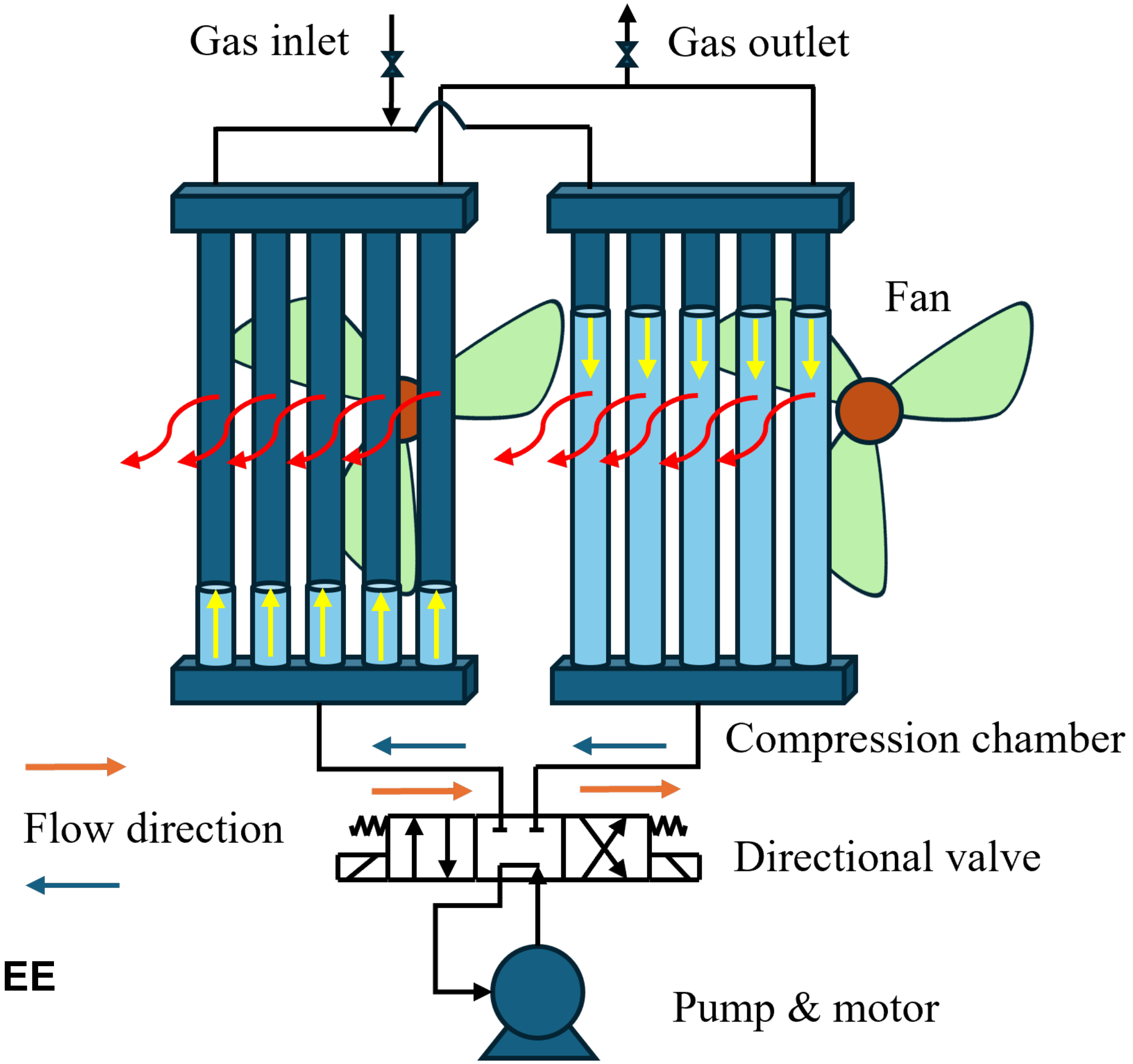
2024 PROJECT PEER REVIEW
U.S. DEPARTMENT OF ENERGY
BUILDING TECHNOLOGIES OFFICE

BTO Peer Review:

Enabling CO_2 Isothermal Compression Using Liquid Piston within Integrated Gas Cooler

DE-EE-0009685



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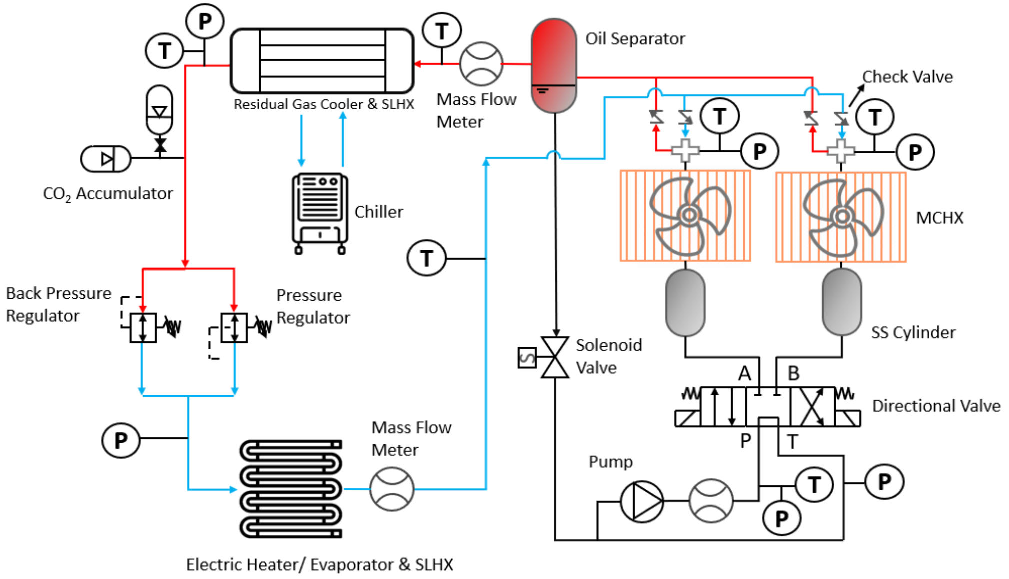
Project Summary

Objectives

- Develop a novel isothermal compressor that reduces energy consumption by an average of 30% in refrigeration compared to isentropic compression.
- Develop a transient isothermal compressor model that is capable of simulating CO_2 compression and heat rejection within the gas cooler.



