kPa)
  - Chamber temperature was suppressed to 55°C compared with 118°C if isentropic compression
- Test results show insufficient heat transfer area to achieve 85% of isothermal efficiency



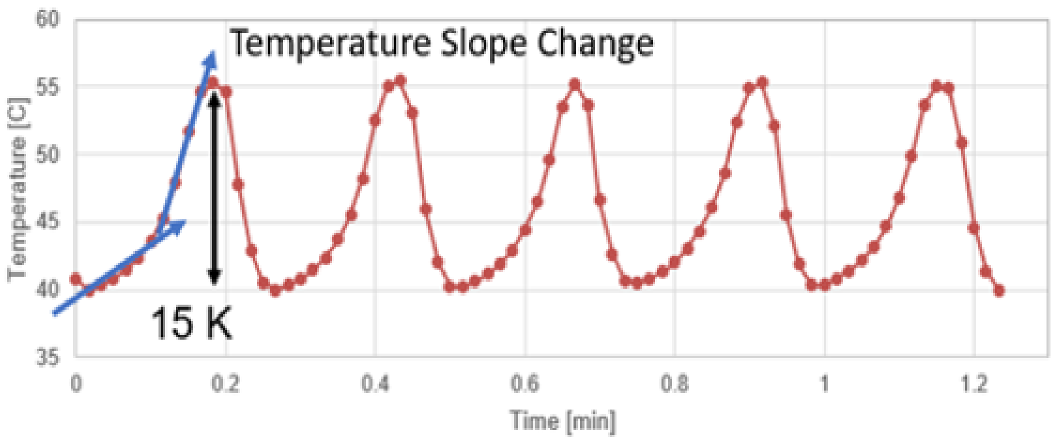
System Pressure

$$\eta = \frac{W_{isothermal}}{W_{actual}}$$

Isothermal Efficiency Definition



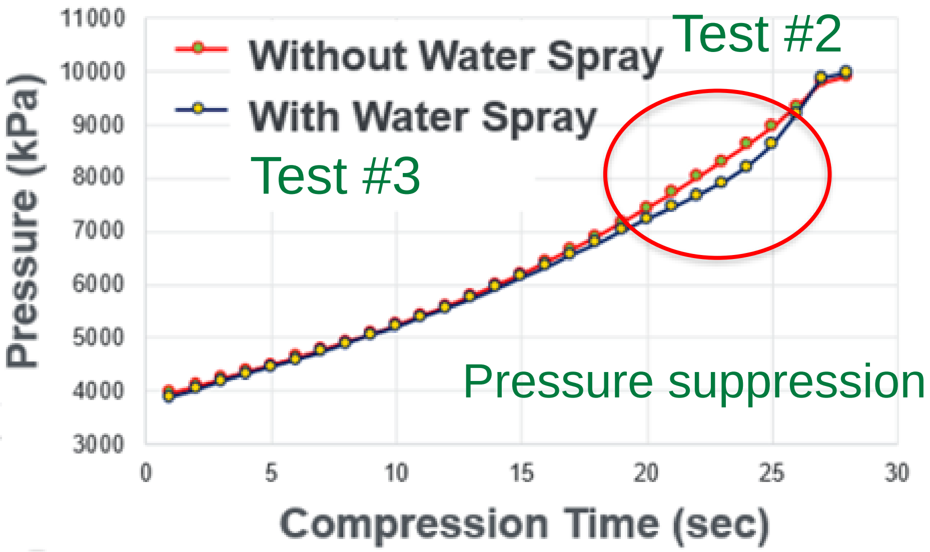
Compressor Power

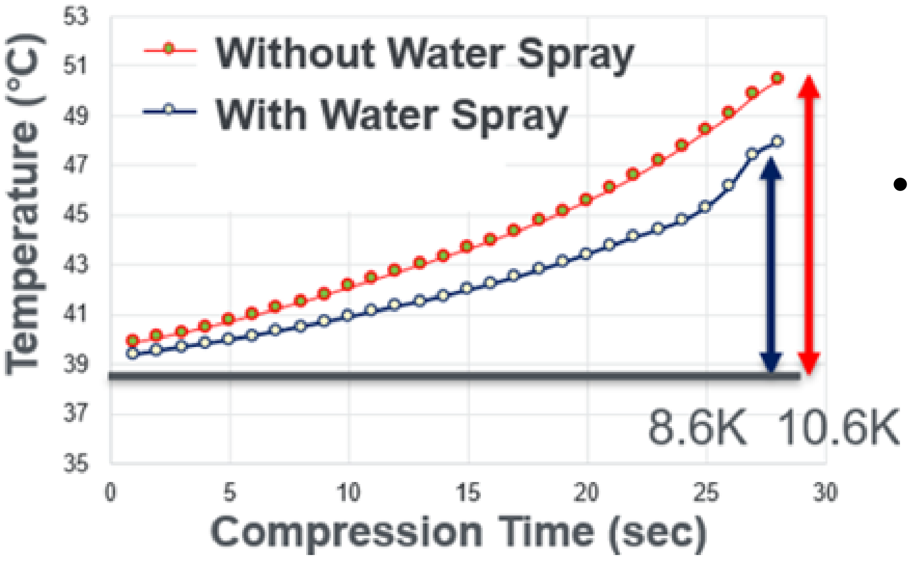


Chamber Temperature

Progress – Proof of Concept Testing Results (cont'd)

- Efficiency Improvement Manipulation
