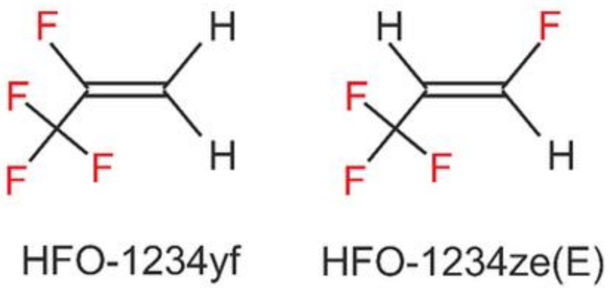
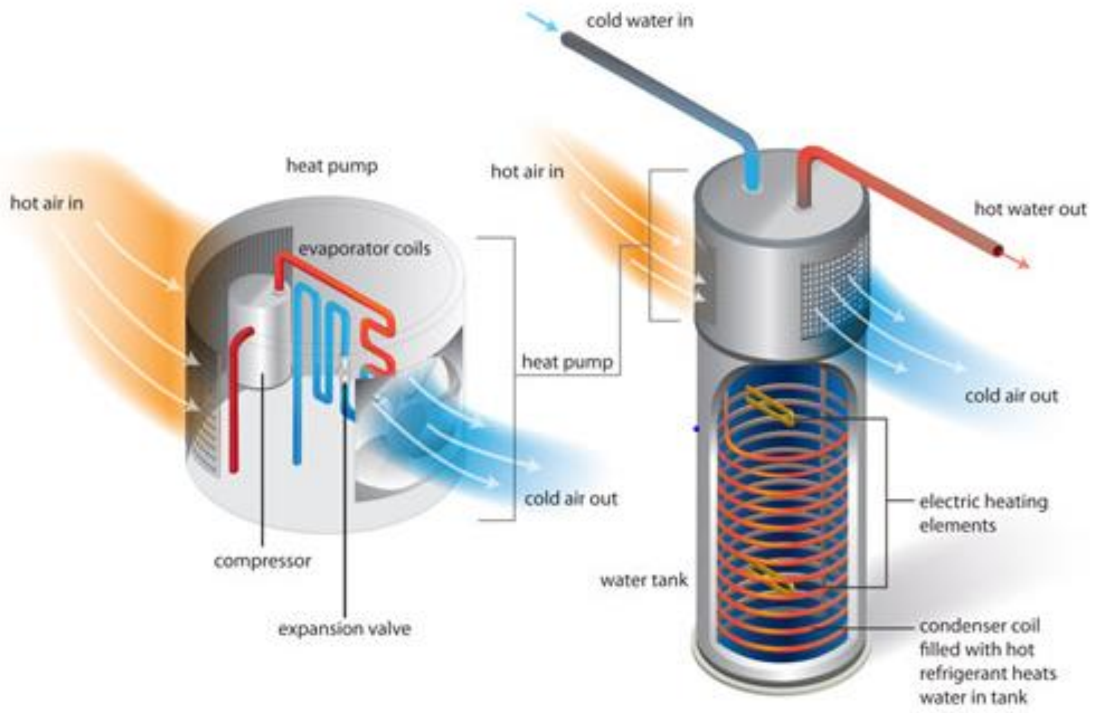
Max Tech Efficiency Electric HPWH with low-GWP Halogenated Refrigerant (A.O. Smith)





Oak Ridge National Laboratory
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Project Summary

Timeline:

Start date: October 2018

Planned end date: October 2021

Key Milestones

1. Feasibility analysis of HFO refrigerants to replace R-134a (May 2019)
2. Development of next generation HPWH with improved UEF and FHR (October 2020)

Budget:

Total Project $ to Date:

- DOE: $1592K
- Cost Share: $200K

Total Project $:

- DOE: $1592K
- Cost Share: $300K

Key Partners:

Oak Ridge National Laboratory

A.O. Smith — Innovation has a name.

Illinois — University of Illinois at Urbana-Champaign

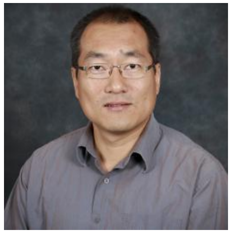
Project Outcome:

The project is focused on two major aspect for the development of next generation heat pump water heating technology.

1. Deployment and performance optimization for hydrofluoroolefins as alternate refrigerants to substitute conventional working fluids (R134a).
2. Design and optimization of individual components and overall system to maximize the performance (Unified Energy Factor- UEF and First Hour Rating-FHR)

Project Team

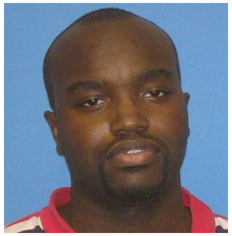
- **Oak Ridge National Laboratory**
  - Kashif Nawaz (R&D staff)
  - Bo Shen (R&D staff)
  - Ahmed Elatar(Post-Doc associate)
  - Van Baxter (R&D staff)
  - Jeff Munk (R&D staff)
  - Tony Gehl (R&D staff)
- **A. O. Smith Corp.**
  - Steve Memory (Research Director)
  - Jiammin Yin (Senior Engineer)
- **University of Illinois** (James Carpenter)
- **Texas A&M, Kingsville** (Joseph Randall)
- **University of Tennessee** (Alic Brigham)