Team and Partners

- University of Maryland
- Copeland

STATS

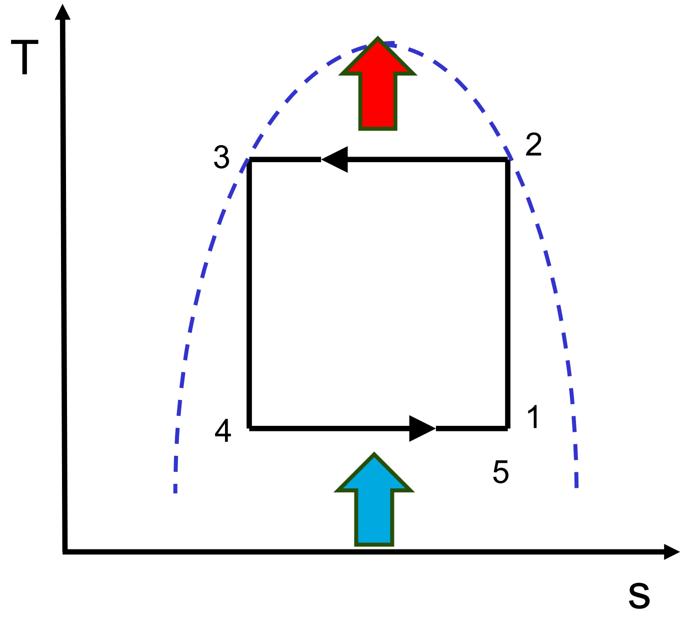
Performance Period: 10/2021 – 09/2024

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

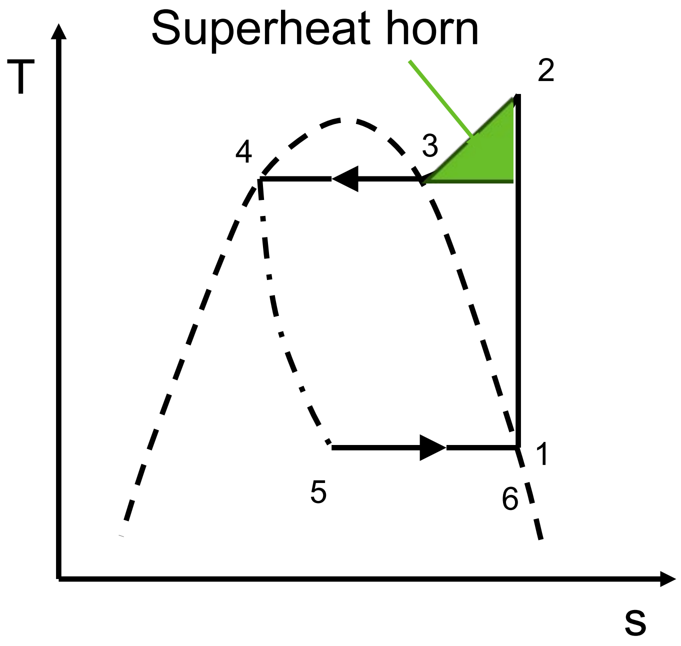
- BP 1: Proof-of-Concept Isothermal Compressor and A Transient Model
- BP 2: Fabricate and Test the 1-ton Ref. System
- BP 3: Scale up and Conduct Field Tests

Fundamentals

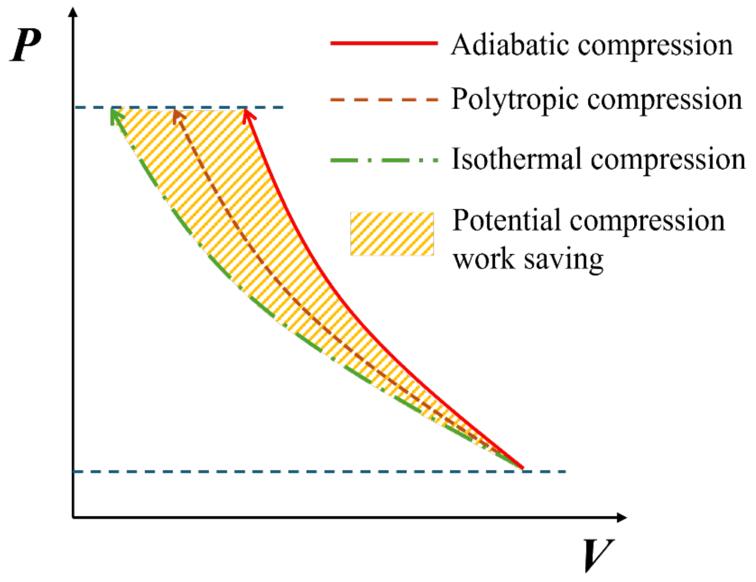
- Vapor compression cycle (VCC) pumps heat from low to high temperatures.
- Since wet compression is not possible, the vapor is compressed, resulting in a superheat horn.
- This causes more compressor work input and condenser heat to be rejected.
- Novel idea: Using liquid piston for gas compression to achieve near-isothermal compression



