Optimization of a Residential Air Source Heat Pump using Refrigerants with GWP <150 for Improved Performance and Reduced Emission

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Outline

- Background
- Objective
- Baseline Heat Pump System & Refrigerants
- Low-GWP Heat Pump Design Optimization Method
- Optimization Results
- Life Cycle Climate Performance Analysis
- Conclusions

Background

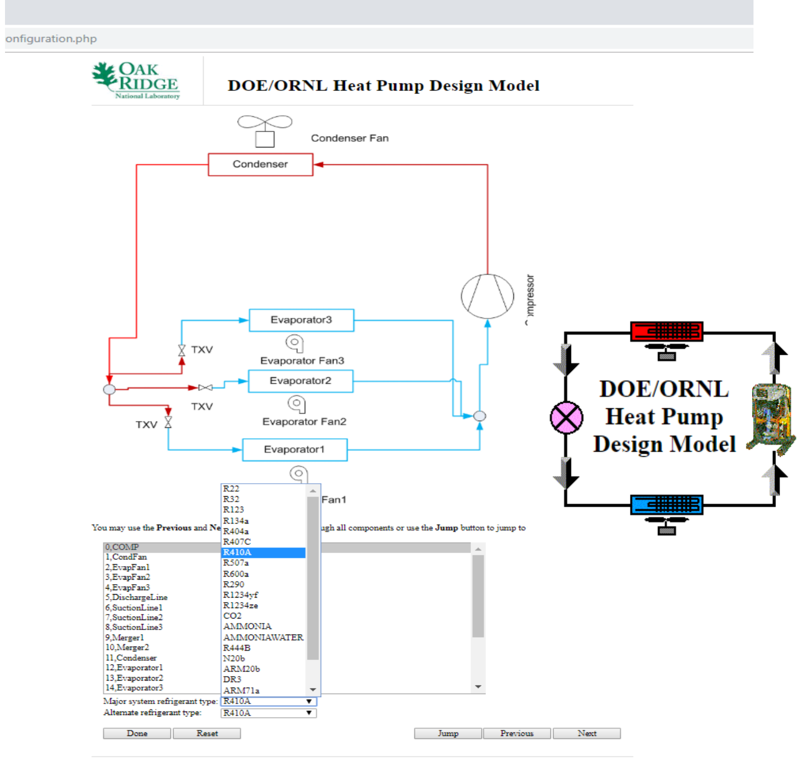
- Environmental concerns are driving a transition in refrigerants
- Many low GWP refrigerants exhibit large temperature glide
  - Requires optimized heat exchanger design for maximum system performance
  - New flow control devices are needed to guarantee heat pump performance under cooling and heating modes
- Most low-GWP mixtures are flammable
  - Heat pump designs must reduce refrigerant charge to reduce risk
- New low-GWP heat pumps must accommodate the current manufacturing and installation processes, and fit into existing homes
- New low-GWP heat pumps must be cost effective and readily accepted by end users