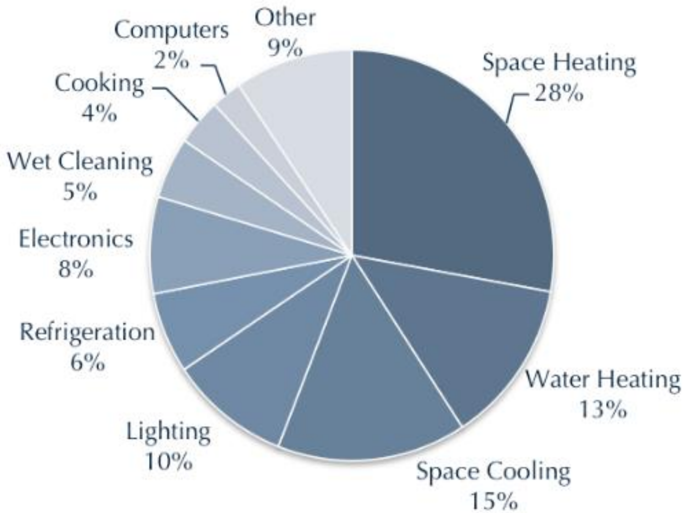




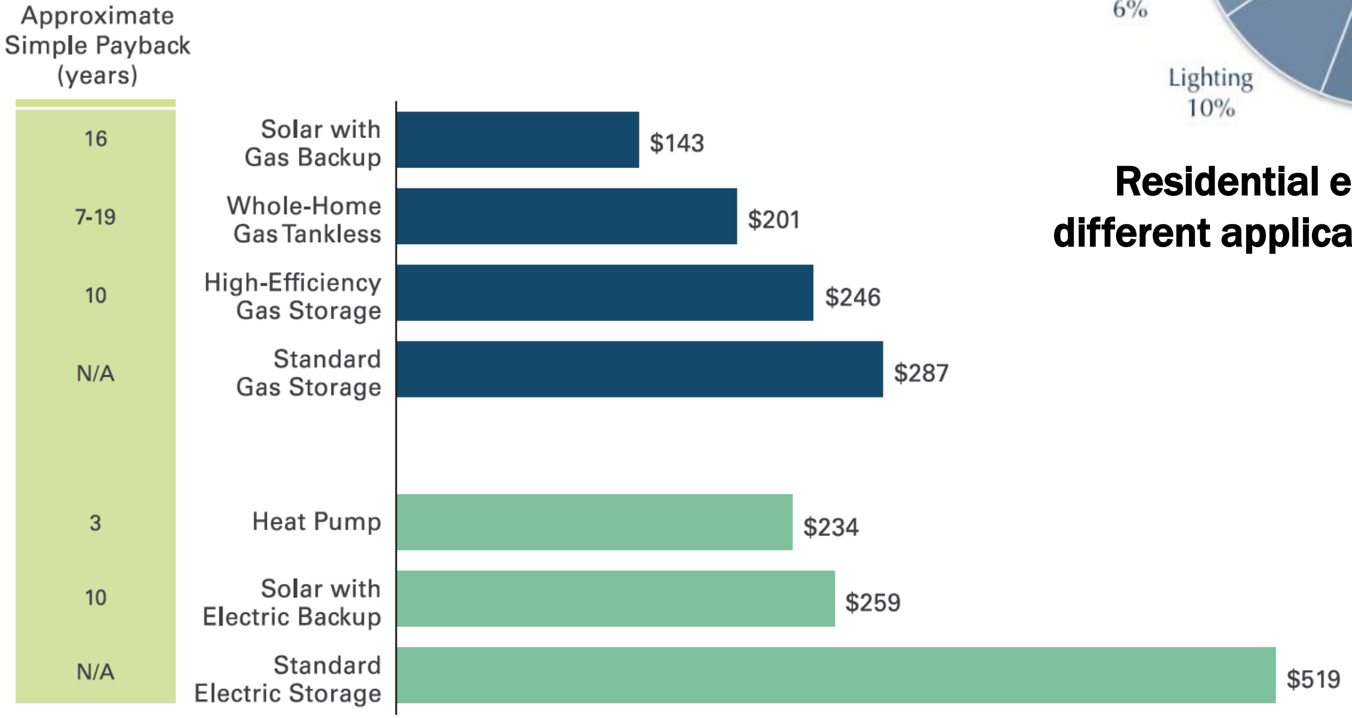



Background

Water heating accounts for about 10% of all residential and commercial site energy use in the United States.



Residential end-use energy by different applications (US EIA, 2013)



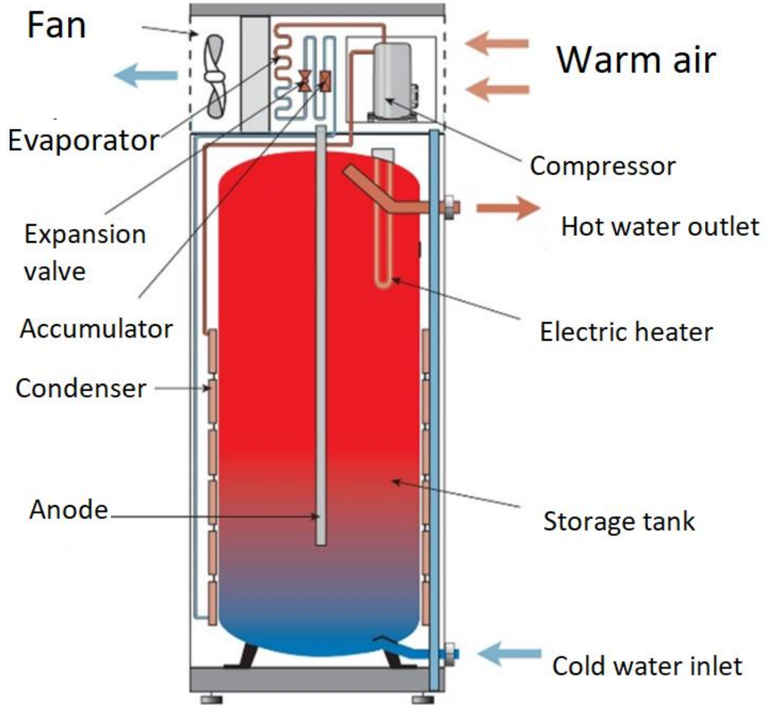
Annual Energy Consumption of Various Water Heating Technologies.

Energy Star Water Heater Market Profile, D&R International, 2010

Background

- HPWH technology has been validated and proven to be successful through lab and field experiments.
- While the technology is mature, there are obvious opportunities to further enhance the performance of the systems.

- Hybrid configuration assist to meet the demand when HP can not provide sufficient heating.
- The overall system performance depends on several factors including
  - Tank thermal stratification
  - Condenser design
  - Compressor
  - Working fluid



Operation of a HPWH

Background

The **First Hour Rating (FHR)** is a measure of the available hot water capacity of the water heater (in gallons).

Unified Energy Factor(UEF)

$$= \sum_{k=1}^{n} \frac{M_k c_p (T_s - T_i)}{W_i}$$

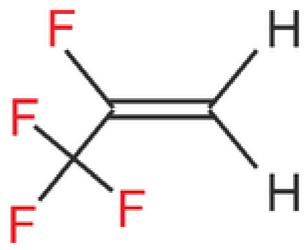
FHR greater or equal to (gals)	FHR less than (gals)	Draw pattern for 24-hr UEF
0	20	Point of use
20	55	Low usage
55	80	Medium usage
80	Max	High usage

- Major limitations of current state-of-the-art systems are an average UEF of 2.8 and a FHR (system capacity) of 48 gallons.
- Most of the existing technology is based on R134a (higher GWP)

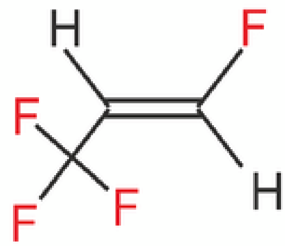
Draw number	Time during test (hh:mm)	Volume (gals/L)	Flow rate (GPM/LPM)
1	00:00	15.0 (56.8)	1.7 (6.5)
2	00:30	2.0 (7.6)	1 (3.8)
3	01:40	9.0 (34.1)	1.7 (6.5)
4	10:30	9.0 (34.1)	1.7 (6.5)
5	11:30	5.0 (18.9)	1.7 (6.5)
6	12:00	1.0 (3.8)	1 (3.8)
7	12:45	1.0 (3.8)	1 (3.8)
8	12:50	1.0 (3.8)	1 (3.8)
9	16:00	1.0 (3.8)	1 (3.8)
10	16:15	2.0 (7.6)	1 (3.8)
11	16:45	2.0 (7.6)	1.7 (6.5)
12	17:00	7.0 (26.5)	1.7 (6.5)
Total volume drawn per day: 55 gallons (208 L)			