(a) Reverse Carnot Cycle



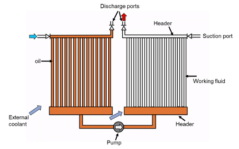
(b) Vapor Compression Cycle



Comparison of the compression process

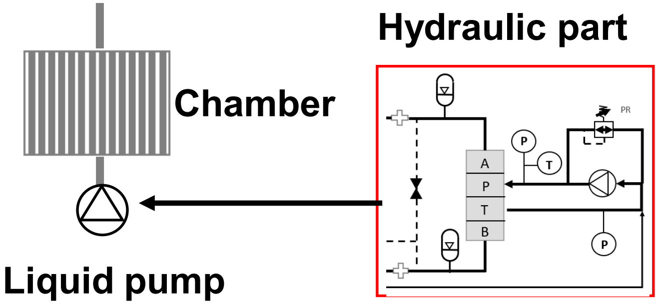
Approach - Framework

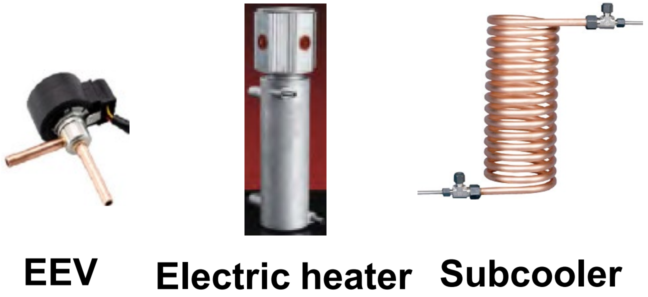
Chamber Concept



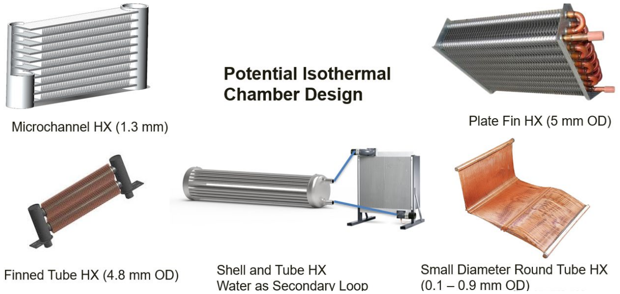
Generic EES Code

Isothermal compressor

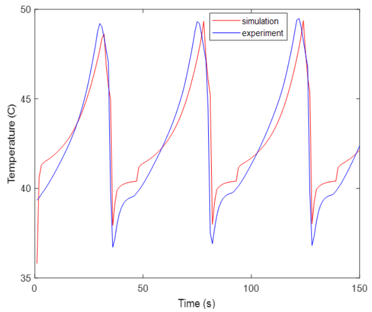




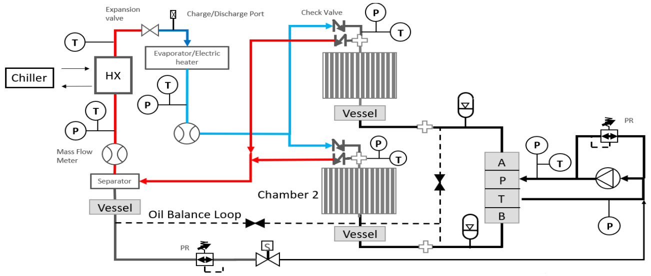
HX Design and Selection



Transient Model Validation



Isothermal compression Experiment



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

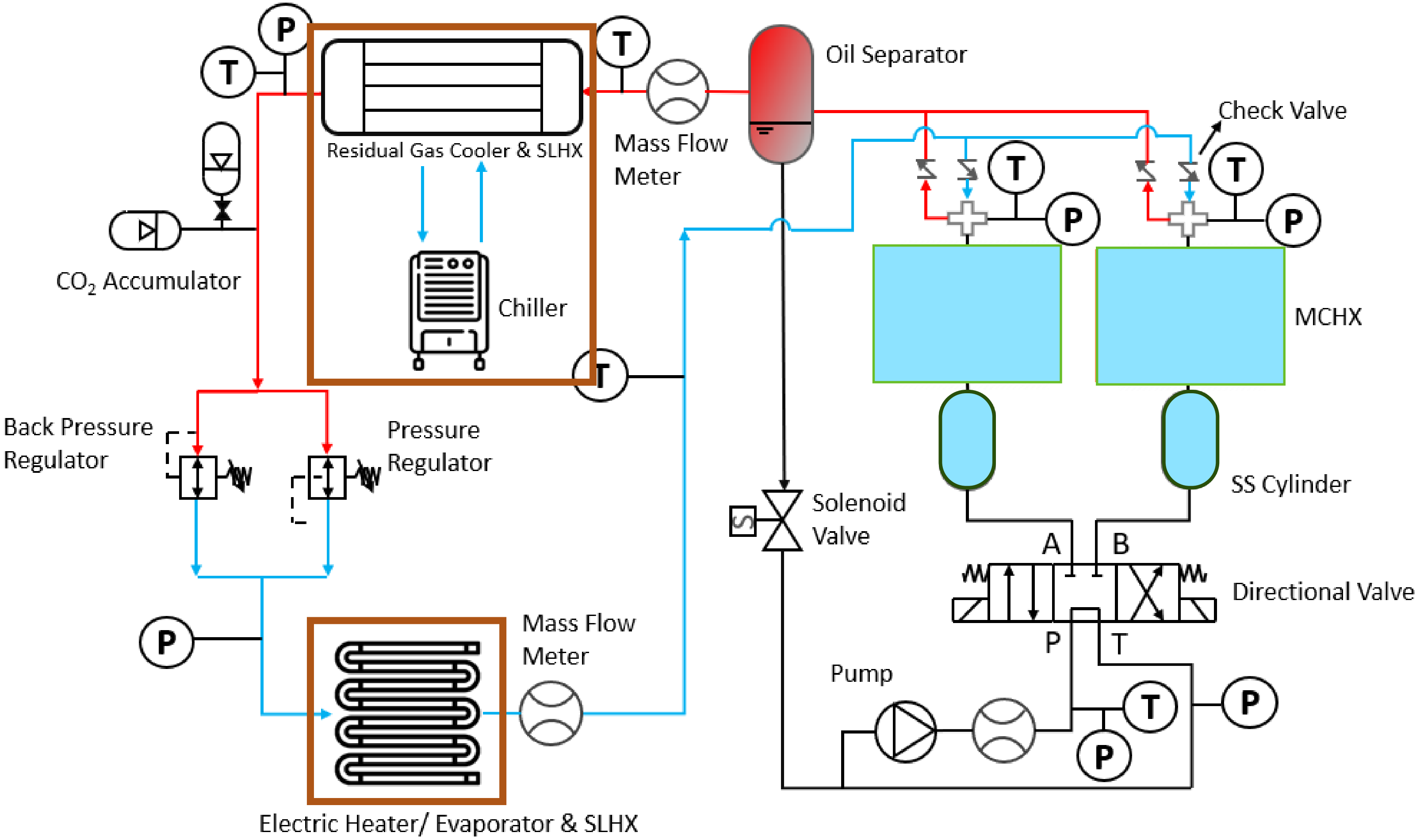
Year-2: Improve the Compressor; Fabricate and Test the 1-ton Refrigeration System (completed)

