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Perform Life Cycle Energy and GHG Emission Analysis, Select Candidate Refrigerant(s) – Next Generation Low Cost Direct-expansion Heat Pumps Using Refrigerant Mixtures with GWP <150, FY21 1st Quarter Milestone Report

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FY21 1st Quarter Milestone Report

Perform life cycle energy and GHG emission analysis, select candidate refrigerant(s), Developing Heat Pump by Using Low-GWP Refrigerants and 5 mm Diameter Tubes

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Perform life cycle energy and GHG emission analysis, select candidate refrigerant(s) (Regular Milestone)

Executive Summary

Reducing environmental impacts from the energy conversion systems has been an important research topic due to recent severe global climate changes. In residential buildings, the space heating and cooling are main energy consumers, which are relying on vapor compression based heat pumps. To mitigate the environmental impacts of residential systems, the heat pumps using low-GWP refrigerants and 5mm-tube heat exchangers are proposed to replace the conventional 9 mm or 7 mm tube heat exchangers.

This research uses a simulation-based design method to optimize the refrigerant circuitries of a 5-ton low-GWP refrigerant heat pumps whose indoor and outdoor heat exchangers adopt 5 mm tubes. Heat pump systems using four commercially available low-GWP refrigerants (R454A, R454C, ARM20A and ARM20B) are optimized and compared with the baseline R410A system. The results indicate that:

- Directly replacing 9 mm tubes into 5mm tubes in the baseline systems induces heat pump performance degradation.
- By optimizing the 5 mm tube heat pumps with added tube rows, the system refrigerant charge is reduced up to 33% compared with the baseline.
- The optimized low-GWP 5 mm tube heat pumps offer the same or higher performance under both cooling and heating mode. Under cooling mode, the EER improvement is up to 10.7% and under heating mode the COP improvement is up to 3.4%.
- A smart flow control device to maintain counter-flow circuitry pattern on both operating modes can improve the heating performance of 5 mm tube optimized system by up to 3.0%.

In an effort to better understand the environmental impacts of these systems, life cycle climate performance (LCCP) evaluation method is used to assess the baseline and optimized systems. LCCP considers the direct and indirect emissions of the system over the course of its lifetime from manufacturing to disposal. Our analyses indicate that the optimized systems using 5mm tubes and low-GWP refrigerants can reduce life-cycle CO_2 emission significantly. And improving system efficiency is the most effective way to reduce the emission of low-GWP refrigerant systems.

This report shows that using 5 mm diameter tubes in heat exchangers is a feasible approach to develop heat pumps with low-GWP refrigerants. Using the proposed design approach can yield higher system efficiency with lower environmental impact.

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1. Background

Reducing environmental impacts of HVAC&R systems has been an important research topic due to recent severe global climate changes. In residential buildings, the space heating and cooling are main energy consumers, which are relying on vapor compression based heat pumps. This project is a CRADA (cooperative research and development agreement) between ORNL and Emerson Commercial and Residential Solutions (the Helix center) to investigate next generation, residential split air conditioning (AC)/heat pump (HP) system configurations which use A2L refrigerant mixtures with low global warming potential and high temperature glide. It will accommodate the mainstream structure of a baseline residential direct-expansion heat pump, having the heat exchangers and other components optimized for both cooling and heating modes. This report assesses the efficacy of a new design method to develop low-charge heat pump systems using 5 mm diameter tubes.

The HVAC&R industry has moved to phase out refrigerants with high global warming potentials (GWP), e.g. R410A, R22, R134a, R404A, etc. The next generation refrigerants are mostly mixtures of HFO (Hydrofluoroolefins) refrigerants, e.g. R1234yf and R1234ze(E) combined with the HFC (Hydrofluorocarbons) refrigerant, e.g. R32. Since most of these low-GWP mixtures are flammable, researches have shown that promoting the use of smaller diameter tubes in heat pump systems is an effective way to reduce refrigerant charge and avoid explosion risk. But it may cause performance degradation. Therefore, a design method is needed to develop 5 mm tube low charge heat pump system using low-GWP refrigerants. Table 1 lists the baseline R410A refrigerant and four low-GWP refrigerants investigated in this study. R454A, R454C, ARM20A, ARM20B are selected due to their small GWP values (GWP $\leq$ 251).