Background

Refrigerant	GWP_{100}
CO_2	1
R-22	1760
R-134a	1300
R-410A	1924



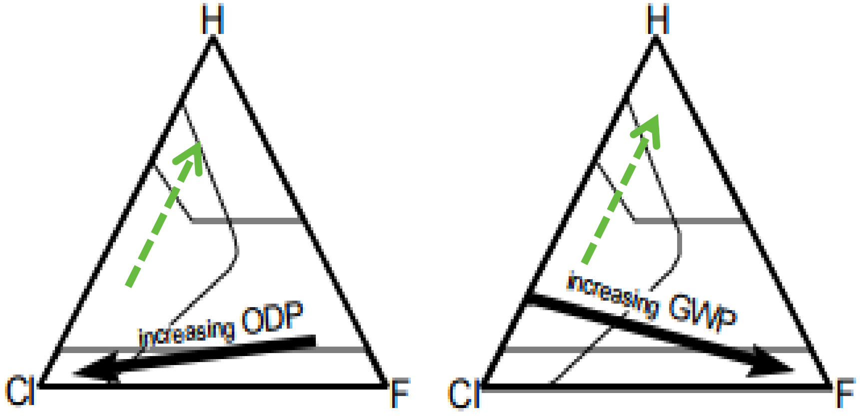
HFO-1234yf



HFO-1234ze(E)

- Hydrofluoroolefins (HFOs)
  - Fluorinated propene isomers
    - R-1234yf ($CF_3CF = CH_2$)
    - R-1234ze ($CF_3CH = CHF$)
  - GWP < 4
  - Mildly flammable

Chemical compounds



Away from Chlorine (ODP) and Fluorine (GWP) inevitably leads to flammability

Solution Approach

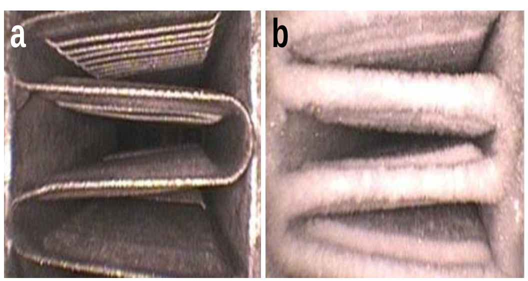
- Halogenated refrigerants have remarkable thermal physical properties, making them appropriate substitutes for R134a.

- Limited research has been conducted on the use of refrigerants in HPWHs.
- HFOs are A2L and are expensive
- Small design modifications will lead to a considerable reduction in total refrigerant charge and significant improvement in performance.

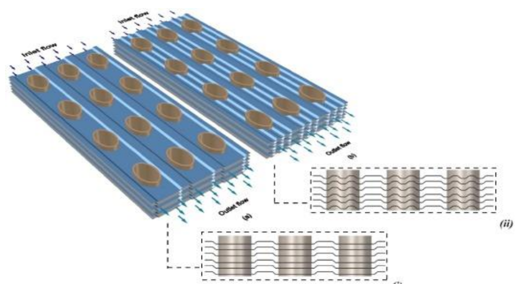
	R134a	R1234yf	R12234ze(E)
Formula	CH_2FCF_3	$CF_3CF=CF_2$	$CHF=CHCF_3$
CAS number	811-97-2	754-12-1	29118-24-9
Molecular mass (g/mol)	102	114	114
ODP	0	0	0
GWP_{100}	1300[a]	<1[a]	<1[a]
Safety classification[b]	A1	A2L	A2L
Critical temperature (K)[c]	374.21	367.85	382.51
Critical pressure (MPa)[c]	4.06	3.38	3.64
Sat. pressure at 280 K(MPa)	0.3774	0.4006	0.2803
Enthalpy of vaporization at 280 K (KJ/kg)	193.17	158.52	179.49
Vapor density at 280 K (kg/m^3)	18.66	22.253	15.004
Volumetric capacity at 280 K(KJ/m^3)	**3604.55**	**3527.55**	**2693.07**
Sat. pressure at 340 K(MPa)	2.04	1.9725	1.551
[a] IPCC 5th report, chapter 8 (Myhre et al., 2013)			
[b] ANSI/ASHRAE standard 34-2013 (A-Non-toxic, 1- Nonflammable, 2L-Mildly flammable, 3- Flammable)			
[c] REFPROP 9.1 (Lemmon et al., 2013)			

Solution Approach

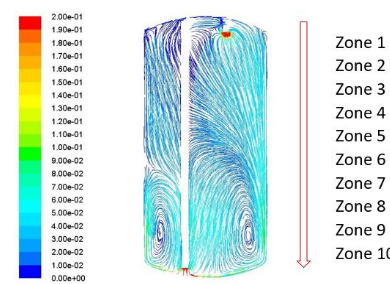
- Frost mitigation technology on evaporator → Improved performance in cold climates.
- Oil management in various components with halogenated refrigerants → Increased capacity and improved durability of the system.
- Small tube evaporator with advanced fin surface; condenser wrap pattern and tube design → Reduction in refrigerant charge; improved system performance.
- New compressor selection and system optimization; other options to increase the system capacity, including incorporating storage media → Higher system capacity; identification of a resilient/flexible grid storage concept.
- Appropriate condenser design and wrap pattern → Higher thermal stratification, leading to improved system performance (UEF and FHR).



Microchannel sample under frosting conditions.



Microchannel sample under frosting conditions.



Streamline for water flow in the tank during draw.