- 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

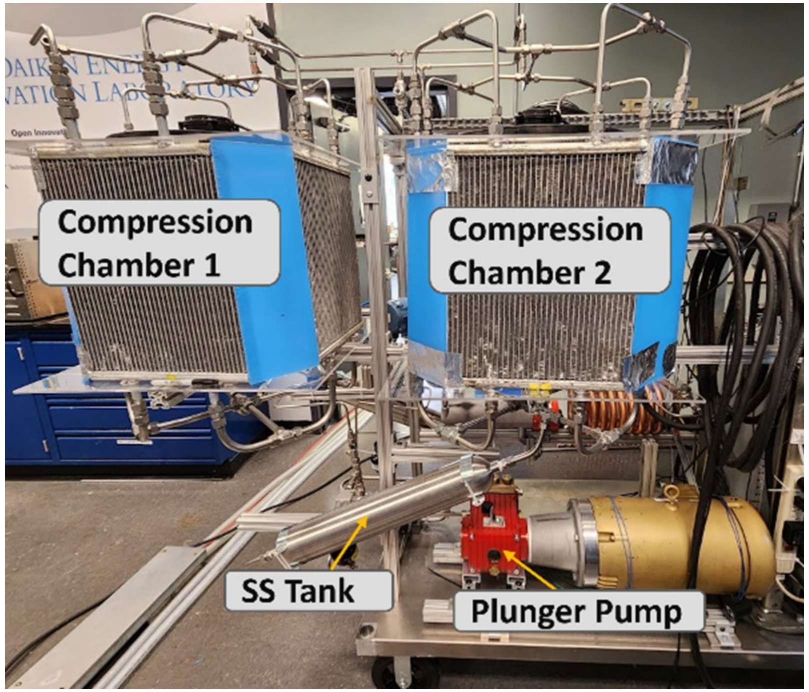
Year-3: Improve and Scale up the Compressor and Conduct Filed Tests (completed)

- 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 – First Prototype (S.T.3.4, M.S.2.3)



1st Prototype System Schematic Diagram

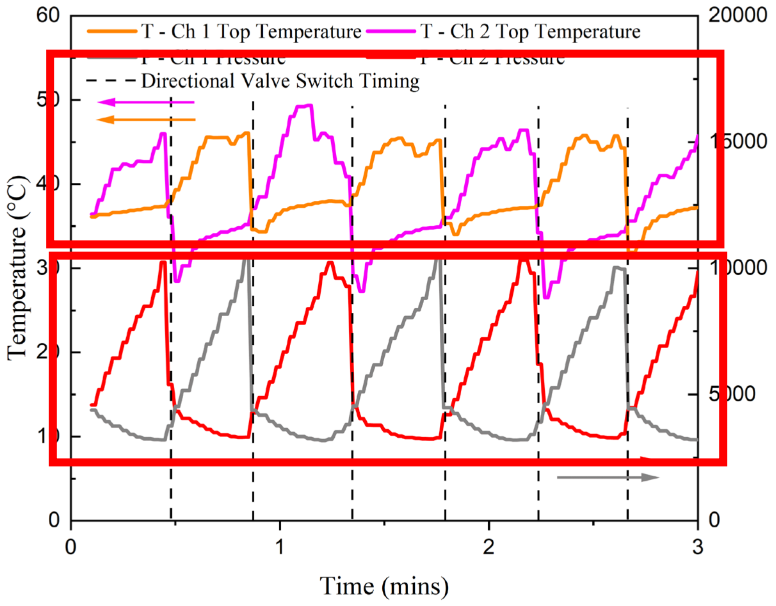


- Double-acting hydraulic system applied for compression.
- A single gas cooler functions as a residual gas cooler plus a suction line heat exchanger.
- A single electric heater functions as an evaporator plus SLHX.

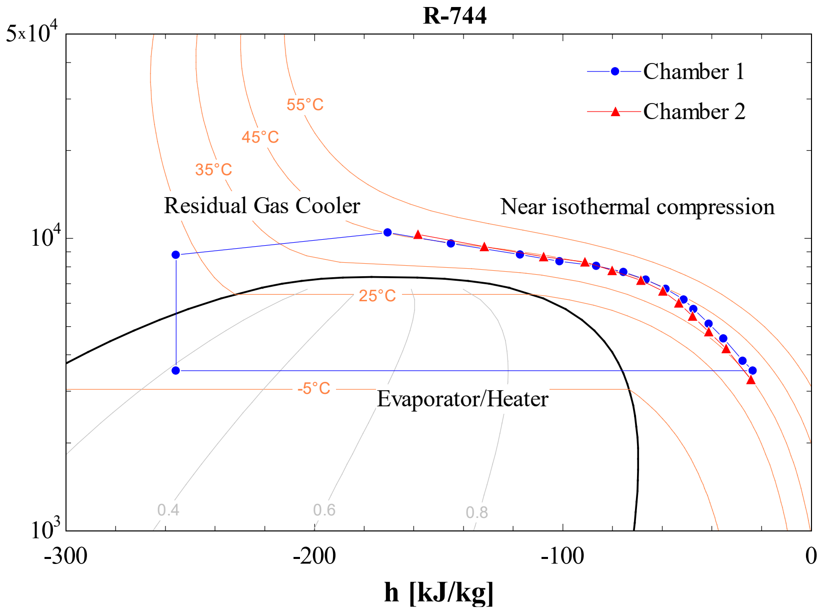
Progress – First Prototype (S.T.3.5, M.S.2.4, M.S.2.5)

Test Conditions for First Prototype

Test No.	Environment Temperature (°C)	Targeting Suction Pressure (kPa)	Pump Speed (RPM)	CO_2 Accumulator No.
Test 1	35	3,000	900	Single



