2024 PROJECT PEER REVIEW

U.S. DEPARTMENT OF ENERGY
BUILDING TECHNOLOGIES OFFICE

BTO Peer Review:

Low-Charge Heat Pump Water Heater Using Propane

Low-Charge Heat Pump Water Heater Using Propane

Oak Ridge National Laboratory (ORNL)
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WBS#03.02.02.43, Lab Call CRADA with Rheem

Project Summary

OBJECTIVE AND OUTCOME

- Develop compact condensers to reduce charge and achieve similar heat transfer effectiveness as wrapped tank *D*-shape coils
- Develop and calibrate a propane heat pump water heater (HPWH) system design tool
- Motivate the supply chain to develop propane-enabling technologies (i.e., a propane-specific compressor @ 60 Hz) and optimized microchannel condensers
- Perform laboratory verification and accelerated life tests on a 220 V HPWH prototype reaching a 3.3 Uniform Energy Factor (UEF) with propane <150 g or UEF> 2.2 with propane < 115 g

Propane (R290), natural refrigerant

TEAM AND PARTNERS

- Rheem Manufacturing Company
- ORNL: Bo Shen, Mingkan Zhang

STATS

Start date: 04/01/2022   Planned end date: 01/30/2025

Budget: DOE total—$300K; Rheem cost share—$300K

<u>Key Milestones</u>

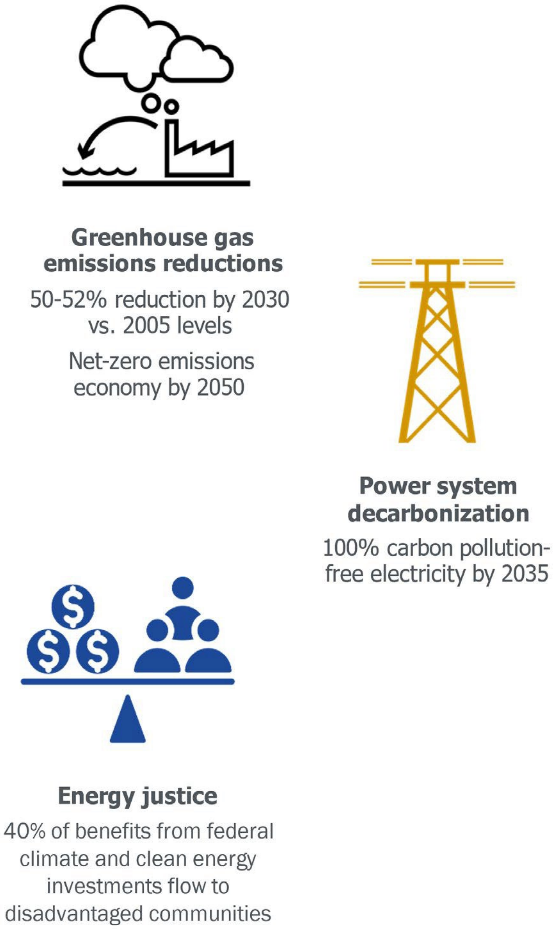
1. Develop compact condenser coil sizing and a propane HPWH system design tool, 06/30/2022
2. Experimentally study the performance of compact condensers (i.e., microchannel and submerged condensers), 09/30/2022
3. One-year life test of a submerged condenser, 08/30/2023
4. Initial lab tests to verify a UEF >3.0 using a propane charge near 200 g, 09/30/2023
5. Design optimization and built lab prototypes, 09/30/2024
6. Experimental results prove a measured UEF >3.3 and a system charge <150 g, or UEF > 2.2, charge < 115 g, 01/30/2025

Problems

- The HPWH industry is phasing out R-134a (global warming potential [GWP] of 1,430).
- Propane has an ultralow GWP (<3.3) and is less expensive and more environment-friendly than hydrofluoroolefin alternatives (R-1234yf and R-1234ze). But propane is extremely flammable and subject to a charge limit (<150 g/115 g) for indoor use.
- The European market prefers propane over fluorinated-gas refrigerants. Propane HPWHs have better marketing potential internationally. However, no propane HPWHs are on the US market.
- Component technologies are not fully ready for propane (i.e., a propane-specific compressor @ 60 Hz) and compact heat exchangers with reduced charge.