Solution Approach

Phase 1 Feasibility analysis	**Phase 2** Pre-Commercialization	**Phase 3** Commercialization

Development of a HPWHs that can achieve at least a 10% higher UEF with a 10–20% increased capacity and 20-30% refrigerant charge reduction

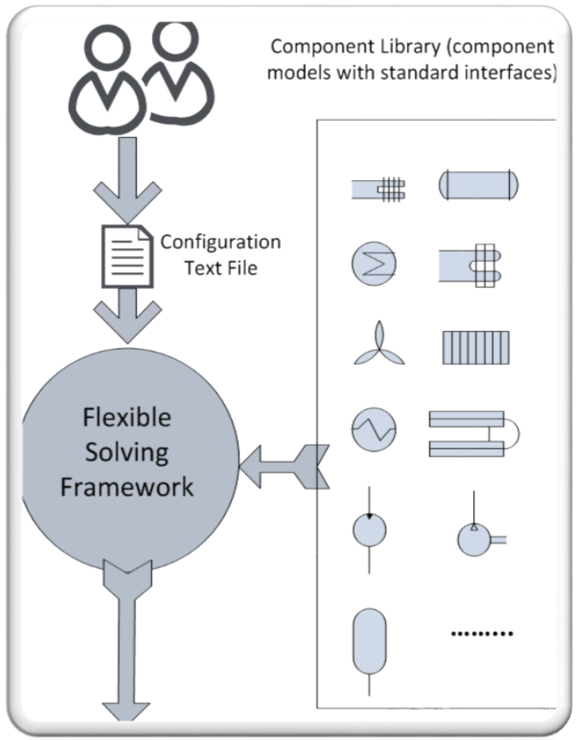
Project Impact

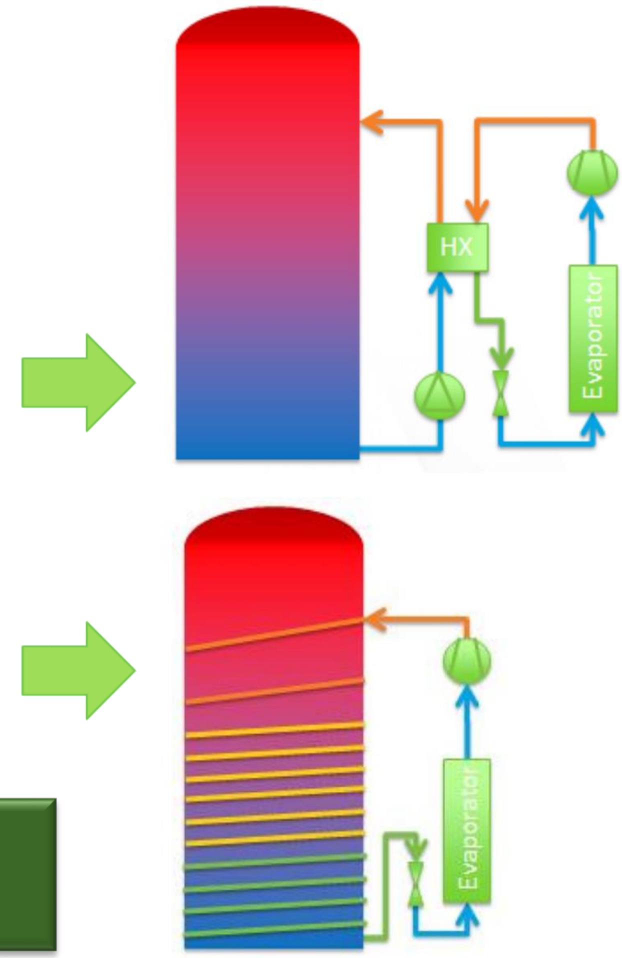
- **An improved refrigeration/commercial cooling technology with**
  - Unprecedented Unified Energy Factor
  - Improved capacity (Higher FHR)
  - Reduced manufacturing cost
- **Enabling development for deployment of A2L and A3 refrigerants**
  - Reduction in refrigerant charge
  - Reduced cost of the working fluid
  - Reduced required maintenance due to compact design
- **Implications for additional processes**
  - Residential air cooling/heating, refrigeration, Process water heating
- **At least 250 TBtu energy saving in water heating technology.**
  - Aligned with BTO goal to develop energy efficient technology to cause 45% energy saving by 2030 compared to 2010 technologies.
  - Opportunities to create more than 4000 new jobs
  - Paving the path for US manufacturer to expand to international markets

Progress - Development of Model

Component-Based

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

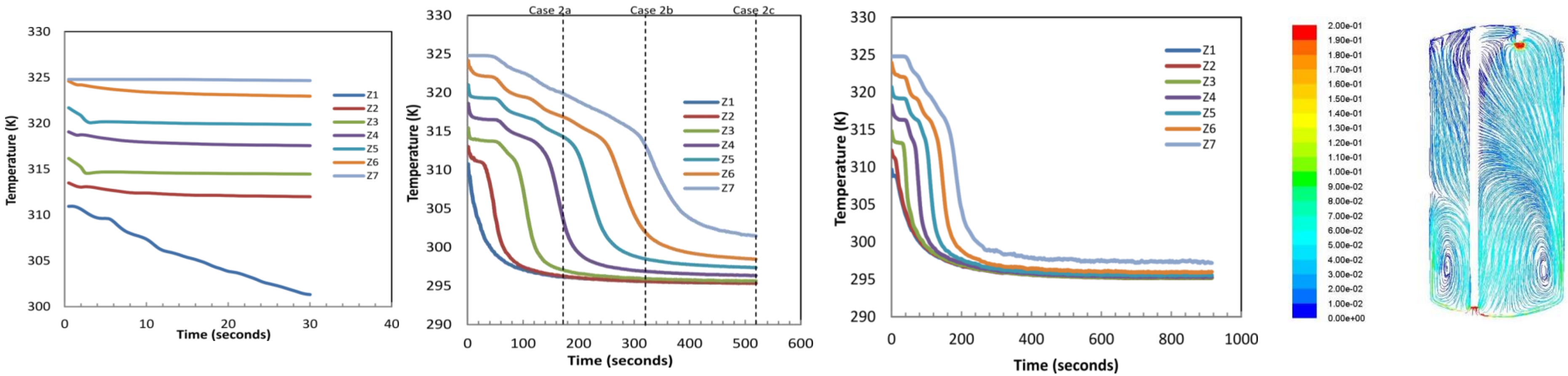




Automatically connect components into required system configuration by user input file.

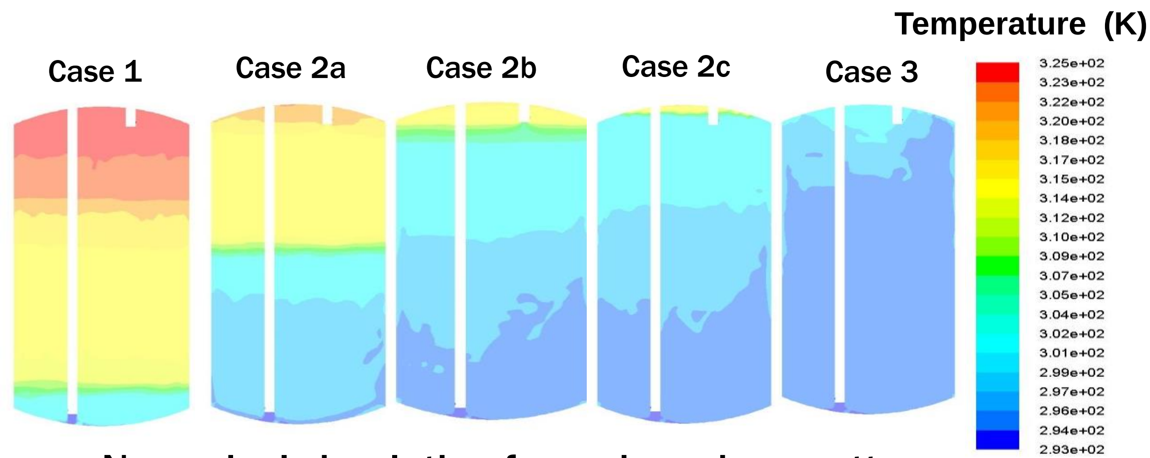
B. Shen, K. Nawaz, A. Elatar, V. Baxter, “Development and Validation of Quasi-Steady-State Heat Pump Water Heater Model Having Stratified Water Tank and Wrapped-Tank Condenser” International Journal of Refrigeration, 2018, 87,78-90.