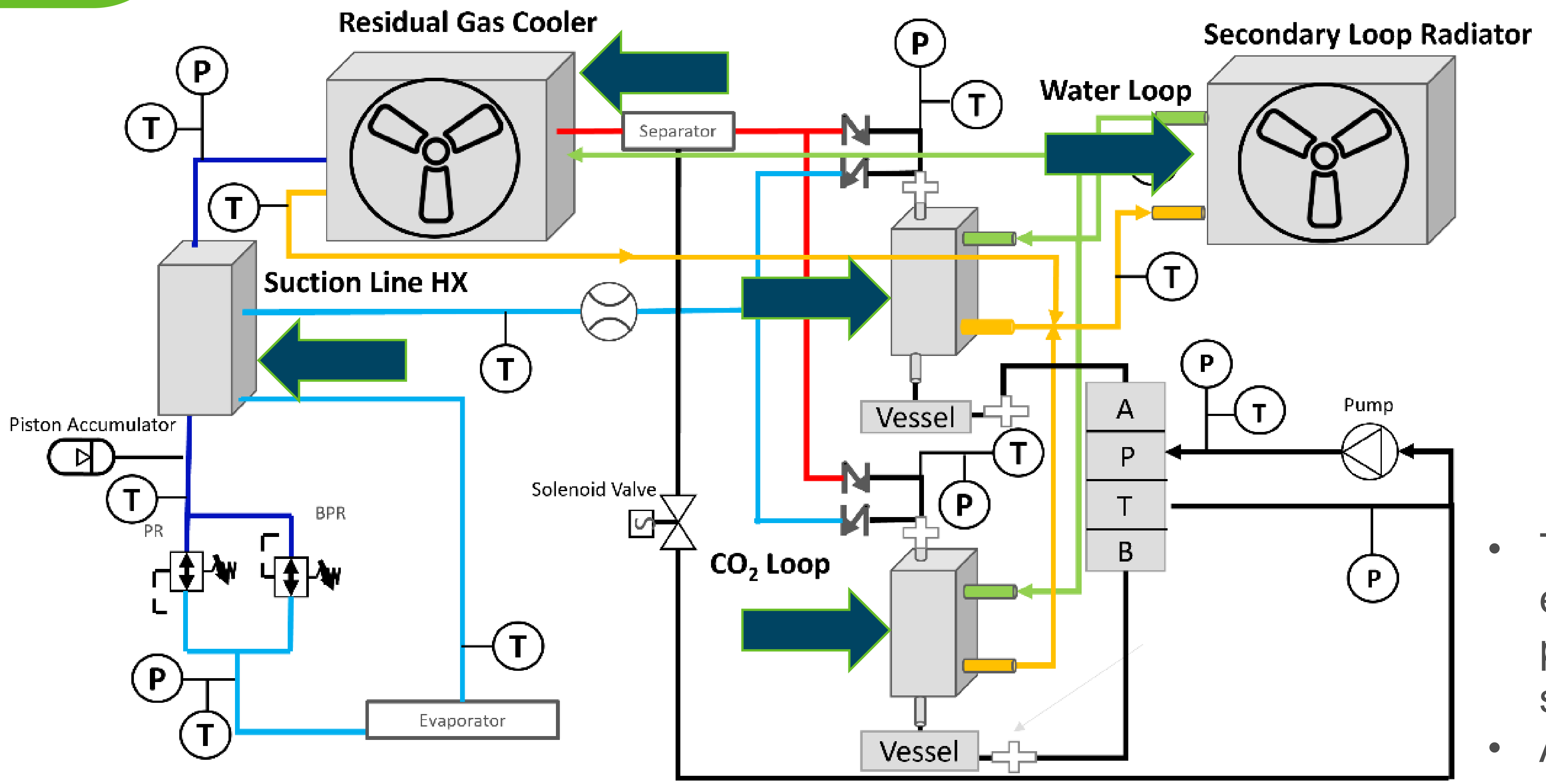
Test 1: Chamber temperature and pressure versus time



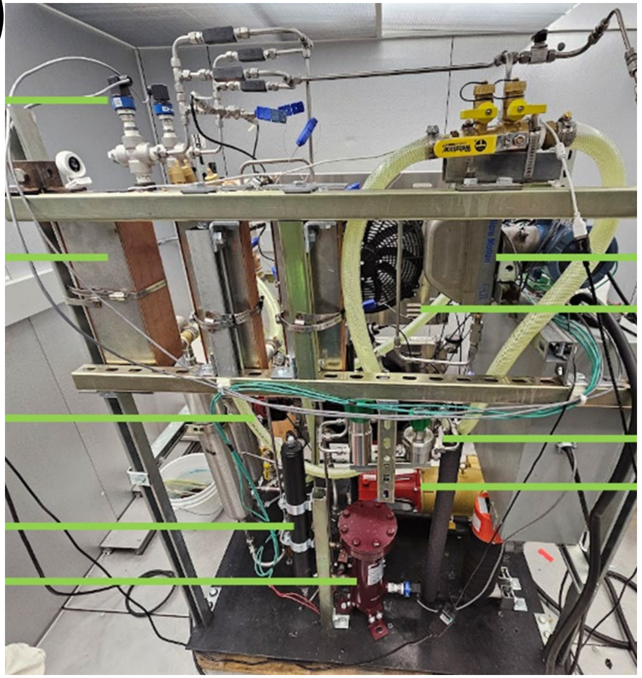
Test 1: Cycle in P-h diagram

- The prototype successfully compressed CO_2 from 3,000 kPa to 10,000 kPa.
- The compression chamber temperature lift is less than 10 K against the isentropic compression process of 100 K.
- The compression process trend in the P-h diagram is similar for both chambers, indicating a similar isothermal compression efficiency, which is 90%.