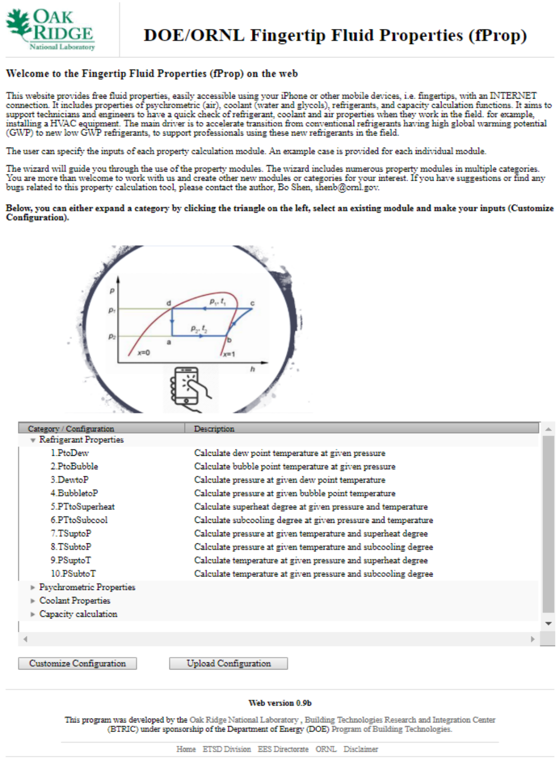
Objective

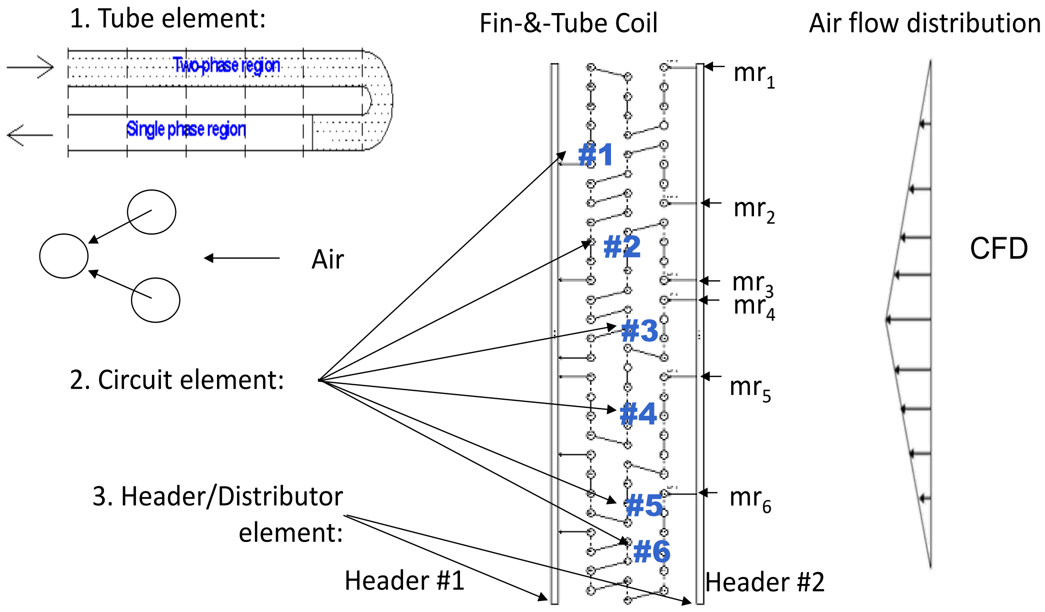
- Evaluate several refrigerant options for residential heat pumps using a modeling tool
  - Consider various refrigerant alternatives
    - Baseline: R410A
    - Short term alternatives with GWP <750: R32, R454B
    - Long-term alternatives with GWP <150: R454C, R455A, R457A, R1234yf, R1234ze(E)
  - Optimize heat exchanger design
    - Maximize energy performance
    - Minimize heat exchanger cost
  - Perform Life Cycle Climate Performance (LCCP) analysis
    - Determine life-time carbon emissions

DOE/ORNL Heat Pump Design Model

- Public-domain heat pump design and optimization tool capable of simulating HVAC components and systems using HFC, HFO, natural refrigerants and low-GWP mixtures
- Discretized coil model reveals temperature glide and variation of local properties enabling optimizing coil circuitry



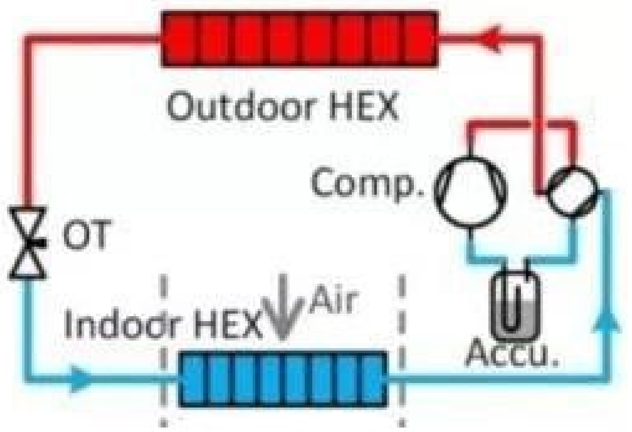




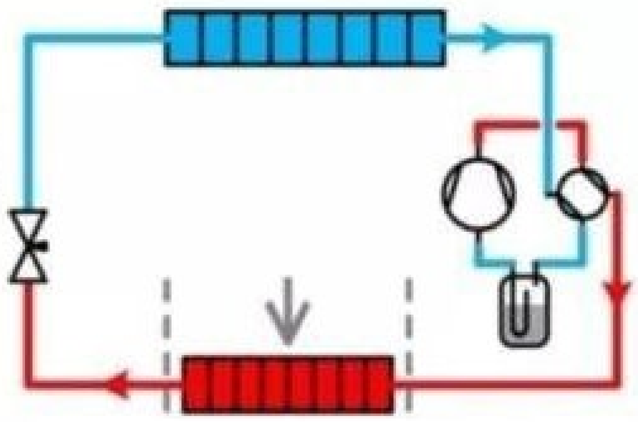
2-D air side distribution; Independent circuit refrigerant entering conditions; Arbitrary circuitry, provides more accurate real-world heat exchanger performance predictions

Baseline Heat Pump System

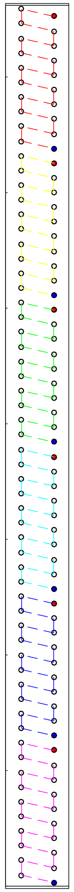
- Refrigerant: R410A
- Nominal cooling capacity: 3 tons
- Single-stage compressor
- Baseline coils: indoor 7 mm-tube, outdoor 9-mm-tube



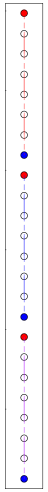
Cooling Mode



Heating Mode



Φ7.95 mm Baseline
Indoor HX
Mixed flow
6 Circuits
120 Tubes
2 Bank
60 Tubes per Bank
Coil height=1.25 m
Coil length=0.43 m