Progress - Numerical Analysis



Impact of thermal stratification on various water draw patterns

Case#	Draw Pattern	Flow Rate ($m^3/s*10^4$)	Time (seconds)	Inlet Velocity(m/s)
Baseline		1.85	220	1.46
1	Very small	1	30	0.49
2a	Medium	1.7	176	0.85
2b	Medium	1.7	318	0.85
2c	Medium	1.7	529	0.85
3	High	3	740	1.49

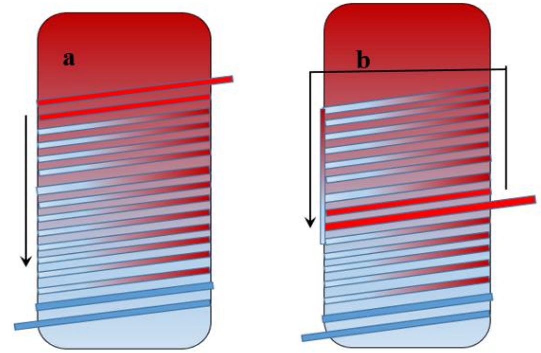


Numerical simulation for various draw patterns

B. Shen, K. Nawaz, A. Elatar, V. Baxter, "Development and Validation of Quasi-Steady-State Heat Pump Water Heater Model Having Stratified Water Tank and Wrapped-Tank Condenser" International Journal of Refrigeration, 2018, 87,78-90.

Progress - Parametric Analysis

- 46-gallon water tank
- Heat pump T-stat at the top: on at 115 °F, off at 125 °F.
- Electric element at the top: on at 110°F, off at 125 °F.
- Two different evaporator sizes and evaporator flow rate
- Two different heat loss factors from tank
- Two different condenser coil wrap patterns
- Two different condenser tube sizes

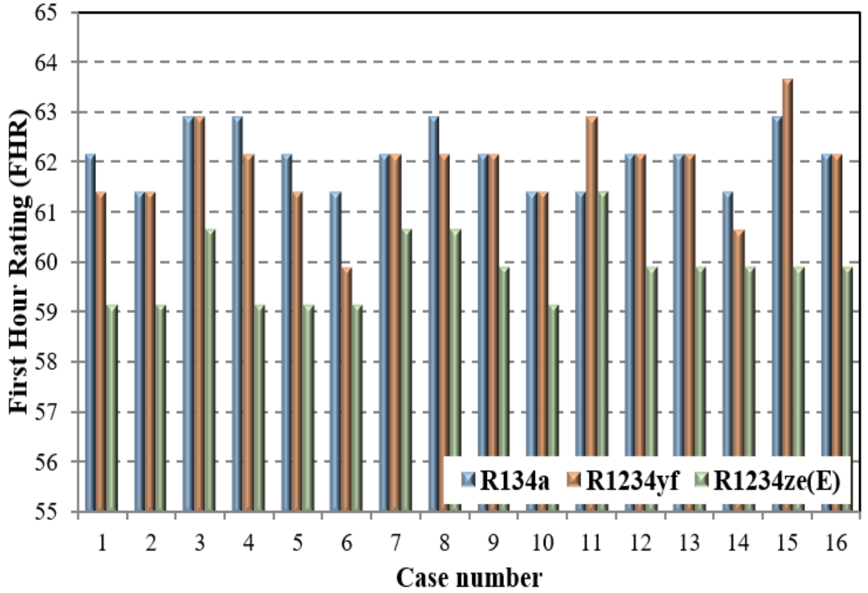


Condenser wrap configurations (a) counter flow (b) parallel-counter flow

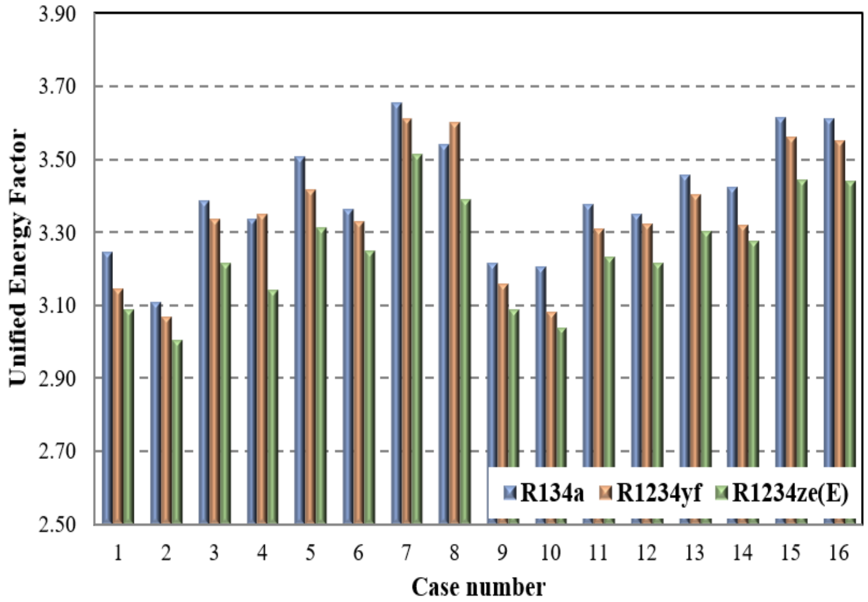
Case number	Wrap pattern	Evaporator size*	Tank insulation effectiveness (%)	Condenser tube size (inches)
1	Parallel-counter	1 Evap	90	0.31
2	Parallel-counter	1 Evap	90	0.50
3	Parallel-counter	2 Evap	90	0.31
4	Parallel-counter	2 Evap	90	0.50
5	Parallel-counter	1 Evap	95	0.31
6	Parallel-counter	1 Evap	95	0.50
7	Parallel-counter	2 Evap	95	0.31
8	Parallel-counter	2 Evap	95	0.50
9	Counter	1 Evap	90	0.31
10	Counter	1 Evap	90	0.50
11	Counter	2 Evap	90	0.31
12	Counter	2 Evap	90	0.50
13	Counter	1 Evap	95	0.31
14	Counter	1 Evap	95	0.50
15	Counter	2 Evap	95	0.31
16	Counter	2 Evap	95	0.50