Alignment and Impact

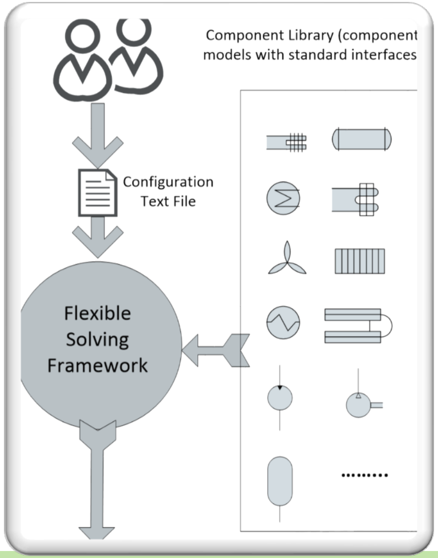
- Greenhouse gas emissions reductions: Replace high-GWP refrigerants in Rheem's residential HPWH product families
- Energy justice: propane leads to HPWHs with low prices
- Develop and calibrate a high-fidelity, public-domain HPWH and heat exchanger modeling and design tool for propane to accelerate product development

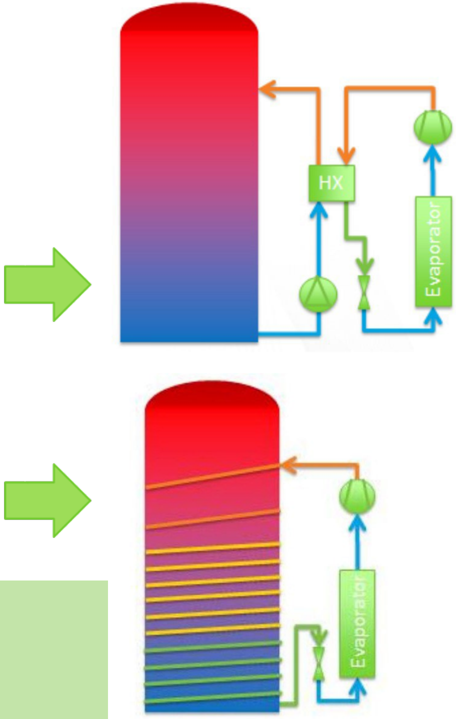


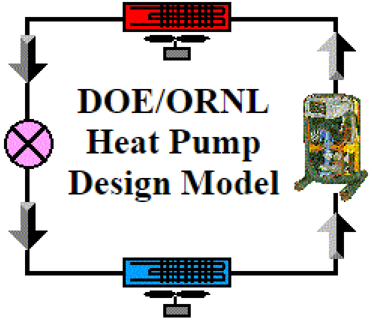
Approach Upgrade DOE/ORNL Heat Pump Design Model

Component models have standard interfaces with the solving framework and generic connections to each other.