One characteristic of these low-GWP alternative refrigerants are their high slides, i.e. temperature rise from the bubble point to the dew point at one pressure. High slide refrigerants prefer multi-row, counter-flow heat exchanger configuration for a single mode operation. If switching mode, the counter-flow heat exchanger (HX) becomes parallel-flow heat exchanger. The reversed flow causes significant efficiency degradation. Therefore, technical improvements are needed to make the high slide refrigerants work for both cooling and heating modes to achieve good energy efficiency and protect the environment. This report also evaluates the necessity to develop such a flow control device, i.e. “smart” four-way valve and bi-directional distributor to maintain the same refrigerant flow direction inside the heat exchangers between mode switching.

To better understand the environmental impacts of optimized heat pump using 5 mm tubes and low-GWP refrigerants, life cycle climate performance (LCCP) evaluation method is used to analyze the direct and indirect greenhouse gas (GHG) emissions of the system over the course of its lifetime from manufacturing to disposal.

Table 1: Characteristics of Selected Low-GWP Refrigerant and Baseline R410A

Refrigerant	GWP	Safety Class	Glide in Condenser [K]	Glide in Evaporator [K]	Critical Temperature [C]	Composition	Vendor
R410A (baseline)	2088	A1	0.1	0.1	72.8	R32 (0.5)/ R125 (0.5)	Honeywell
R454A (XL-40)	238	A2L	5.4	6.2	78.9	R32 (0.35)/ R1234yf (0.65)	Chemours
R454C (XL-20)	146	A2L	6.0	6.0	82.4	R32 (0.215)/ R1234yf (0.785)	Chemours
ARM20A	139	A2L	6.1	6.9	90.2	R32 (0.18)/ R1234yf (0.7)/ R152a (0.12)	Arkema
ARM20B	251	A2L	5.3	6.0	88.7	R32 (0.35)/ R1234yf (0.55)/ R152a (0.1)	Arkema

2. Baseline Heat Pump Systems

To compare the refrigerants in an existing heat pump system, a commercial 5-ton R410A residential single-speed heat pump is modeled. Figure 1 shows the schematic of the baseline heat pump system operating under cooling (i.e. AC) mode and heating (i.e. HP) mode. The refrigerant direction inside the heat exchangers are reversed after mode switching without a smart flow direction control device.

Table 2 lists the structural parameters of the baseline heat exchangers as well as the air volume flow rate and fan power for the indoor and outdoor fans.

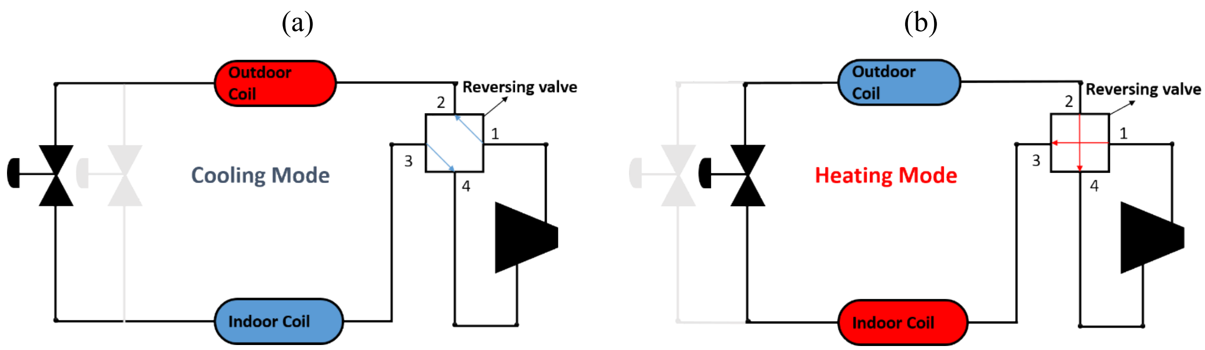


Figure 1: 5-ton R410A Baseline Heat Pump System: (a) Cooling Mode Operation; (b) Heating Mode Operation.