Progress - Parametric Analysis

First Hour Rating



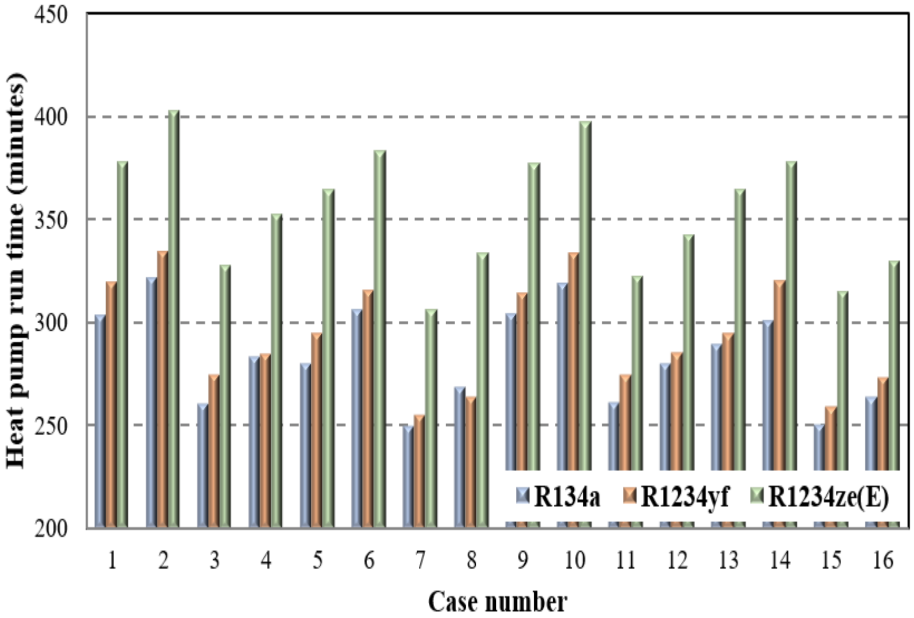
Unified Energy Factor



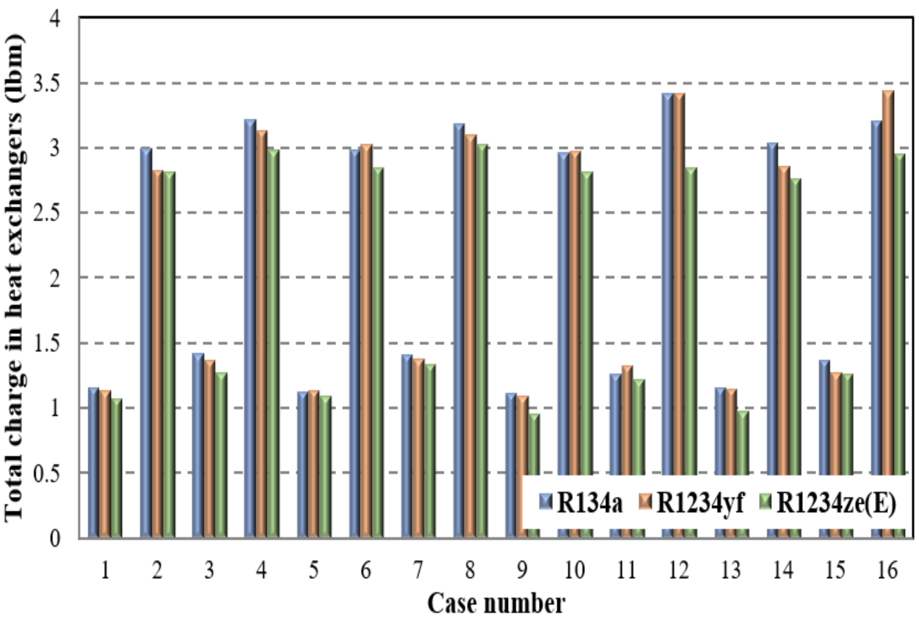
- FHR rating for all various cases is comparable- Medium pattern
- R1234ze (E) has reduced FHR due to lower volumetric capacity
- UEF is more sensitive to tank effectiveness and condenser tube size.