Component-based



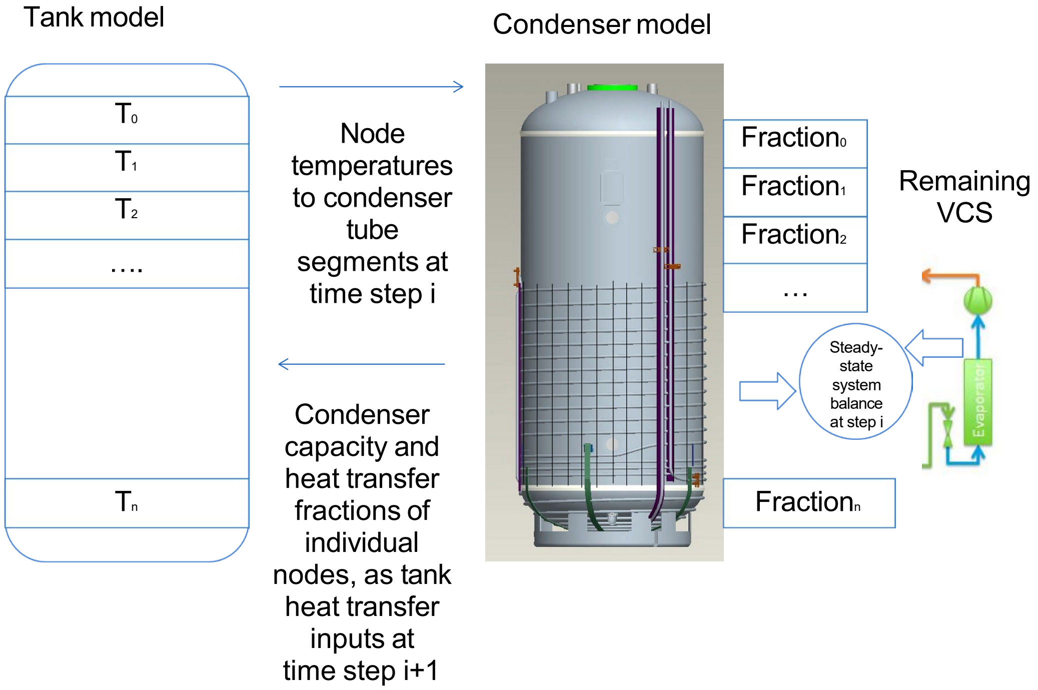


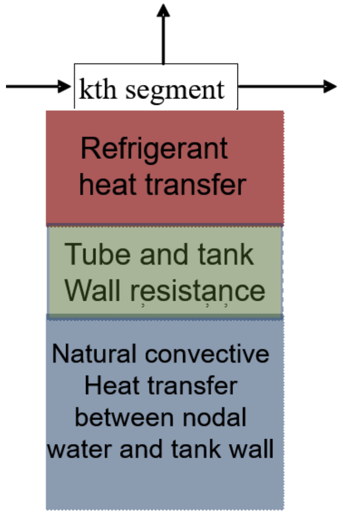


https://hpdmflex.ornl.gov

Automatically connect components into the required system configuration by user input file.

Segment-to-Segment Tank Coil Model





24 h UEF and first-hour rating simulated within 5 min

Coupled a segment-to-segment coil model to a stratified tank model

- Pattern of the wrapped-tank coil affects stratification
- Water stratification is a boundary condition to the segment-to-segment coil model

Approach Laboratory Investigations of Compact Condensers

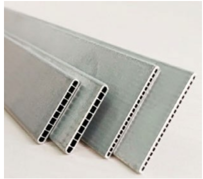
- Investigate a microchannel condenser for charge reduction: The refrigerant charge (inner volume) in a tube relative to its surface area is
  $(\pi \times d^2/4 \times \textit{Tube Length})/(\pi \times d \times \textit{Tube Length}) = d/4$.
- Evaluate a finned, double-wall submerged condenser and study the impact of water-side scaling via an extended period of life test.

Develop and Integrate Compact Condensers

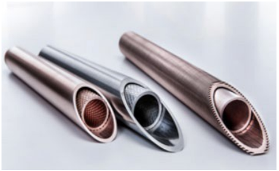
Conventional

D-shape tube, wrapped tank coil

Proposed designs



Microchannel, wrapped tank coil



Double-wall submerged condenser (internal)

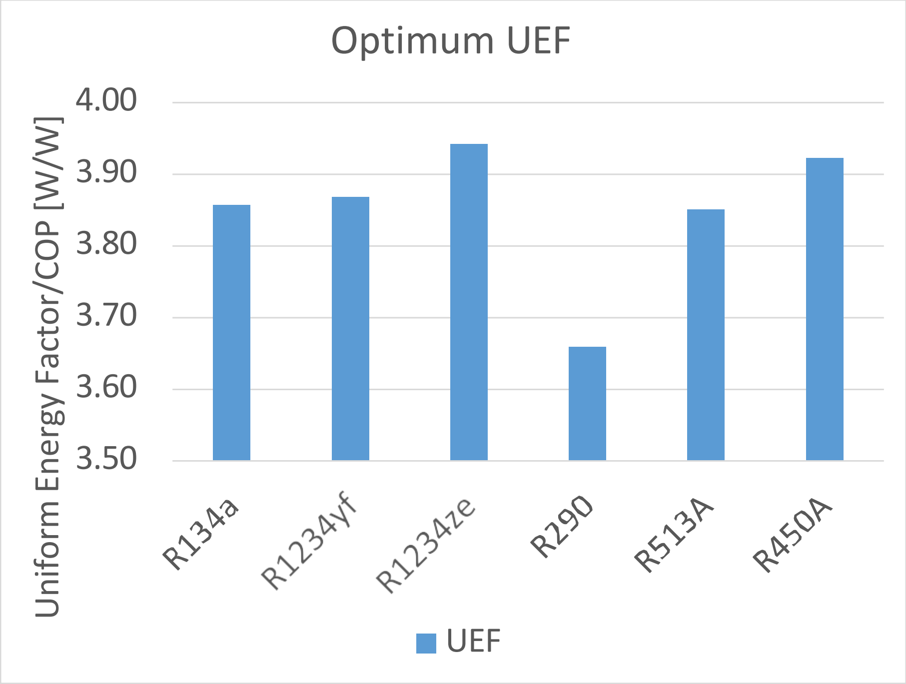
Progress Propane HPWH System Model with Other Alternatives