Table 2: Parameters of Indoor and Outdoor Units of Baseline 5-ton Single-Speed Heat Pump

Parameters (heating mode)	**Indoor TFHX**	**Outdoor TFHX**
Face area, ft^2	3.6	33.7
Total Tube Number	72	96
Number of Rows	3 (cross mixed flow)	2 (cross mixed flow)
Number of Circuits	8	8
Fin Type	Slit	Slit
Fin Density, fins/ft	168	276
Tube Outside Diameter [mm]	9.52	9.52
Tube Horizontal Spacing [mm]	25.4	22.0
Tube Vertical Spacing [mm]	25.4	25.4
	Indoor Blower	**Outdoor Fan**
Flow Rate [CFM]	1770	4215
Power [W]	478	181

The circuitries of the baseline R410A indoor and outdoor HXs are shown in Figure 2(a) and Figure 2b), respectively. Both HXs are adopting cross mixed flow circuitry pattern. The indoor HX has 72 tubes and 3 tube rows and is divided into 8 mixed flow circuits. The outdoor HX has 96 tubes and 2 tube rows and is also divided into 8 mixed flow circuits. In Figure 2, a solid line represents a U-bend (i.e., hairpin) on the front end of the HX, while a dotted line represents a U-bend on the farther end. The different colors represent different circuits. The distributor distributes the refrigerant into the inlet tube of each circuit.

(a) (b)

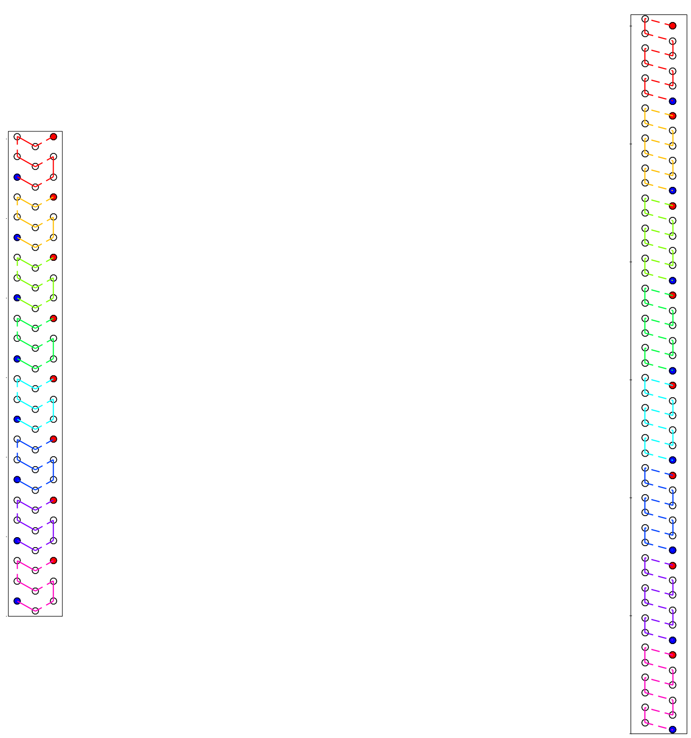


Figure 2: Baseline Tube-fin Heat Exchanger Circuitries: (a) Indoor HX; (b) Outdoor HX.

3. Design Method

To develop low refrigerant charge system, fin-and-tube heat exchangers with small diameter tubes (smaller than or equal to 5 mm) are gradually replacing conventional tubes with 9 mm and 7 mm diameter. Researches have shown that when tube diameter decreases from 9 mm to 5 mm, the tube cross-sectional area will reduce by 49%, and the refrigerant charge can be decreased accordingly. Due to the lower refrigerant charge, the explosion risk of using flammable refrigerants can be reduced. However, changing to 5 mm tubes will affect thermo and hydraulic behaviors of both air side and refrigerant side. In order to make the modified systems to offer the same or even better performance than the baseline system, it is necessary to optimize the tube-fin heat exchangers.

In this research, we conducted two groups of optimization runs. For the first group of optimization runs, the 9.52 mm tubes in both the indoor and outdoor HXs are replaced by 5 mm tubes. Then the refrigerant circuitry of the 5 mm tube indoor and outdoor HXs are optimized for each of the four low-GWP refrigerants. This optimization practice aims at evaluating whether it is possible to reach the baseline R410A unit performance solely by replacing 5 mm tubes. For the second group of optimizations, in addition to replacing 9.52 mm tubes into 5 mm tubes, the tube rows in indoor and outdoor HXs are doubled. That is, the total number of the tubes are doubled. And heat exchanger circuitry optimization is enforced on the added-tube-row heat exchangers to investigate the potential performance improvement from the larger HX designs.