Progress – Second Prototype (S.T.4.3)



2nd Prototype System Schematic Diagram

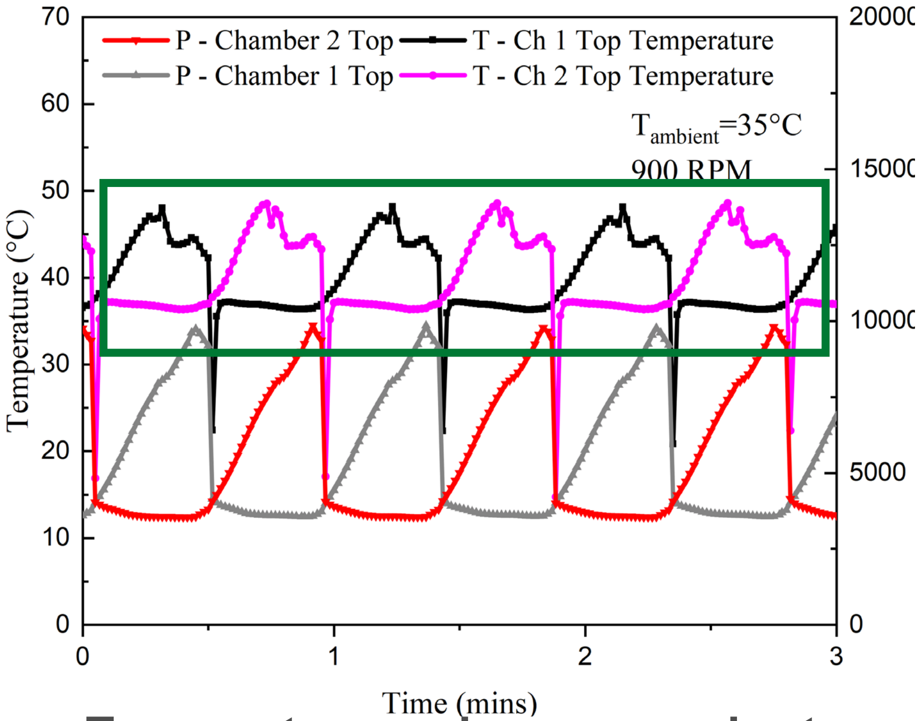


- The compression chamber heat exchangers were replaced with plate heat exchangers to make the system more compact and robust.
- A secondary loop was used to dissipate heat to the surroundings.
- The volumetric dimensions were reduced by 30% compared to the first prototype.

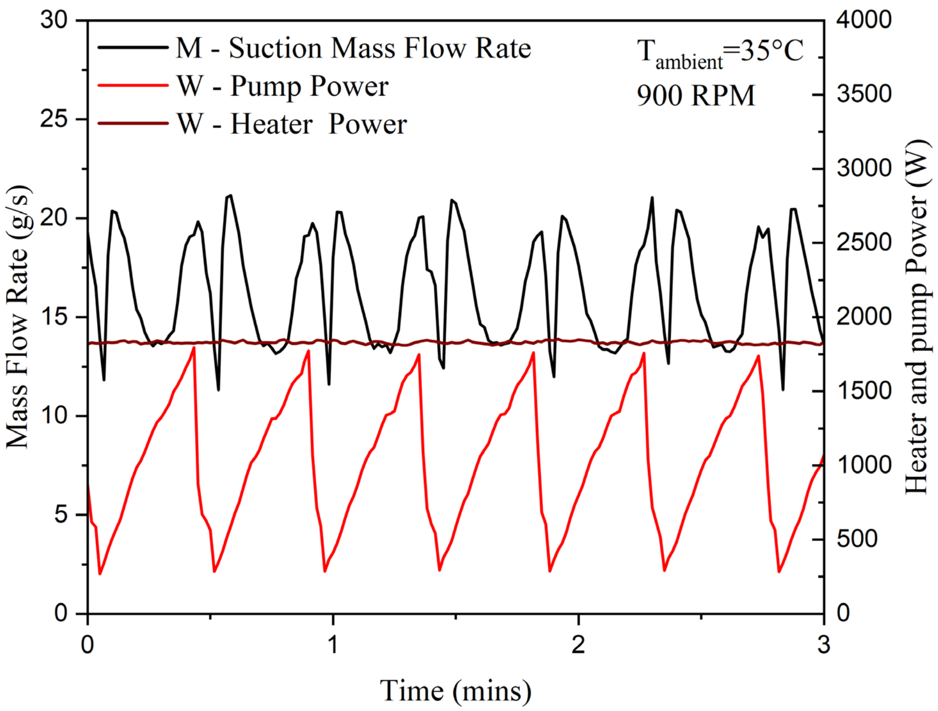
Progress – Second Prototype (S.T.4.3)

Test Conditions for Second Prototype

Test No.	$T_{Ambient}$ (°C)	Driving Speed (RPM)	Suction Pressure (kPa)
1	35	900	3,500