Φ9.52 mm Baseline
Outdoor HX
Mixed flow
8 Circuits
24 Tubes
1 Bank
24 Tubes per Bank
Coil height= 0.61 m
Coil length= 2.49 m

Heat Pump Design Optimization Method

$$\text{Maximize: } EER$$

$$\text{Subject to:}$$

Operation constraints

$$\Delta T_{\text{superheat, evaporator outlet}} = 10 - \frac{\Delta T_{glide}}{2} \ [R]$$

$$2 \ [R] \leq \Delta T_{\text{subcooling, condenser outlet}} \leq 15 \ [R]$$

$$Q_{evaporator} = 10.55 \text{ kW}$$

Dimension constraints

$$| SHR_{evaporator} - SHR_{baseline,evaporator} | \leq 1\%$$

$$1 \leq N_{circuits,evaporator} \leq Ntubes \ per \ bank \ of \ evaporator$$

$$1 \leq N_{circuits,condenser} \leq Ntubes \ per \ bank \ of \ condenser$$

$$Height_{evaporator} = Height_{baseline}$$

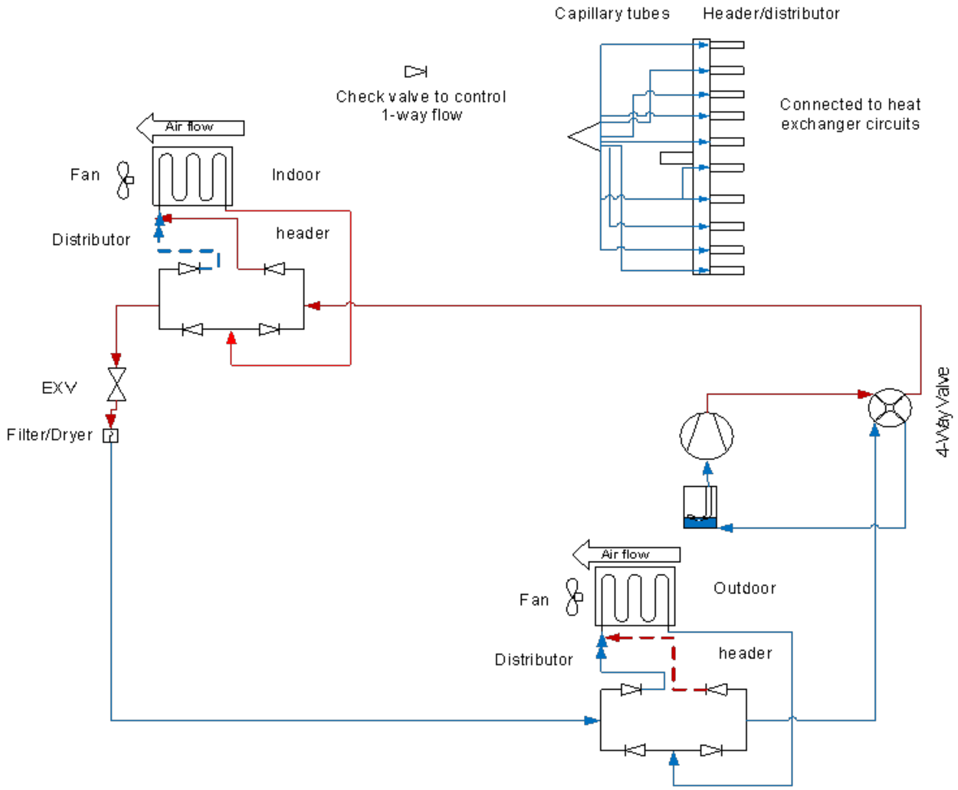
$$Length_{evaporator} = Length_{baseline}$$

$$Height_{condenser} = Height_{baseline}$$

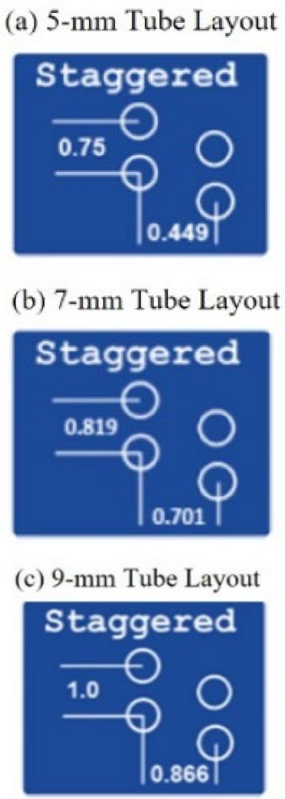
$$Length_{condenser} = Length_{baseline}$$

$$Tube \ diameter \text{ varies among } 5 \ mm, 7 \ mm, 9 \ mm$$

Check-valve assembly to facilitate counter-flow heat exchangers in both cooling and heating modes (arrows in heating mode)