Eq. (1) shows a problem formulation for the optimization of the heat pump under cooling mode. The objectives are to maximize the cooling mode EER. In previous research, Shen et al. (2012) developed an optimization framework that integrates HPDM with GenOpt to perform automatic calibration of a heat pump model based on experiment data. The optimization package used in this research is developed based on Shen et al. (2012)'s framework. Because the baseline indoor HX has 24 tubes in each row, the number of circuits is a discrete variable which varies among all common divisors of 24. Similarly, the number of circuits of the outdoor HXs as well as the added-tube-row heat exchangers also varies among the common divisors of tubes per row of the corresponding heat exchangers.

$$
\begin{aligned}
&Objective:\ Maximize(EER)\\
&Subject\ to:\\
&\quad N_{circuits,\ evaporator} \in \{1,2,3,4,6,8,12,24\}_{originalTubeLayout}\ \text{or}\ \{1,2,3,4,6,8,12,16,24,48\}_{DoubleRowsLayout}\\
&\quad N_{circuits,\ condenser} \in \{1,2,3,4,6,8,12,16,24,48\}_{originalTubeLayout}\ \text{or}\ \{1,2,3,4,6,8,12,16,24,32,48,96\}_{DoubleRows}\\
&\quad \Delta T_{superheat,evaporator,outlet} = 10 - \frac{\Delta T_{glide}}{2}\ \text{R}\\
&\quad 2\ \text{R} \le \Delta T_{subcooling,condenser,outlet} \le 15\ \text{R}\\
&\quad Q_{evaporator} = 16.1\ kW
\end{aligned}
\tag{1}
$$

In Equation (1), the cooling capacity of evaporator is fixed to be the same as that of the original 5-ton R410A heat pump; the evaporator outlet superheat degree is specified based on the temperature glide of different refrigerants as recommended by refrigerant OEM. The compressor displacement volume is automatically altered in HPDM to meet the target evaporator cooling capacity. The condenser outlet subcooling degree is automatically adjusted, but it is constrained between 2 R to 15 R.

Upon obtaining the cooling optimized system, the performance of the optimized systems under heat pump mode is simulated following the below steps.

Step 1: Specify the optimized circuitry, required compressor displacement volume, optimized subcooling degree from the cooling optimized system as inputs in HPDM to simulate the heat pump system

Step 2: Conduct the first heat pump simulation assuming the refrigerant flow direction inside HXs are reversed (i.e. simulate conventional reversible heat pump system without flow control device)

Step 3: Conduct the second heat pump simulation assuming the same refrigerant flow direction inside HXs (i.e. simulate heat pump system with a smart flow control device)

4. Performance of 5 mm Tube Heat Pumps without Adding Tubes

This section discusses the results from the first group of optimization runs, i.e. optimizing system using 5 mm tubes in the HXs without adding tube rows. Figure 3(a) shows the EER of the optimized systems. Only by replacing 9.52 mm tubes into 5 mm tubes, the baseline performance cannot be achieved from heat exchanger circuitry optimization. Figure 3(b) shows the system charge of the baseline system as well as the optimized systems. The refrigerant charge is significantly reduced due to the reduced internal volume of 5 mm tube HXs.

(a) (b)

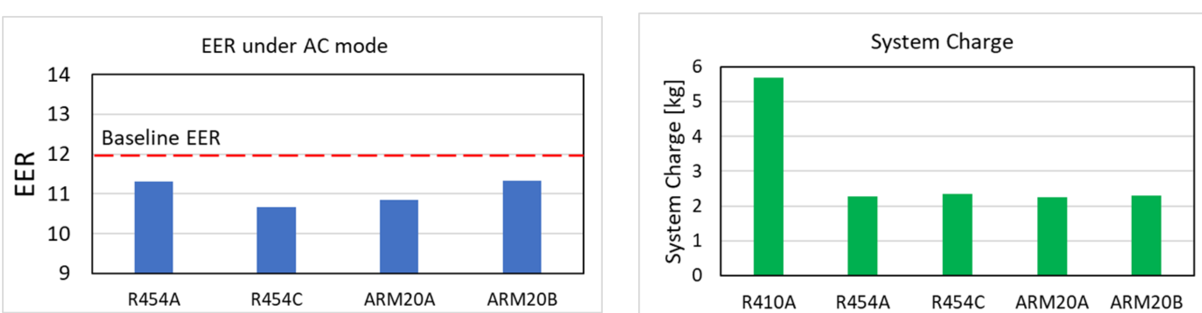


Figure 3: 5mm-Tube Heat Pumps without Adding Tubes: (a) EER under Cooling Mode; (b) System Charge under Cooling Mode.