  - Pump speed was lowered to one-third in tests #2 and #3 for extending heat transfer time
  - Apply evaporative cooling on the compression chamber surface for heat transfer enhancement





- By slowing the process and combined with evaporative cooling, the efficiency improved to 80% and 94%, respectively

	Test #1	Test #2	Test #3
Pump Speed	900	270	270
Water spray*	No	No	Yes
Efficiency	60%	80%	94%

*Room Conditions: 35°C and 20% in humidity
Water Temperature: 35°C

- Significant Temperature Reduction

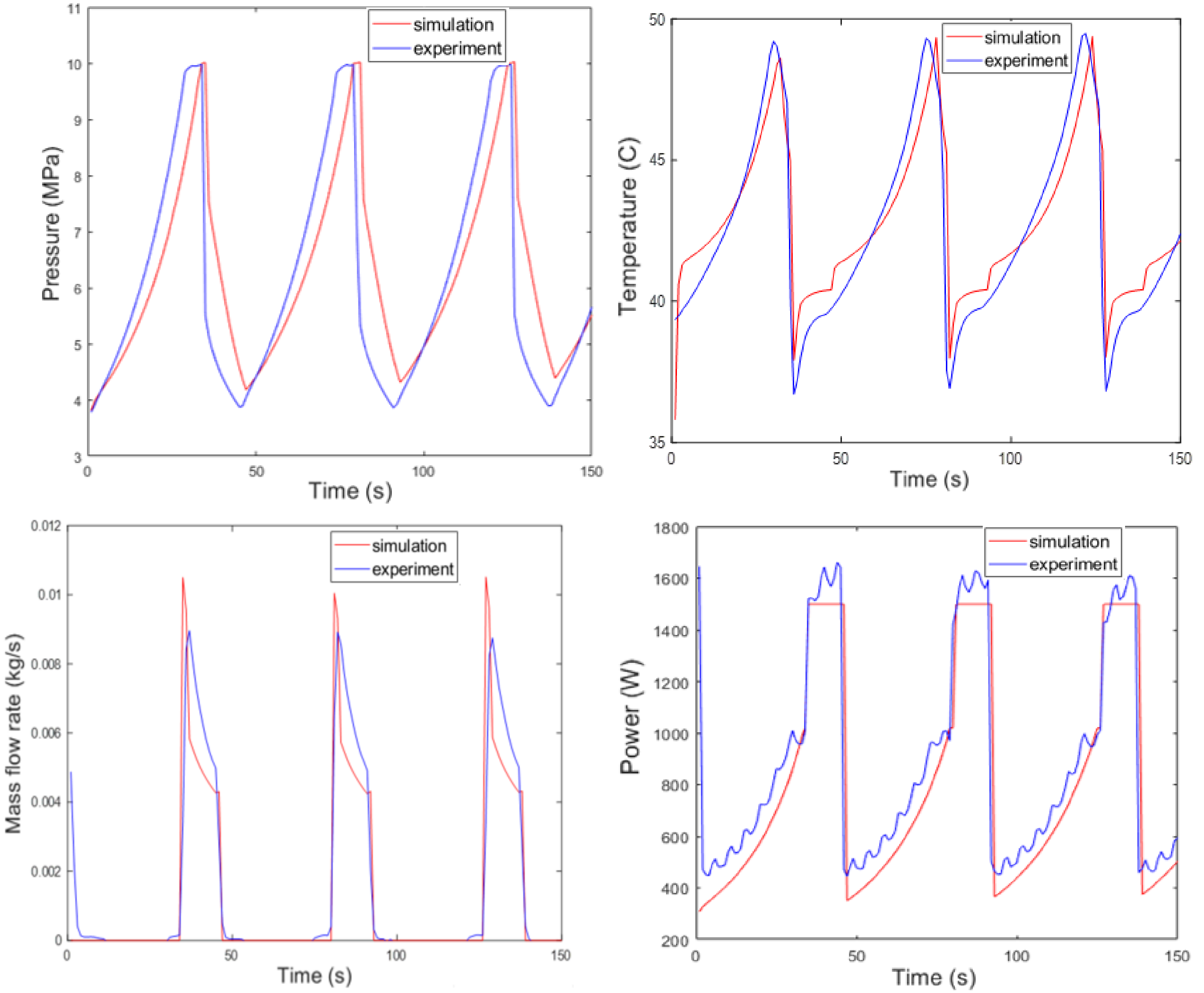
Progress - Modeling and Validation for Isothermal Compressor