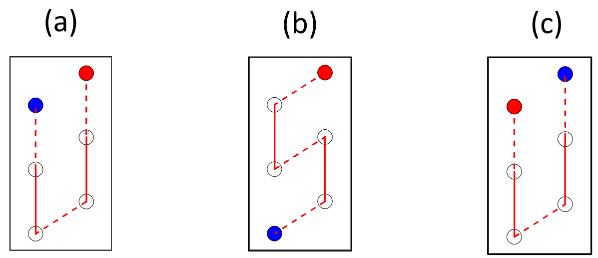
New System Configuration Maintaining Counter-flow HXs in Dual Modes



Off-the-shelf tube layout

Investigated Refrigerants and Circuitry Patterns

Refrigerant	GWP	Safety Class	Composition: Mass Fraction	Glide in Evaporator [K]	Critical Temperature [°C]
R410A	2088	A1	R32/R125: 50%/50%	0.1	72.8
R32	675	A2L	R32: 100%	0	78.1
R454B	466	A2L	R32/R1234yf: 68.9% /31.3%	1.3	78.1
R454C	146	A2L	R32/R1234yf: 21.5% /78.5%	7.7	85.7
R457A	139	A2L	R32/R1234yf/R152a: 18%/70%/12%	6.9	90.1
R455A	145	A2L	R32/R1234yf/CO2: 21.5%/75.5%/3%	11.71	85.61
R1234yf	4	A2L	R1234yf: 100%	0	94.7
R1234ze(E)	4	A2L	R1234ze(E): 100%	0	153.7

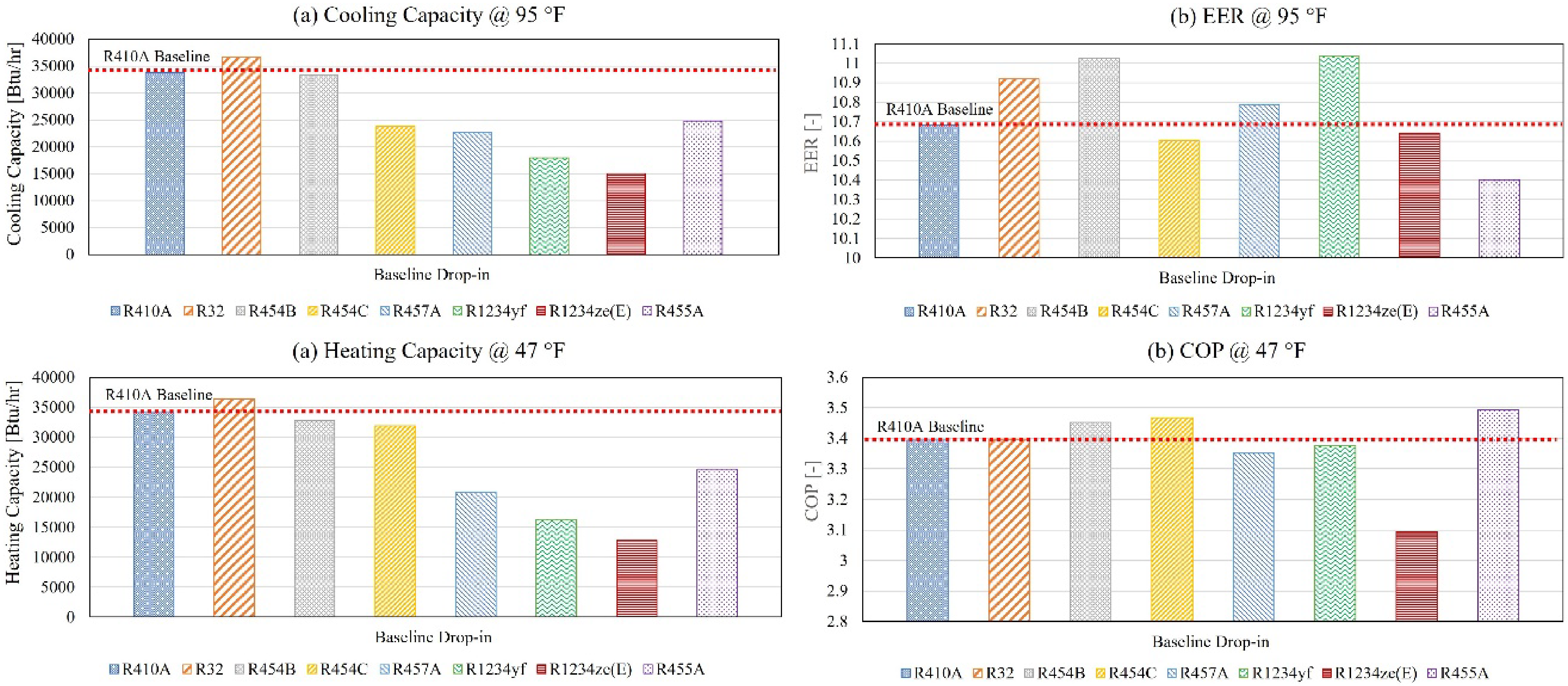


Heat exchanger circuitry patterns
(a) counterflow (b) mixed flow (c) parallel flow