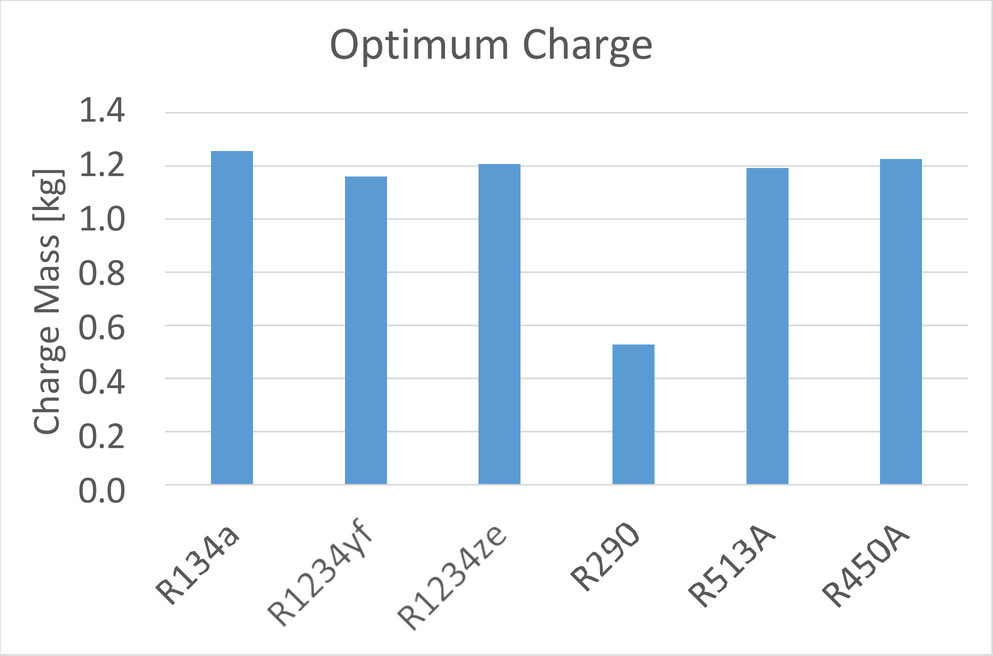
Refrigerant	GWP	Safety Class	Glide/Pressure in Condenser @ 54.4°C [K/kPa]	Glide/Pressure in Evaporator @ 4.4°C [K/kPa]	Critical Temperature/ Mole Weight [C/(g/mol)]	Volumetric Vaporization Heat @ 54.4°C [kJ/m³]	Volumetric Vaporization Heat @ 4.4°C [kJ/m³]
R-134a (baseline)	1,430	A1	0/1469	0/342	101.06/102.03	10,959.4	3,276.0
R-290	3	A3	0/1883	0/541	97.0/40.06	11,800.3	4,335.3
R-1234yf	4	A2L	0/1444	0/366	95.0/114.04	10,024.4	3,263.7
R-1234ze	6	A2L	0/1114	0/254	153.7/114.04	8,522.1	2,473.2
R-450A[a]	547	A1	0.60/1284	0.64/297	104.4/108.67	9,700.5	2,861.0
R-513A[b]	573	A1	0.01/1530	0.01/377	96.5/108.43	10,832.0	3,442.8

[a] R-450A has mass-based compositions of R-1234ze (0.58) / R-134a (0.42).
[b] R-513A has mass-based compositions of R-1234yf (0.56) / R-134a (0.44).

Propane has a higher working pressure and volumetric capacity (smaller compressor).

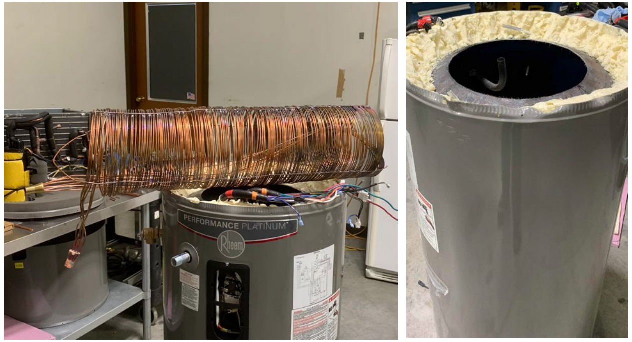
Progress Feasibility Study by Simulation (direct drop in)





A propane HPWH can reach a similar 24 h uniform heating efficiency (95%) as and the required 50% charge of R-134a because of propane's small molecular weight.