Progress - Parametric Analysis

Heat Pump Run Time

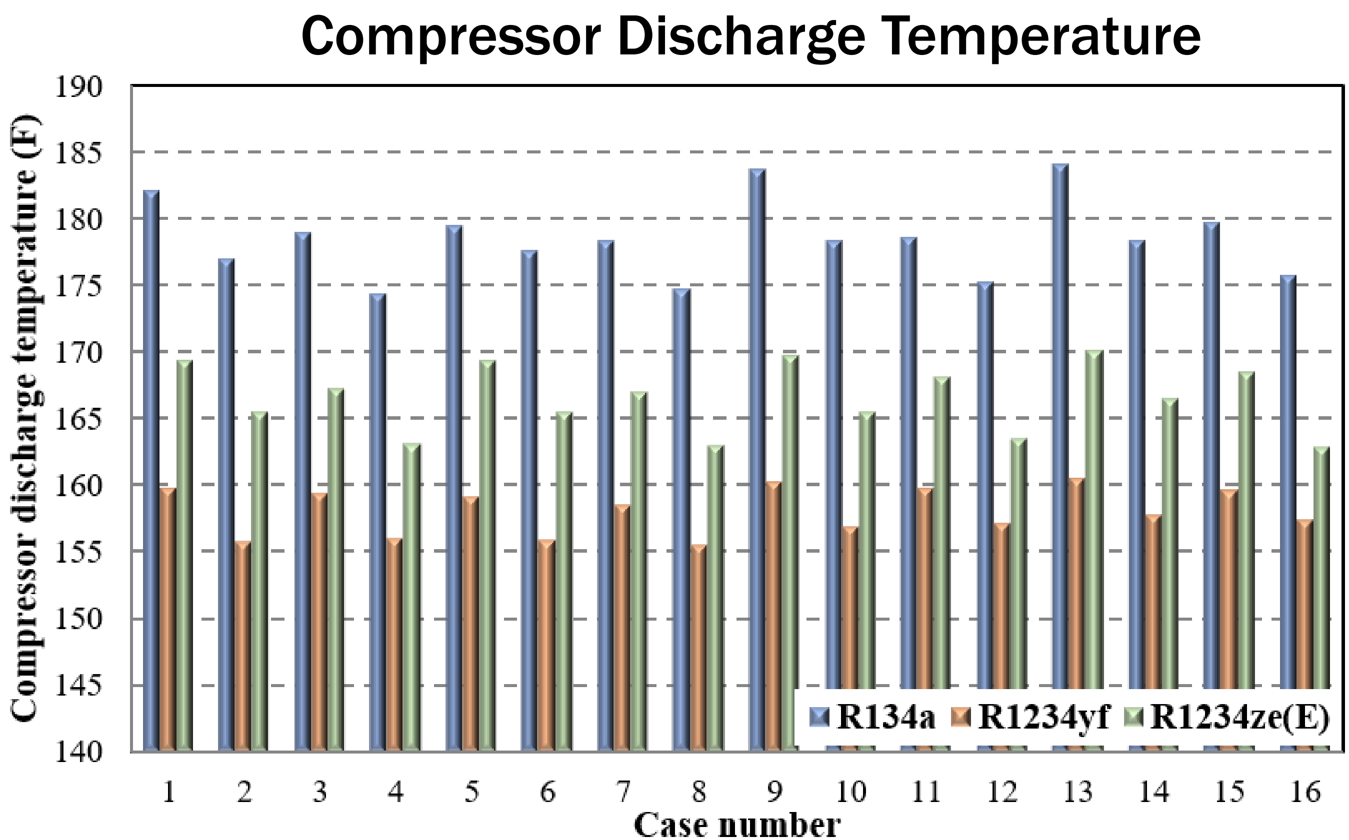


Total System Charge



- Higher heat pump run time is NOT desired. R1234ze (E)'s reduced volumetric capacity impacts the performance.
- Almost equal amount of charge in heat exchangers is an indication of feasibility of drop-in-replacement.

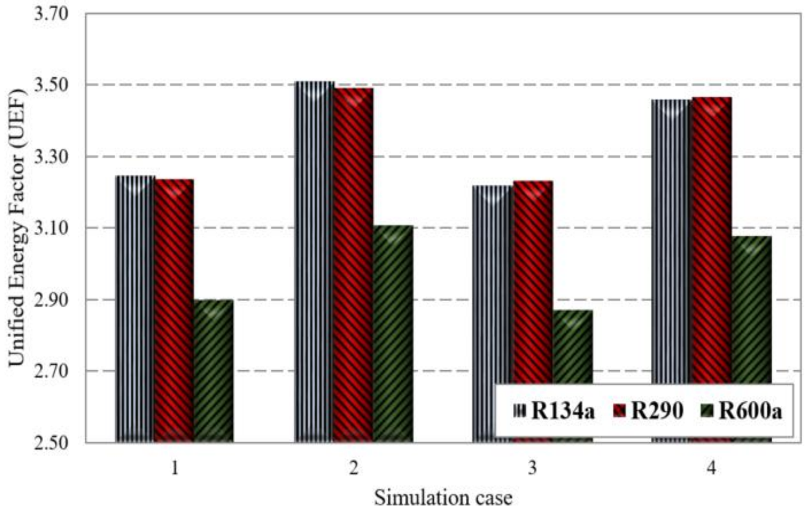
Progress - Parametric Analysis



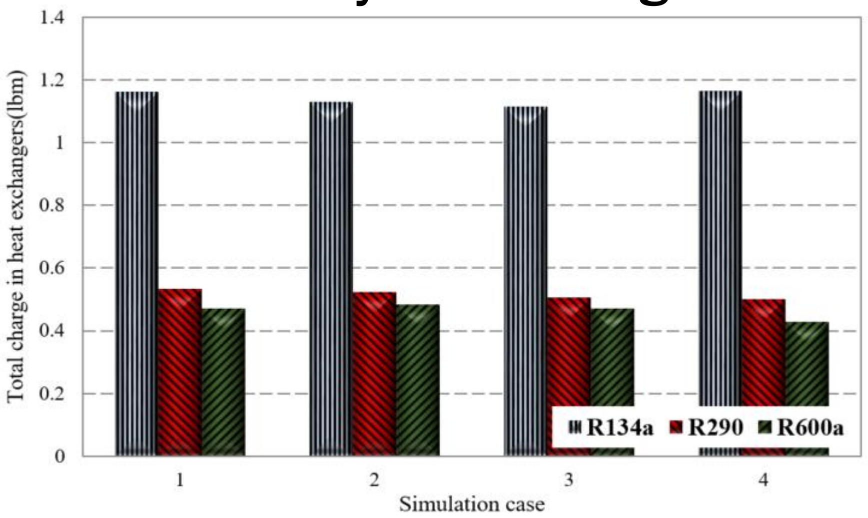
- Due to comparable compressor discharge temperature, no significant modifications are required (compressor type, lubricating oil etc.)

Progress - Parametric Analysis (R290 and R600a)

Unified Energy Factor

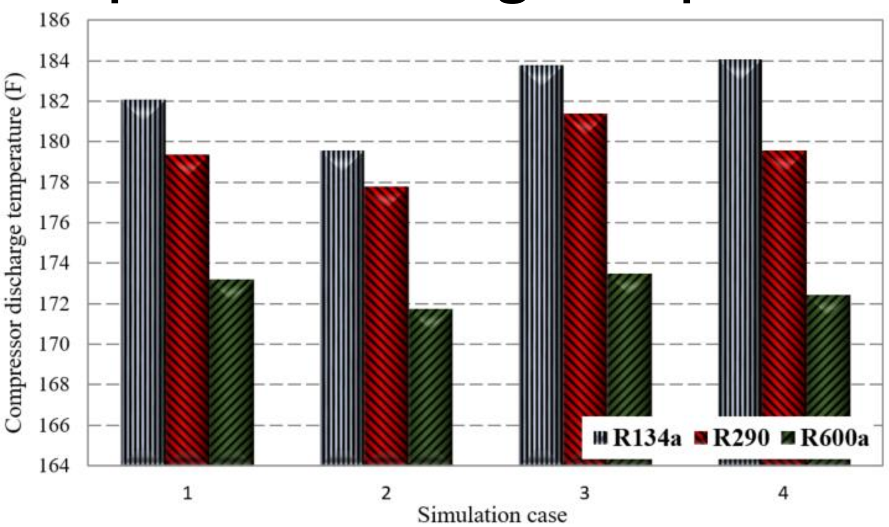


Total System Charge

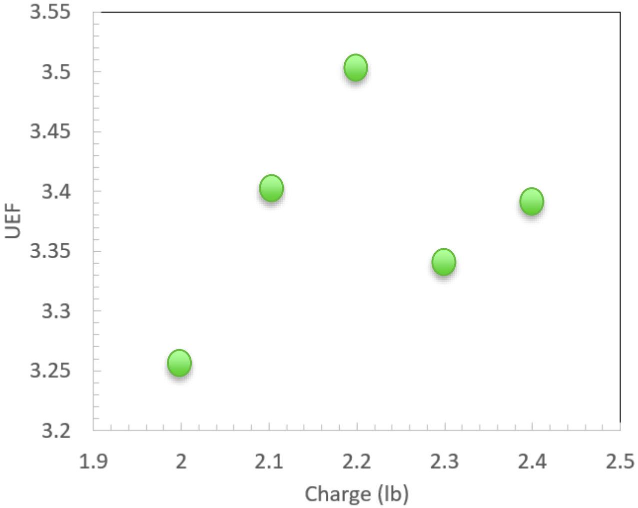


Case number	Wrap pattern	Tank insulation effectiveness (%)
1	Parallel-counterflow	90
2	Parallel-counterflow	95
3	Counterflow	90
4	Counterflow	95