Drop-in Performances for Baseline System

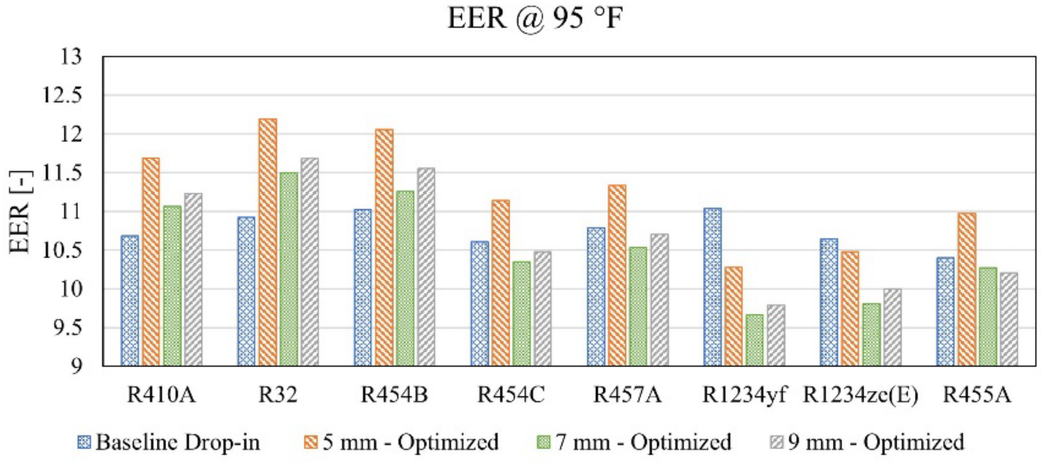
Cooling mode

Heating mode

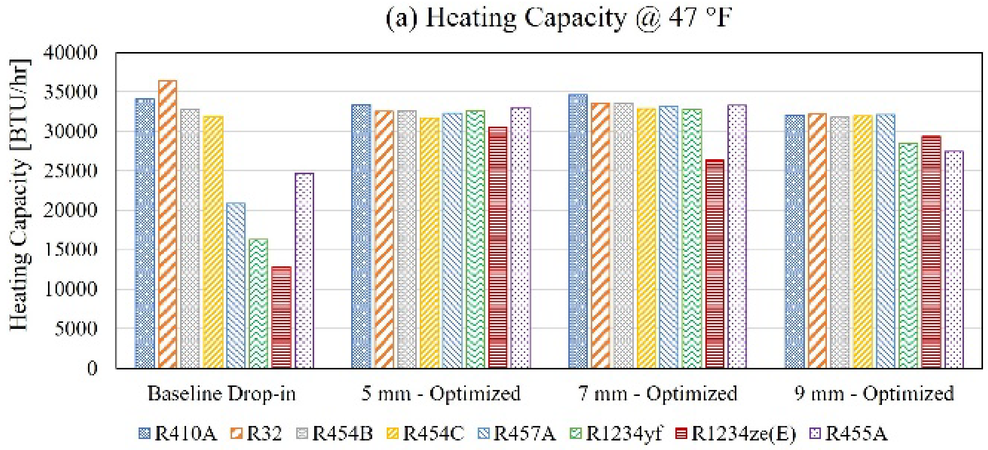


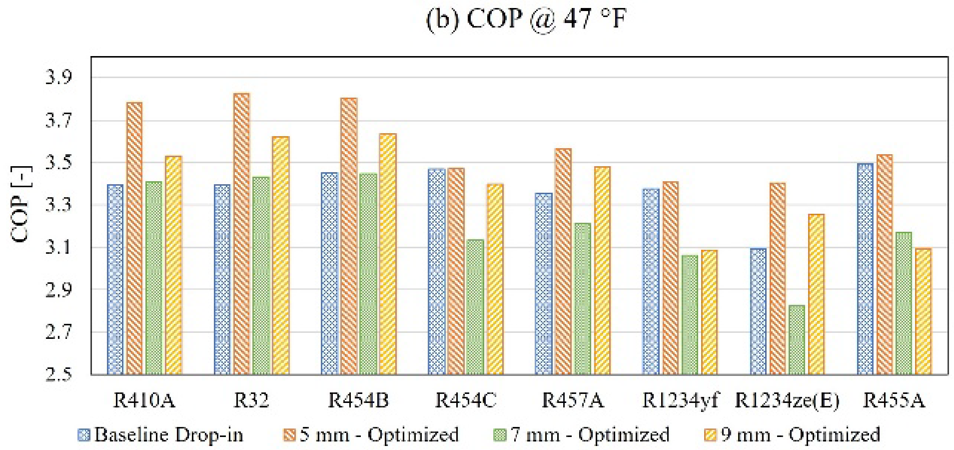
Performances of the Optimized Systems

Cooling mode



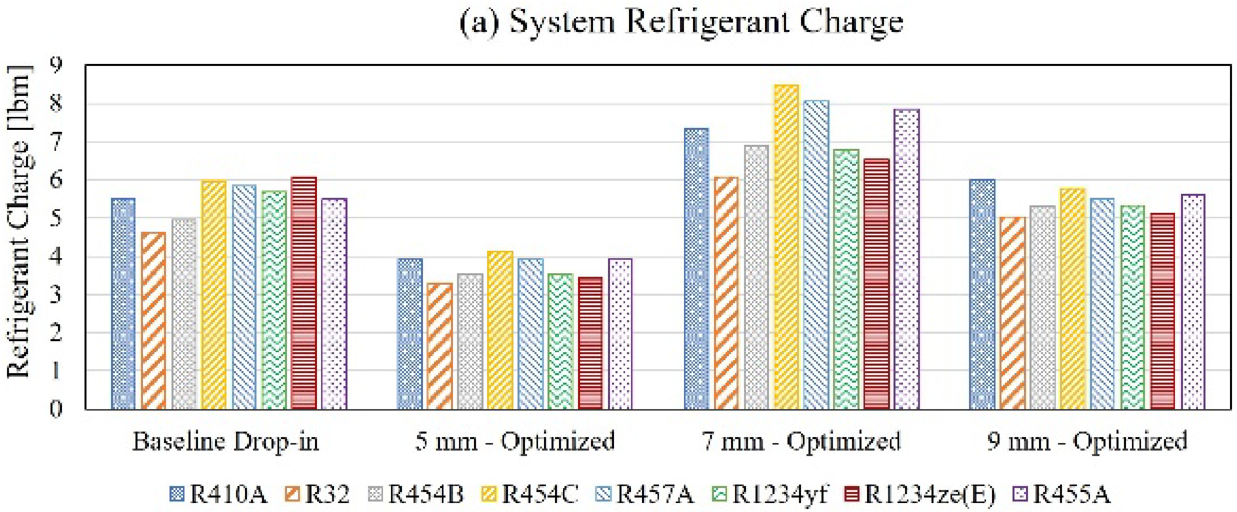
Heating mode

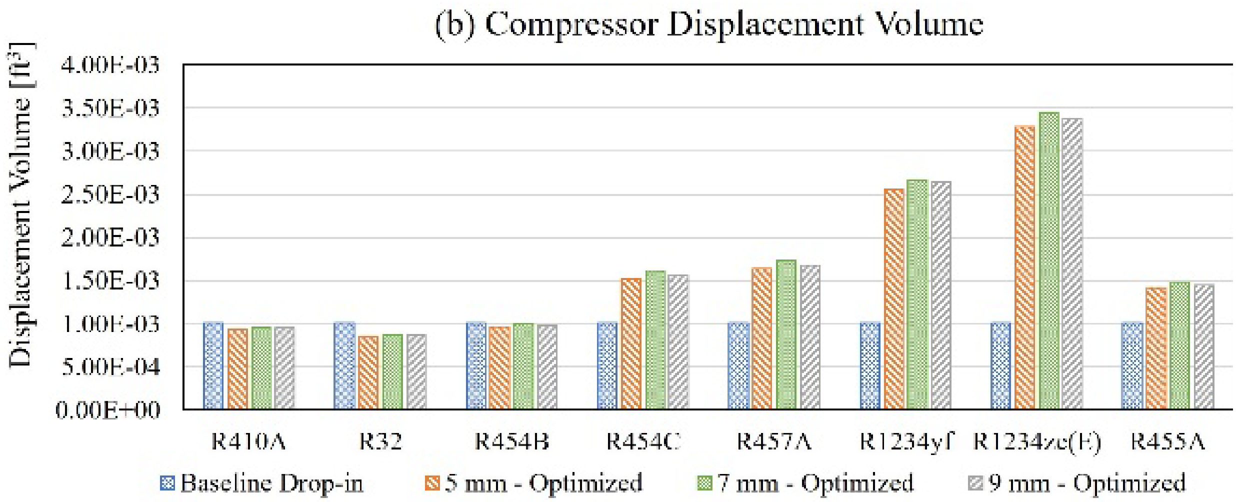




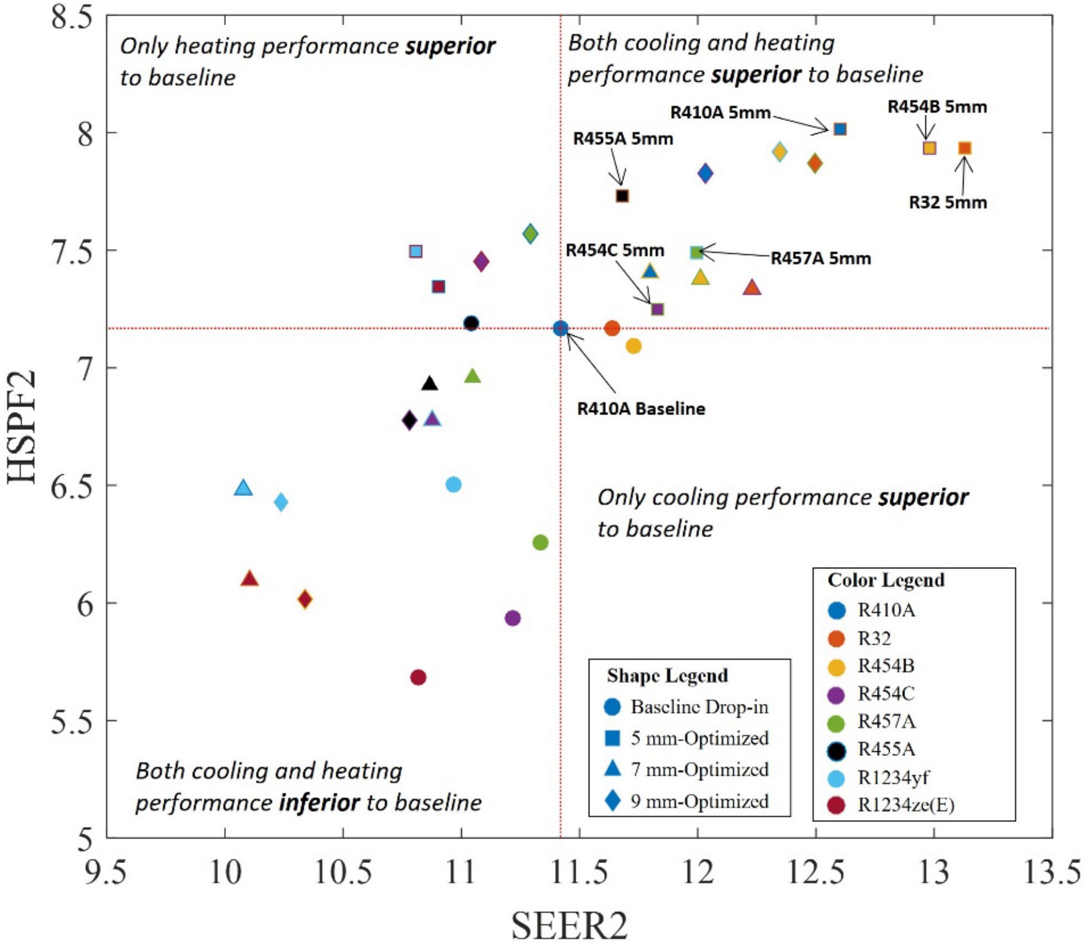
Charge and Compressor Displacement Volume

- Compressor displacement volume is optimized for each low-GWP refrigerant at AHRI 210/240 Test Condition A to target the same cooling capacity