Progress Development of a Submerged Capillary Tube Condenser



First version

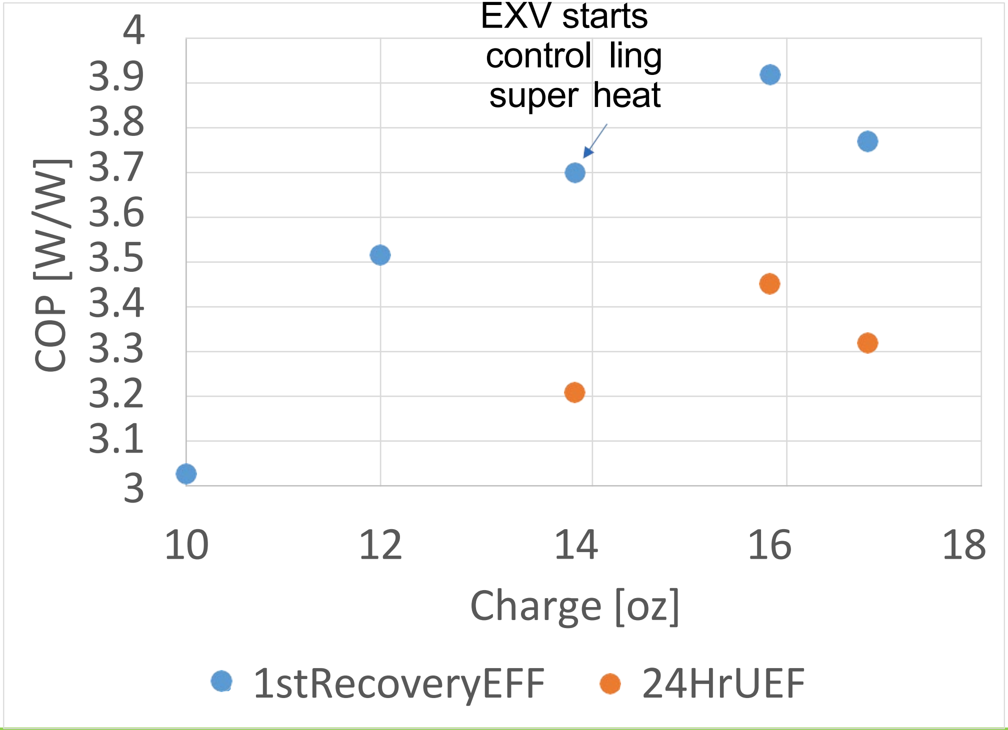
Third version

Four prototypes to find optimized parameters

R-134a	**Baseline *D*-shape tube**	**First microtube bundle**	**Second microtube bundle**	**Third microtube bundle**	**Fourth microtube bundle**
Tube outside diameter [mm]	10.6	3	3	3	3
Total tube length [ft]	118	400	250	136	180
# circuits	1	8	12	12	16
Tube surface area at water side [ft^2]	4.1	12.4	7.7	4.2	5.6
UEF [W/W]	3.55	2.8	3.0	3.20	3.26
Charge [oz]	22	22	22	14	18
Coil pressure drop [psid]	20	80	40	30	20