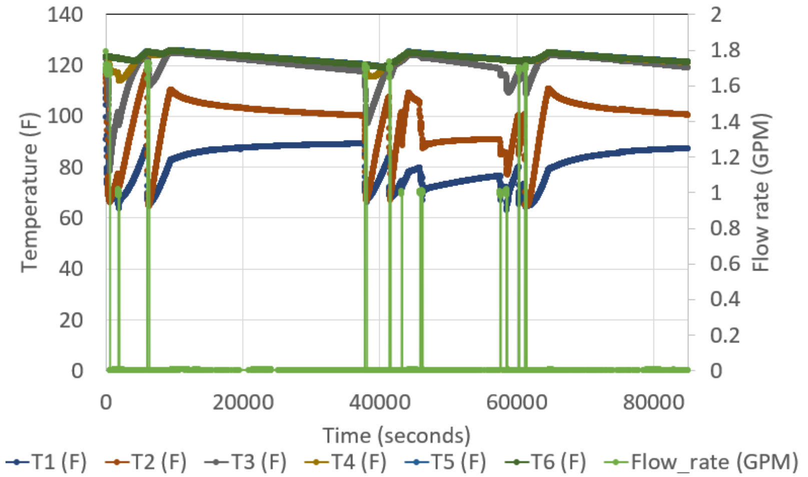
Compressor Discharge Temperature

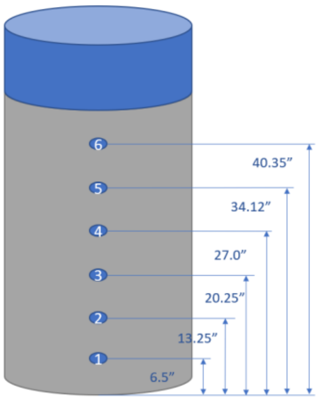


Progress - Experimentation



System UEF at various refrigerant charge





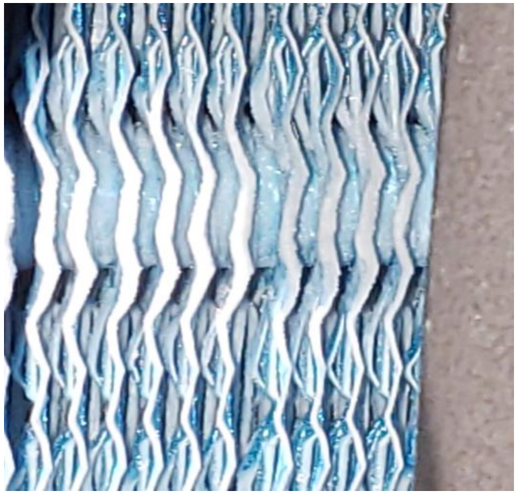
Tank thermal stratification

- Charge optimization is a complex process
- A highly instrumented experimental apparatus has been designed for performance evaluation
- Thermal stratification can be characterized.

Progress - Experimentation

Parameter	R134a	R1234yf	R290
Optimum refrigerant charge	2.3	2.2	1.05
First Hour Rating (FHR)	66	68	67
Unified Energy Factor	3.44	3.40	3.60

- HPWH performance degrades significantly at reduced ambient temperatures.
- Relative humidity becomes an important parameter due to frost growth on evaporator.
- Implementation of compact heat exchangers can lead to reduced refrigerant charge.



Frost growth on the evaporator of HPWH

Stakeholder Engagement

- **Development of the technology**
  - Refrigerants selection
  - Design of experiments
  - Parametric analysis
  - Frost formation and oil migration
- **Meetings with experts at technical platform**
  - ASHRAE (TC 8.5, TC 1.1)
  - Purdue
- **Presentations/Conference papers**
  - Five journal articles have been published (ATE, IJR)
  - More than twelve conference papers
  - ACEEE Hot Water Forum
  - IJR and ATE papers have been sited more than 20 times in merely a year

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Remaining Project Work

Name	Description
Baseline testing at various operating conditions	Evaluation of the performance of HPWH using R134a (standard working fluid) at various operating conditions
Development of performance model and validation	Heat Pump Design Modeler to predict the performance of HPWH (UEF and FHR) using baseline working fluid
Modeling of alternate refrigerant and performance evaluation	Heat Pump Design Modeler to predict the performance of HPWH (UEF and FHR) using alternate refrigerants (HFOs, HCs and Blends)
Experimentation- Drop in replacement for alternate refrigerants	Testing in appliance chamber at various operation modes using HFOs, HCs and blends as drop in replacement.
Development of Condenser and Evaporator Technology	ORNL, with assistance from A. O. Smith, will conduct detailed analysis of state-of-the-art evaporator and condenser technology.
Alpha Prototype Design and Construction	A. O. Smith will work in conjunction with ORNL to design and build at least one first-generation prototype advanced electric HPWH.
Alpha Prototype Testing	The alpha prototype will be tested.
Beta Prototype Design, Construction, and Testing	Beta prototype will be designed, built, and tested.
Market Study	A.O. Smith will assess the market potential for the advanced electric HPWH based on cost, energy consumption, reliability, and other factors.
Field Validation	ORNL and A. O. Smith will jointly conduct field validation of the advanced electric HPWH.

Thank You

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REFERENCE SLIDES

Project Budget

Project Budget: $1,592K ($1,200K CRADA)
Variances: None
Cost to Date: $940K
Additional Funding: None

Budget History CRADA					
FY 2018 (past)		FY 2019 (current)		FY 2020 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$400K	$100K	$375K	$100K	$425K	$100K

Project Plan and Schedule

Project Schedule		
Project Start: 10-01-2017	■	Completed Work
Projected End: 09-30-2020	■	Active Task (in progress work)
	◆	Milestone/Deliverable (Originally Planned)
	◆	Milestone/Deliverable (Actual)

	FY2018				FY2019				FY2020			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Development of CRADA	■ ◆											
Baseline system assessment		■	■ ◆									
Development of system model and validation			■	■	■ ◆							
Performance prediction of alternative fluids				■	■	■ ◆						
Experimentation using alternative fluids					■	■	■ ◆					
System modification for imporved performance						■	■	■	■	■	■ ◆	
Filed study and reporting							■	■	■	■ ◆		
Cost-benefit analysis										■	■	■ ◆