- State space form of governing equations

$$\begin{bmatrix} V\dfrac{\partial\rho}{\partial P}h - V & V\dfrac{\partial\rho}{\partial h}h + V\rho & 0 & \rho h - P \\ V\dfrac{\partial\rho}{\partial P} & V\dfrac{\partial\rho}{\partial h} & 0 & \rho \\ 0 & 0 & C_{th,w} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{P} \\ \dot{h} \\ \dot{T}_w \\ \dot{V} \end{bmatrix} = \begin{bmatrix} \dot{m}_{in}h_{in} - \dot{m}_{out}h - \alpha_r A_i\left(T_r - T_w\right) \\ \dot{m}_{in} - \dot{m}_{out} \\ \alpha_r A_i\left(T_r - T_w\right) - \alpha_a A_a\left(T_w - T_a\right) \\ -A_s v \end{bmatrix}$$

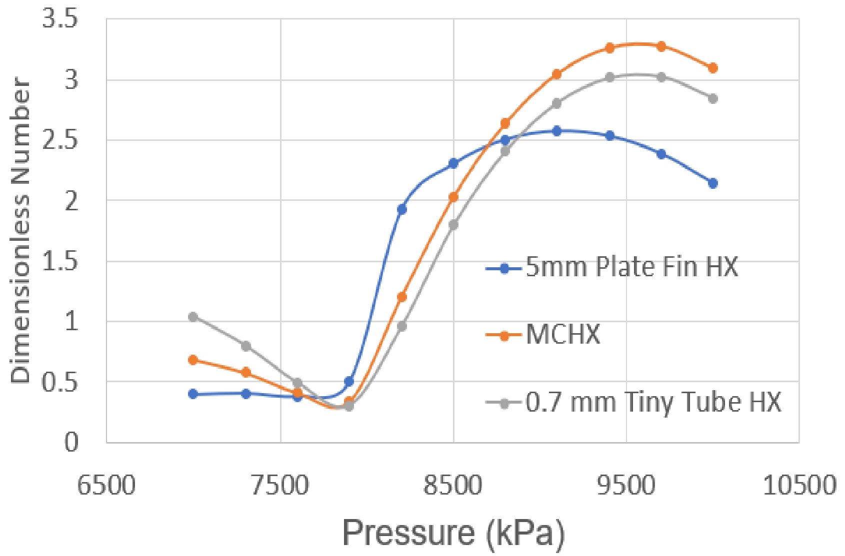
  - The model shows satisfying agreement between modeling and experiment results in terms of overall trends
  - Pressure and temperature delays are observed. Improvements should be made by calibrating the thermal capacitance of chamber
  - The fluctuation of liquid pump power from experiment could be a result of system noise
  - The model didn't consider the make-up refrigerant that dissolved in oil during experiment

Validation Results

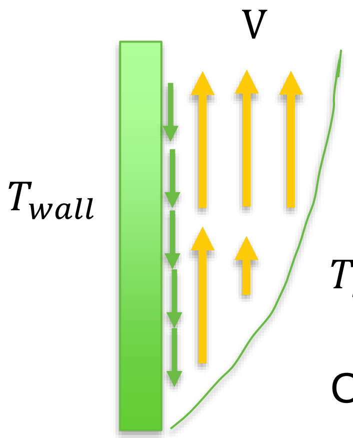


Progress –1-ton System Development

- Compression Chamber Heat Transfer Calculation and Selection
  - CO_2 was the dominant heat transfer resistance
  - Coefficient correlations for combined forced and natural convection were selected from open literature*
  - An EES code was developed to compare different type heat exchanger's performance
  - A dimensionless number was defined to evaluate the heat transfer capability against required discharge heat stored in the CO_2, the higher, the better