Achieved 40% charge reduction with a 10% lower UEF than the baseline

Progress Evaluate a Finned, Double-Wall Submerged Condenser

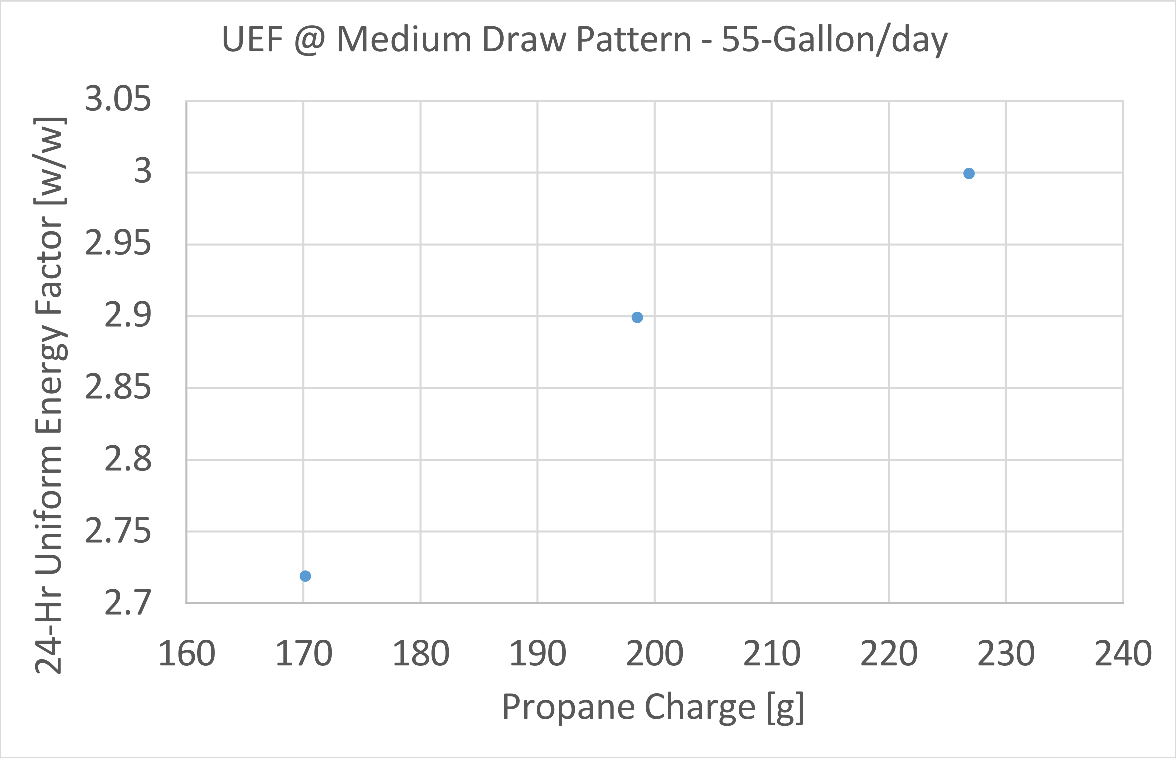


R-134a

Achieved a 3.45 UEF @ 16 oz (versus the 3.55 UEF @ 24 oz for the wrapped tank coil) using the same evaporator, fan, and blower

Performed an 8-month life test (Draw 55 gal UEF test, Tennessee city water every day); no apparent performance degradation due to water scaling

Progress Lab Tests to Verify a UEF Near 3.0 Using a Propane Charge of 200g

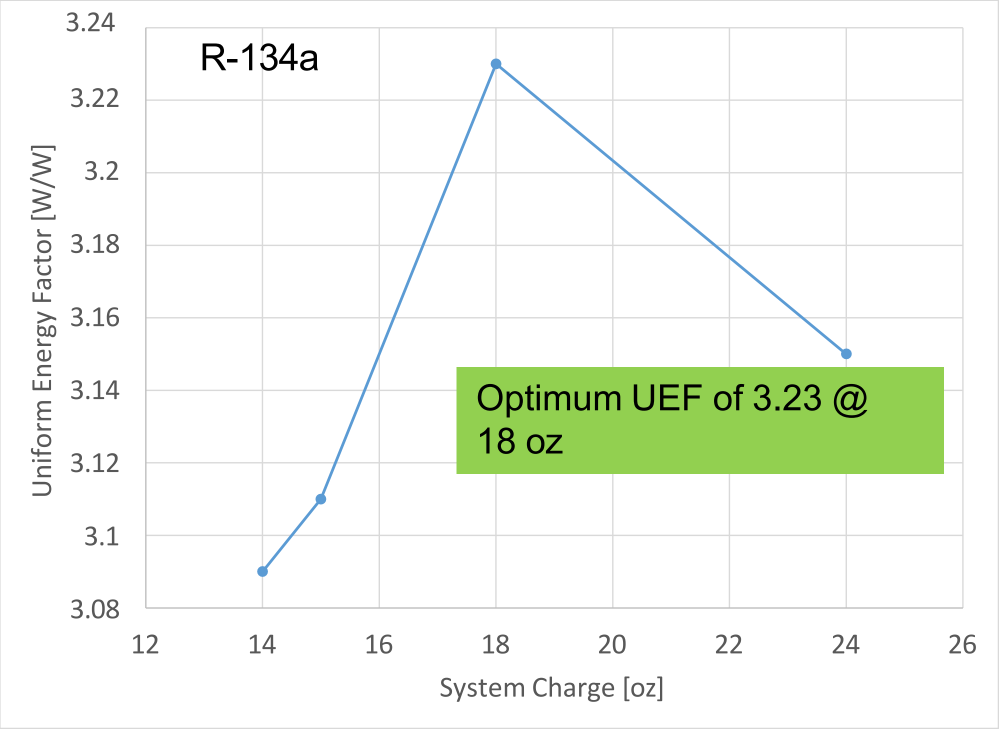


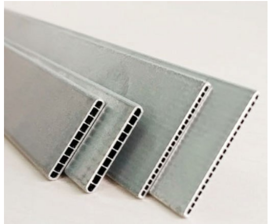
- Laboratory investigations @ UEF test condition
- 50 gal tank
- 24 h medium draw pattern
- Entering water @ 58°F
- Temperature set @120°F
- Finned, double-wall submerged condenser