- The compressor isentropic efficiency is fixed as 0.74 and the volumetric efficiency is fixed at 0.98 to be consistent with the baseline R410A system





Seasonal Performances and Optimized HX Structure



Heat Exchanger Structure of Optimized Systems*

HX Structure	5 mm - Optimized		7 mm - Optimized		9 mm - Optimized	
	Indoor HX	Outdoor HX	Indoor HX	Outdoor HX	Indoor HX	Outdoor HX
R410A	64x3-16	32x2-16	60x2-6	30x2-6	48x2-6	24x1-2
R32	64x3-16	32x2-16	60x2-6	30x2-5	48x2-6	24x1-2
R454B	64x3-16	32x2-16	60x2-6	30x2-10	48x2-4	24x1-2
R454C	64x3-32	32x2-16	60x2-12	30x2-6	48x2-6	24x1-3
R457A	64x3-32	32x2-16	60x2-12	30x2-6	48x2-6	24x1-3
R455A	64x3-32	32x2-16	60x2-15	30x2-6	48x2-8	24x1-3
R1234yf	64x3-32	32x2-16	60x2-15	30x2-6	48x2-8	24x1-3
R1234ze(E)	64x3-32	32x2-16	60x2-15	30x2-6	48x2-8	24x1-3

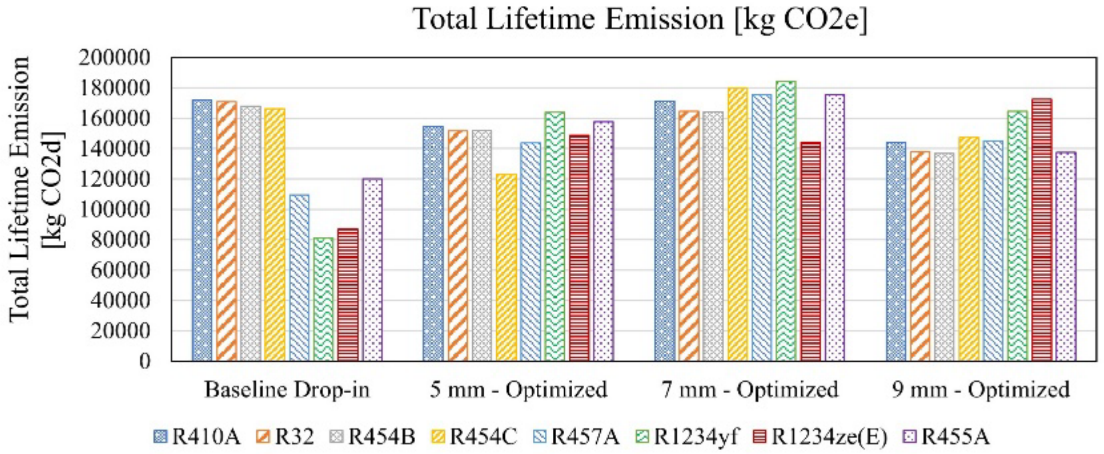
*HX Structure Naming Convention: "*Number of Tubes per Row* x *Number of Rows* - *Number of circuits*"