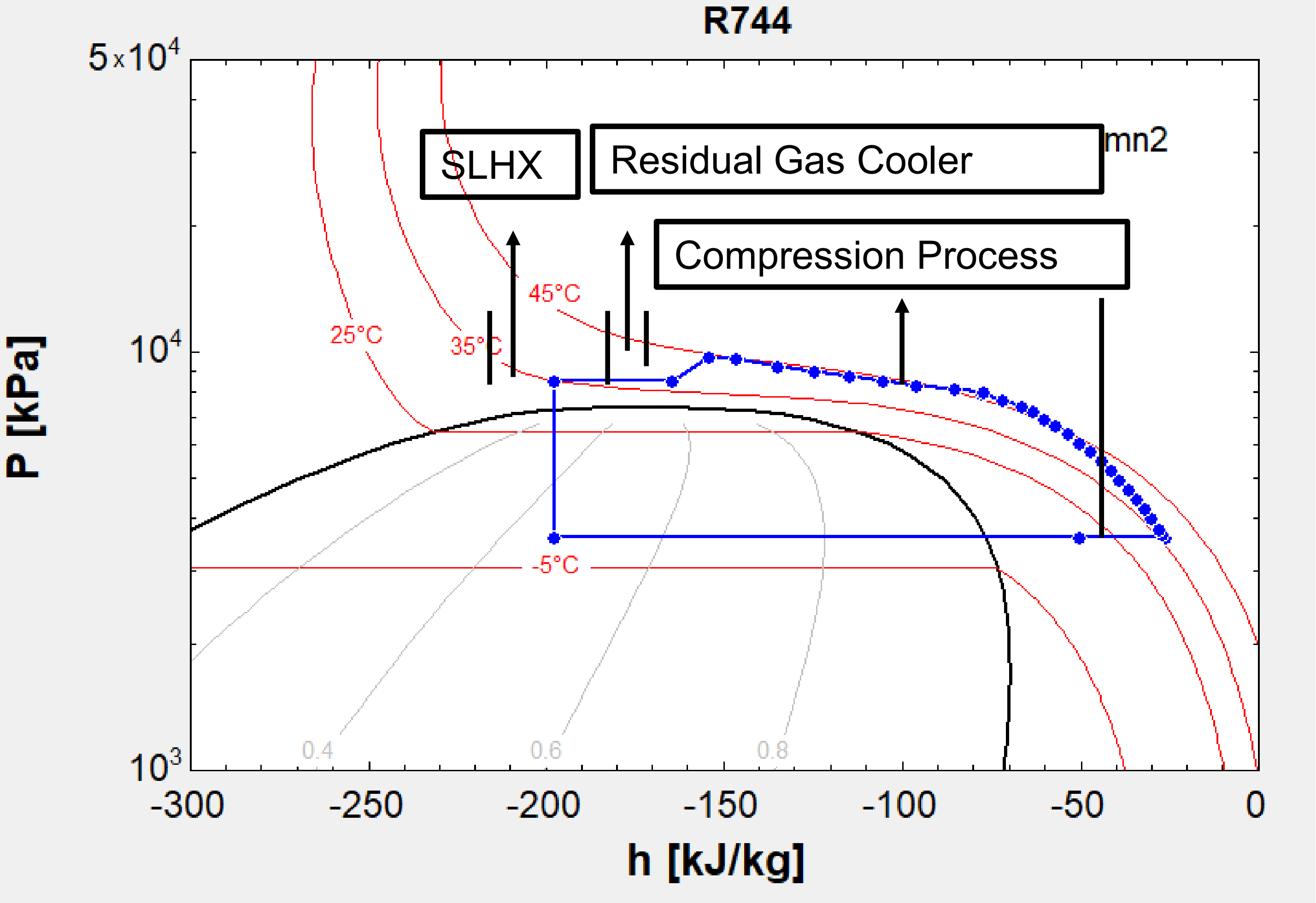
Temperature and pressure chart



Heater/pump power and mass flow rate

- The second prototype demonstrated a more symmetric temperature and pressure profile than the first prototype.
- Switching from pressure regulators to an electronic expansion valve results in larger mass flow rate fluctuations, but the flow remains continuous.

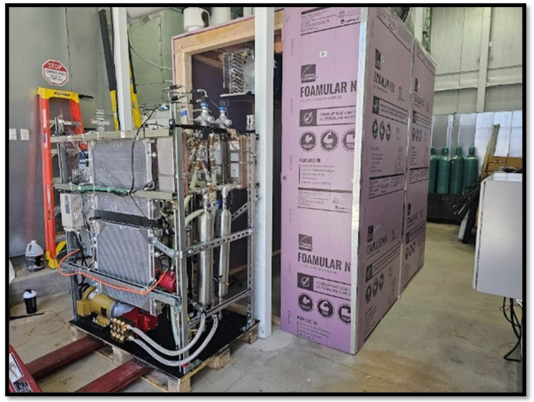
Progress – Second Prototype (S.T.4.3)