$$C_{iso} = \frac{\frac{\Delta T}{R} \cdot S}{\Delta H \cdot mass + W \cdot S}$$



$T_{wall} < T_{bulk}$

Cold Vertical Wall

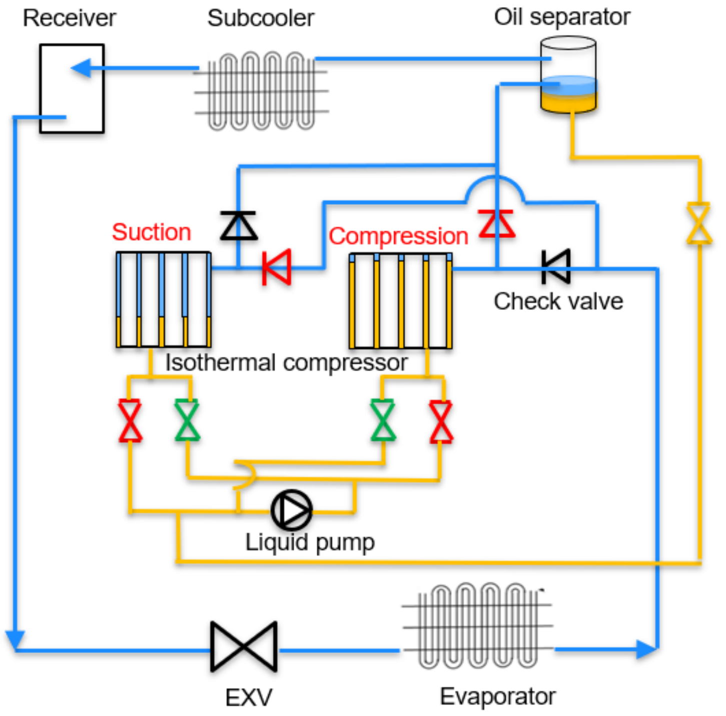
Combined forced and natural convection (Gr/Re ~ 1)

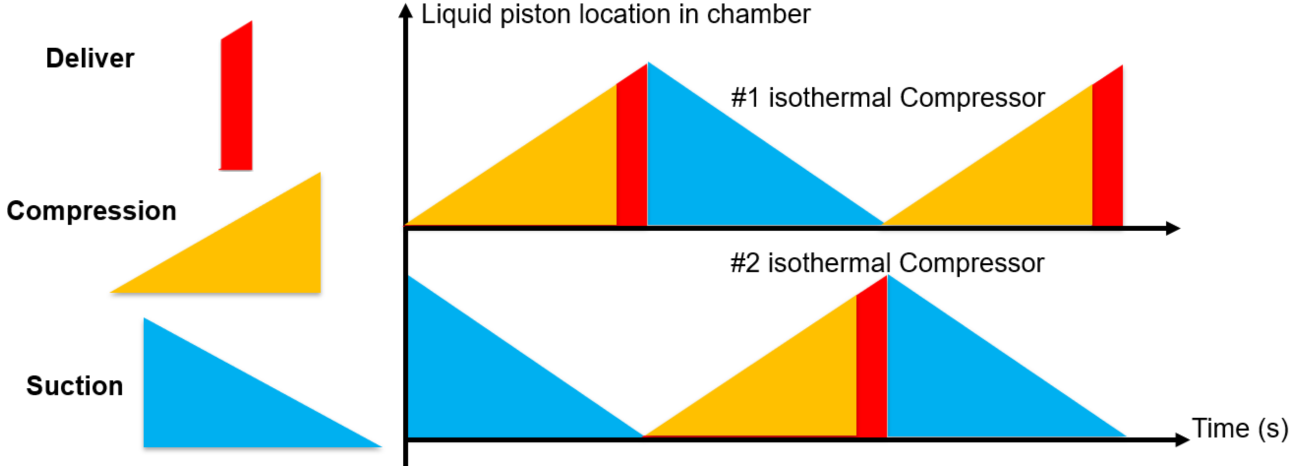
*Mohammed, H. A. (2008)
Aicher, T., & Martin, H. (1997)

Progress - System Level Model Development

- Challenge
  - The refrigerant mass flow rate is intermittent through the system
  - System can't reach to steady state or quasi-steady state
  - Heat transfer correlations for both air-side and refrigerant- side significantly affect isothermal efficiency
- Strategies
  - Consider the receiver in the system model to provide the continuous mass flow rate
  - Ensure the suction period equals to the time for compression and deliver process
  - Calibrate the heat transfer coefficient based on the experimental data