- Confirmed control (electronic expansion valve) is directly workable for propane systems

Progress Evaluate Microchannel Condenser

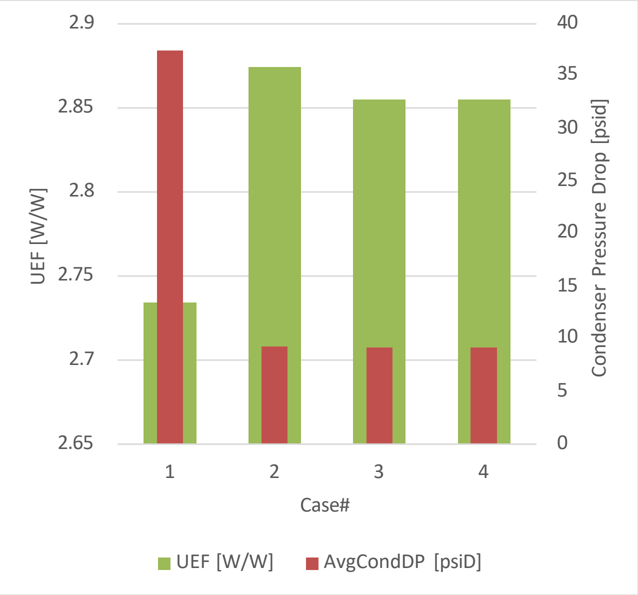
- Because of the inlet and outlet headers, eliminating contact resistance is difficult
- Refrigerant flow merges and separates in multiple intermediate passes, causing two-phase refrigerant flow maldistribution at downstream passes

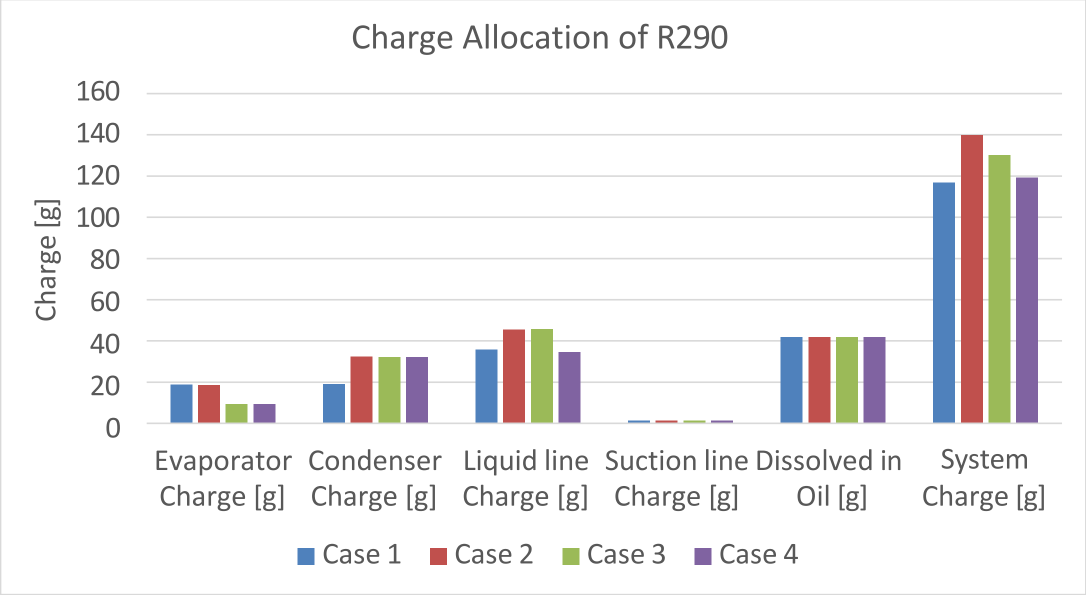




Simulation based design and charge minimization

- Case 1: 3.2cc compressor, 6 microchannel wraps, 16mm width, fin-and-tube evaporator,16 mm microchannel liquid line
- Case 2: 3.2cc compressor, 5 microchannel wraps, 32mm width, fin-and-tube evaporator, 32mm microchannel liquid line
- Case 3: 3.2cc compressor, 5 microchannel wraps, 32mm width, equivalent microchannel evaporator, 32mm microchannel liquid line
- Case 4: 3.2cc compressor, 5 microchannel wraps, 32mm width, equivalent microchannel evaporator, 5mm round tube liquid line