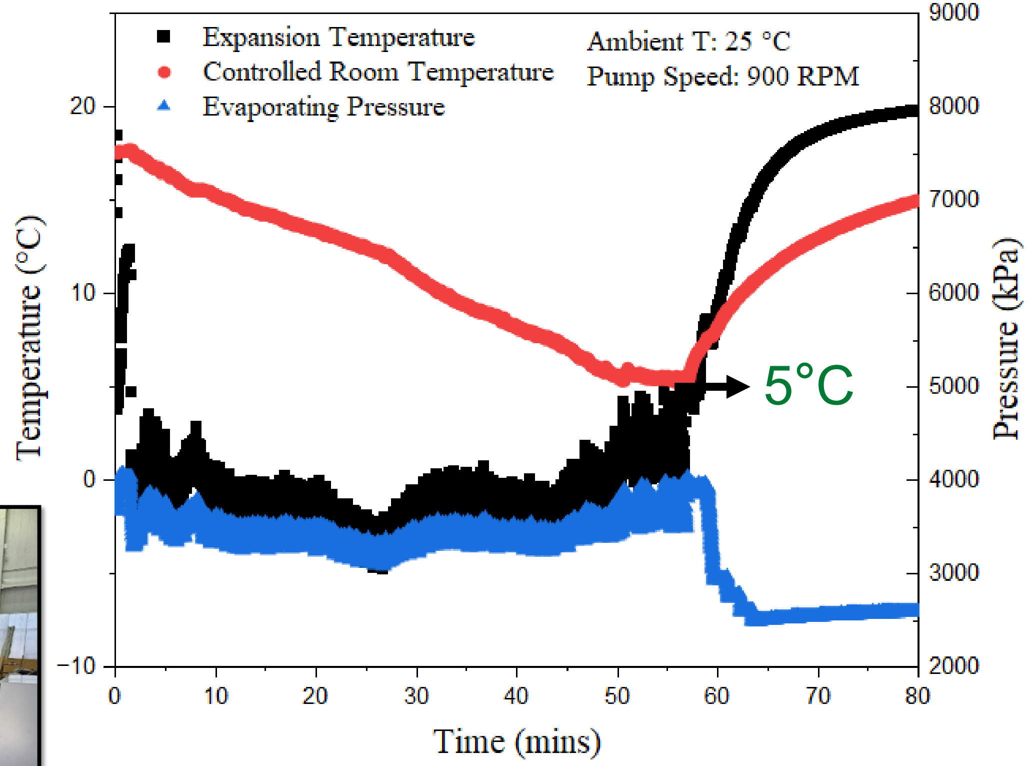


Cycle in P-h diagram

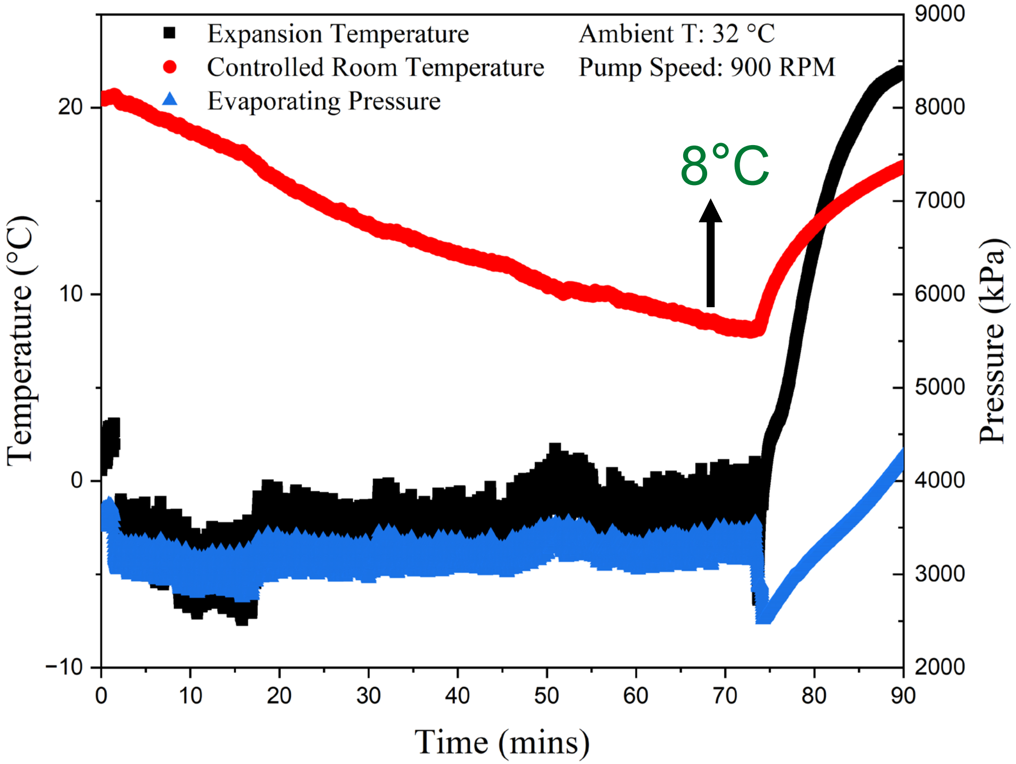
- Isothermal Efficiency: 89.1%
- Avg. Pump Power: 1,005 W
- Avg. Heater Power: 1,828 W
- Avg. Suction Pressure: 3,789 kPa (T_{evap}=3.2 °C)
- COP: 1.82
- This represents a 40% improvement in the system performance compared to Prototype 1.

Progress – Field Test at the Helix Innovation Center (S.T.4.4, M.S.3.3)





Test 1: Subcritical Operation at 25°C Ambient Temperature



Test 2:Transcritical Operation at 32°C Ambient Temperature

Heat Transfer Analysis and Scenario Comparison

	Heat transfer (wall + roof)		Heat transfer (floor)		Fan power load		Infiltration load		Overall cooling capacity	
Test 1	585 W	29.9 %	576 W	29.5 %	200 W	10.2%	593 W	30.4 %	1,954 W	100%
Test 2	702 W	40.0 %	490 W	27.9 %	200 W	11.4%	362 W	20.7 %	1,754 W	100%

Progress – Modeling Results Comparison (S.T.3.3)

- In simulations, the energy losses associated with volumetric, mechanical, and motor loss were not considered.
- Pump assumptions
  1. Volumetric efficiency: 70% (because of degassing)
  2. Mechanical efficiency: 90%
  3. Motor efficiency: 95%

Cases	COP
Simulation baseline case	1.62
Simulation chamber optimization 1 – Cone shape	1.66
Simulation chamber optimization 2 – Varied heat transfer areas	1.68
Simulation chamber optimization 3 – Variable flow rate	1.75
Experimental prototype 1 (Air-Refrigerant HX)	1.3
Experimental prototype 2 (Secondary loop)	1.8

+8%

- The simulations show comparable performance results with the experiment.
- Chamber design optimization can improve the COP by 8%.
- The experimental prototype utilizing a secondary loop outperforms the other cases with a COP of 1.8.

Progress – Application Other Than CO_2 Compression (M.S.3.4)

Applications Exploration

Applications	Conditions	Isothermal Efficiency at 0.05 Hz
CO_2 Compression	$P_{initial}$ = 3,000 kPa, P_{end} = 10,000 kPa, $T_{initial}$ = 40°C, $T_{ambient}$ = 35°C,	Simulation: 91.5% Experiment: 89.7%
Compressed Air Energy Storage		Simulation: 99.0%
Hydrogen Compression		Simulation: 98.8%
Compressed Natural Gas	$P_{initial}$ = 3,000 kPa, P_{end} = 16,000 kPa, $T_{initial}$ = 25°C, $T_{ambient}$ = 25°C,	Simulation: 93.8%

- A simulation model was developed and validated using experimental CO_2 data.
- Applying the liquid piston compressor to air, hydrogen, and natural gas demonstrates promising compression efficiency.

Outcome and Impact

- **Advancement of Compressor Technology**
  - Realize the near-isothermal compression for 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[a]
- **Acceleration of Energy Intensity Improvement toward NZB by 2050**
  - In 2022, the energy consumption for the residential and commercial sectors was 33 Quads[b]
  - Space cooling and refrigeration account for 20% (6.6 Quads)
  - If deployed the technology to both sectors with a 30% energy consumption reduction, the yearly energy savings will be 2.0 Quads

Future Work

- **Experimental Work**
  - Develop a hermetic or semi-hermetic pump to eliminate the use of mechanical seals. Reducing the leakage risk and improving the compressor efficiency.
  - Replace the mineral oil with polar liquids, such as water and glycerol, to reduce the CO_2 solubility.
  - Elevate the compression frequency to further downsize the dimensions of the liquid piston compressor by increasing the liquid flow rate and using compact and efficient HX.
- **Simulation Work**
  - Develop a system-level model, conduct an optimization study, and improve the experimental setup design.
  - Develop a comprehensive simulation model that considers the solubility of the hydraulic fluid.

Thank You

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