Schematic diagram of system model





Futural Work

- **Experimental Work**
  - Select a type of compressor chamber based on the proof-of-concept compressor
  - Modify and design the 1-ton refrigeration system
  - Conduct system-level refrigeration cycle tests with the isothermal compressor
  - Scale up and modify the 1-ton refrigeration system for supermarket environment
  - Conduct field test and collect data including cooling capacity, COP of the refrigeration system, isothermal compression efficiency
- **Simulation Work**
  - Develop system level model and instruct the experiential setup design and prototyping based on the simulation results
  - Conduct system level validation and performance assessments

Thank You

Performing Organization(s): University of Maryland, Emerson Climate Technologies
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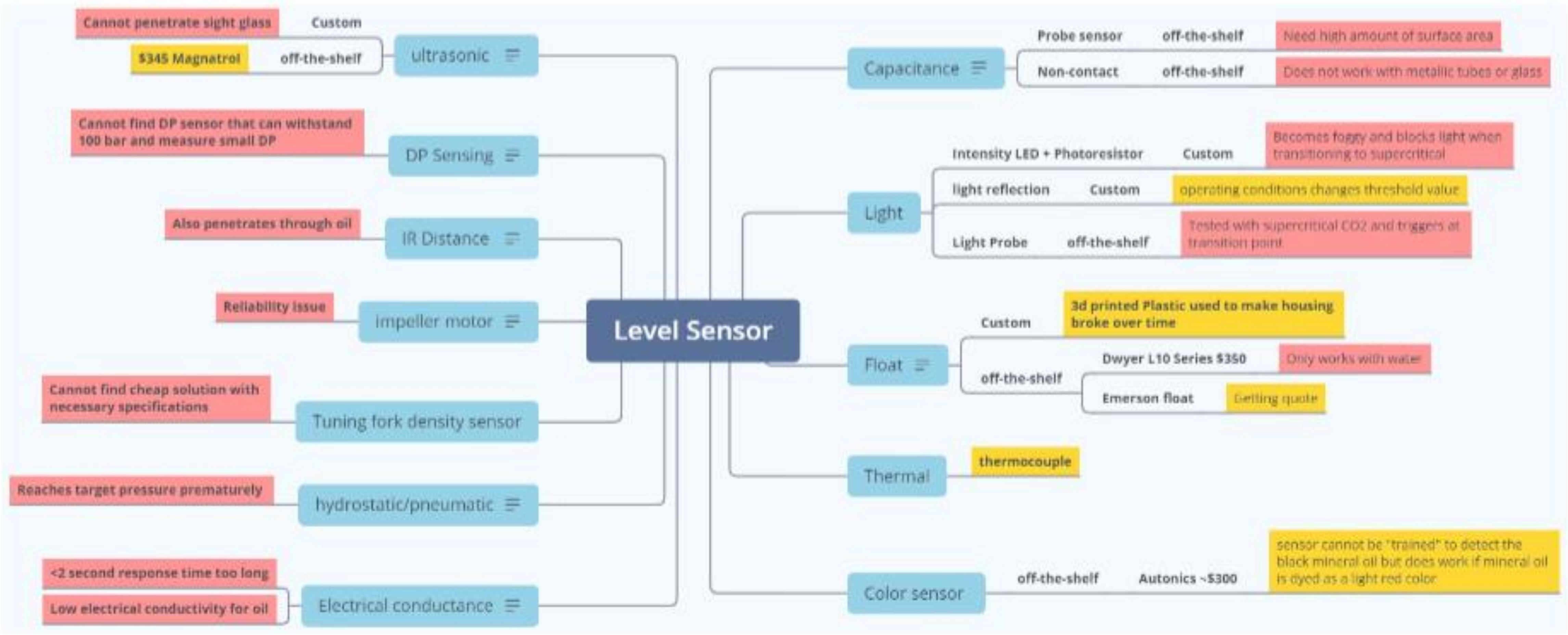
REFERENCE SLIDES

Mind Map of Liquid Sensor



Approach - Simulation

- Conservation differential equations for the refrigerant (CO2) energy

$$\dot{U} = m_{in} h_{in} - m_{out} h_{out} - \alpha_r A_i \left(T_r - T_w\right) + W$$