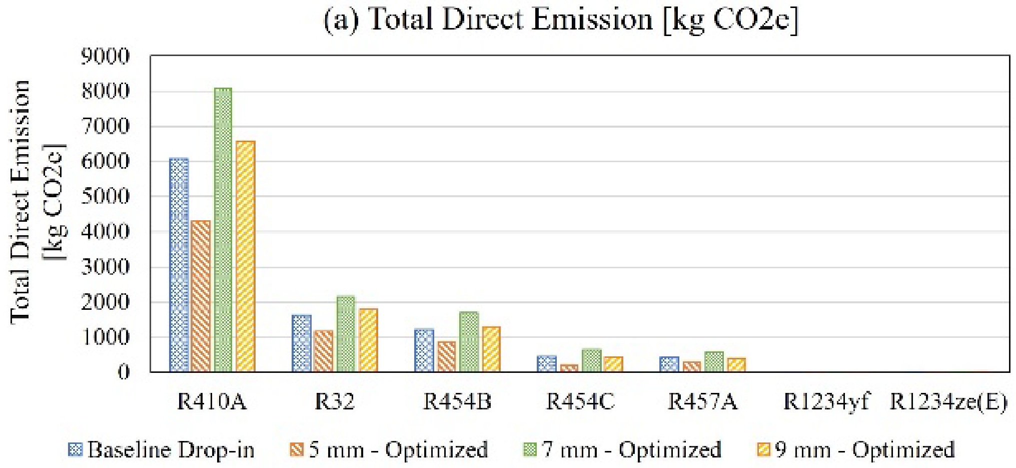
Life Cycle Climate Performance (LCCP) Analysis

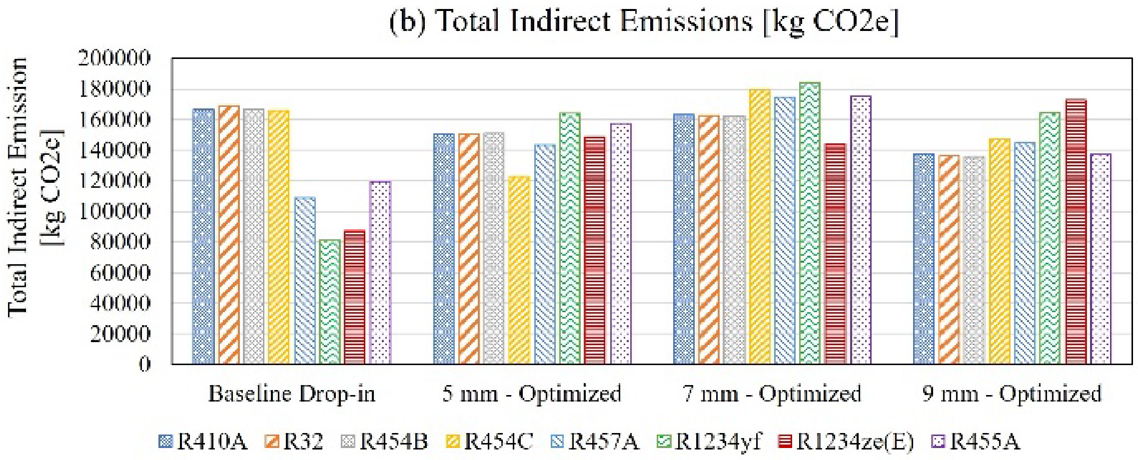
- Determine life-time carbon emissions of the HP designs
  - *Direct emissions:* Refrigerant release during operation and at End-of-Life (EOL)
  - *Indirect emissions:* From energy consumption, manufacturing of materials and unit, manufacturing of refrigerants and disposal of unit

Factor	Value
Refrigerant	R410A or its alternatives
Refrigerant charge (kg)	Obtained from System Simulation
Unit weight (kg)	190
Annual refrigerant leakage (%)	2
EOL leakage (%)	80
Lifetime (years)	18
Cut-off temperature (°C)	−17.8
Temperature at which the heat pump starts (°C)	−12.2
Weather data	Chicago TMY-3

Life Cycle Climate Performance Analysis Results







Conclusions

- To support the transition to refrigerants with GWP < 150 and high glide
  - New heat exchanger designs
  - New flow control schemes
  - New compressors
- Improved performance possible, with reduced refrigerant charge and reduced lifetime carbon emissions
- Higher efficiencies in both cooling and heating modes than R410A baseline system are achieved using refrigerants with GWP < 150
- Establish a production and installation path to produce cost-effective low-GWP heat pumps which will be readily accepted by end users

Thank you!

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