Charge percentages in liquid line and compressor oil become considerable

Ongoing Project Work

- Design optimization to size the compressor; configuration of the condenser and evaporator
- Prototyping:

✓ Acquired three propane-specific compressors with different capacities

✓ Built two HPWH prototypes that both use microchannel condensers: one with a microchannel evaporator and the other with a fin-and-tube evaporator

Note: Waiting for ORNL to upgrade test facilities to evaluate propane >120 g

Publication:
“A Numerical Modelling Study on Submerged Condensers for Heat Pump Water Heaters Using Low-GWP Refrigerants,” Mingkan Zhang, Bo Shen, International Refrigeration Conference at Purdue, 2022.
Heat Pump Design Model online version: https://hpdmflex.ornl.gov/

Future Work and Commercialization Plan

- Rheem to launch propane HPWHs with a charge limit of <115 g and a UEF of >2.2

Thank you

Oak Ridge National Laboratory

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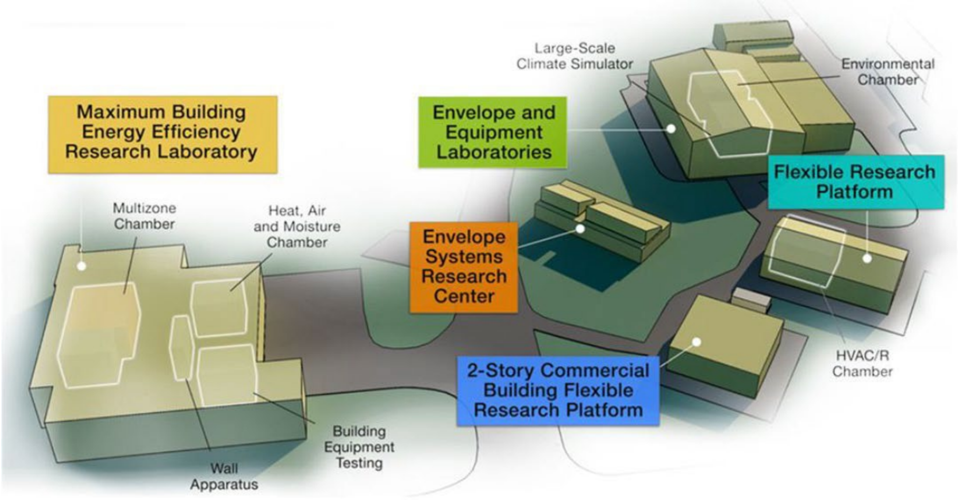

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Scientific and Economic Results
139 publications in FY24
140+ industry partners
60+ university partners
16 R&D 100 awards
64 active CRADAs

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Stakeholder Engagement

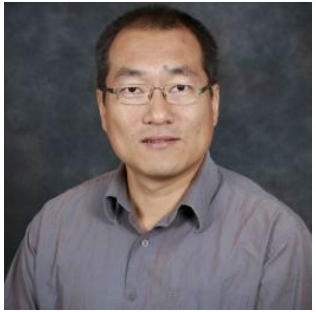
Industry Partner – Rheem Manufacturing Company

- Supported Rheem team to use DOE/ORNL Heat Pump Design Model to optimize heat exchanger design and accelerate HPWH system development.
- Rheem motivated its suppliers to improve microchannel condenser design and make propane specific compressor @ 60 Hz.
- Rheem fabricated system prototypes embedded with numerous condenser technologies for ORNL’s system level experiments.
- Weekly meetings with Rheem engineers to monitor the progress.

Project Execution

	FY2022				FY2023				FY2024			
Planned budget	100K				100K				100K			
Spent budget	100K				100K				50K			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Develop compact condenser coil sizing and propane HPWH system design tool												
Experimentally study performance of compact condensers, i.e., microchannel and submerged condensers												
One year life test of submerged condenser												
Initial lab tests verify a UEF > 3.0 using propane charge near 200 grams												
Current/Future Work												
Design optimization and built lab prototypes												
Experimental results prove measured UEF > 3.3, system charge < 150 grams; or UEF > 2.2, system charge < 115 grams												

Team



Dr. Bo Shen
- System design and modeling
- Laboratory testing

Dr. Saman Beyhaghi
Manager, Advanced Technology Research
- Procure parts
- Manufacture prototypes

Dr. Mingkan Zhang
- CFD analysis
- Laboratory testing