- **Conservation differential equations for the refrigerant mass**

$$\dot{m}_e = m_{in} - m_{out}$$

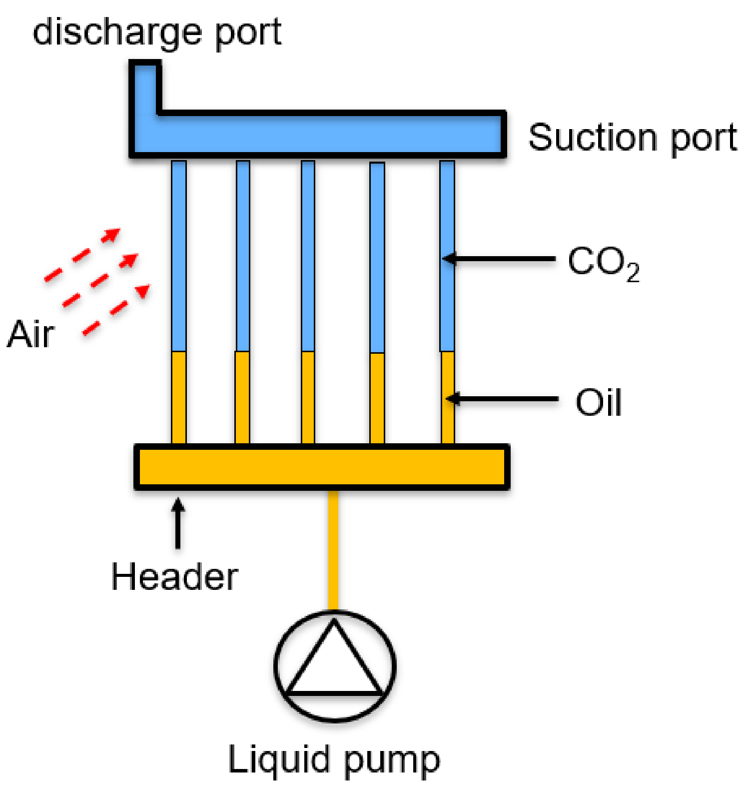
- **Conservation differential equations for the tube wall energy**

$$\dot{E} = C_{th,w} \dot{T}_w = \alpha_r A_i \left(T_r - T_w\right) - \alpha_a A_a \left(T_w - T_a\right)$$

- **Reformulation of the above governing equations**

$$\begin{bmatrix} V \frac{\partial \rho}{\partial P} h - V & V \frac{\partial \rho}{\partial h} h + V \rho & 0 & \rho h - P \\ V \frac{\partial \rho}{\partial P} & V \frac{\partial \rho}{\partial h} & 0 & \rho \\ 0 & 0 & C_{th,w} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{P} \\ \dot{h} \\ \dot{T}_w \\ \dot{V} \end{bmatrix} = \begin{bmatrix} \dot{m}_{in} h_{in} - \dot{m}_{out} h - \alpha_r A_i \left(T_r - T_w\right) \\ \dot{m}_{in} - \dot{m}_{out} \\ \alpha_r A_i \left(T_r - T_w\right) - \alpha_a A_a \left(T_w - T_a\right) \\ -A_s v \end{bmatrix}$$

Isothermal compressor



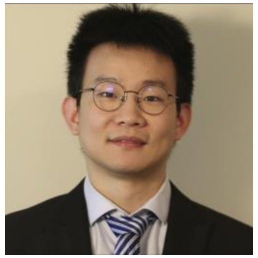
Project Execution

	FY2022				FY2023				FY2024			
Planned budget												
Spent budget												
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Q1 Milestone: IPMP is completed												
Q1 Milestone: A comprehensive summary on literature review is completed												
Q1 Milestone: A Matlab-based transient isothermal compressor model												
Q2 Proof-of-concept compressor test setup is assembled												
Q3 Milestone: The proof-of-concept is fabricated												
Q4 Milestone: The proof-of-concept compressor generate 0.5-ton cooling capacity												
Current/Future Work												
Q1 Milestone: Brainstorm on Year 1 design feedback is completed												
Q1 Milestone: The Matlab-based transient model validated and improved												
Q2 Milestone:Design of 1-ton refrigeration system is completed												
Q3 The test setup can conduct refrigeration test												
Q4 The isothermal compressor successfully created 1-ton cooling												

Team

- University of Maryland:
  Expertise: 30+ years of experience in R&D of heat pumps, refrigerant, HVAC&R components and systems, modeling and optimization software development; system and component test facilities; funded by industry and government



- Emerson Climate Technologies
  Expertise: 30 years of experience in air-conditioning compressors and system design and development.