Figure 4(a) and Figure 4(b) show the COP of the optimized heat pumps under heat mode. Figure 4(a) shows the result without a smart flow device. Figure 4(b) shows the result with flow control device. Despite the baseline performance cannot be achieved by any of the optimized design, the advantage of having the flow control device to make the heat exchangers as counter-flow heat exchanger under heating mode is prominent. For example, the optimal system using R454A can tie the baseline heating performance with the flow control device.

(a) (b)

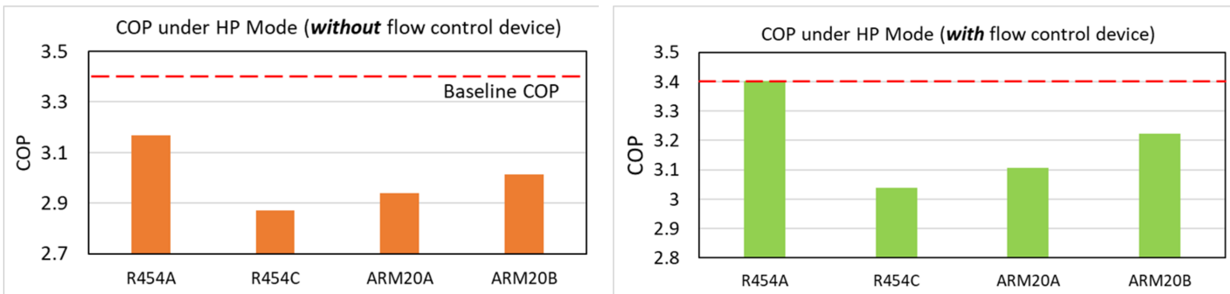


Figure 4: COP under Heating Mode of 5mm-Tube Heat Pumps without Adding Tubes: (a) No Flow Control Device; (b) Flow Control Device Installed.

Figure 5 shows the airside pressure drop for the indoor and outdoor HXs after replacing into 5 mm tubes. For both heat exchangers, the air side pressure drop is reduced compared to the R410A baseline 9 mm tube system. This attributes to the large free flow area between tube and fin for 5mm tube HXs.

(a) (b)

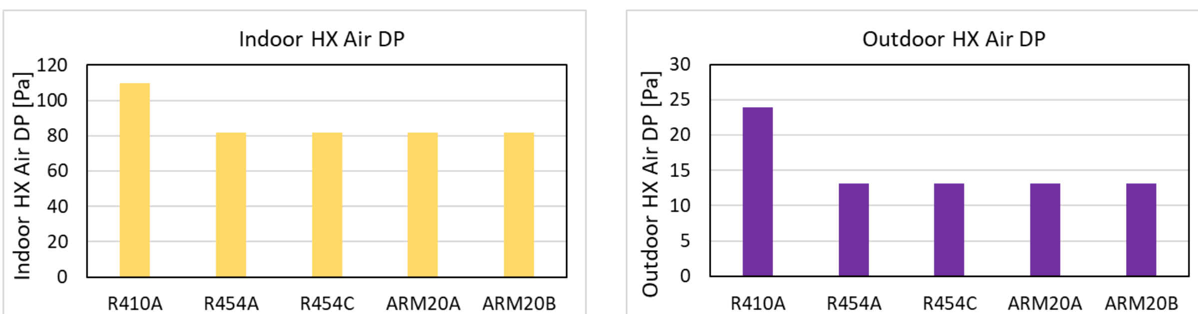


Figure 5: Air Side Pressure Drop of 5mm-Tube Heat Pumps without Adding Tubes: (a) Indoor HX; (b) Outdoor HX.

Table 3 and Table 4 details the performance of the optimized 5mm-tube heat pump without and with the flow control device, respectively. The optimal circuitry designs for both indoor and outdoor HXs using different low-GWP refrigerants are listed at the bottom of the tables. For indoor HXs, the number of circuits increases from 8 to 12 (or 24). For outdoor HX, the number of circuits increases from 8 to 24. The large number of circuits can reduce the refrigerant pressure drop by reducing the refrigerant mass flux in each circuit and shortening the flow path length. Thus, the refrigerate pressure drop increases induced by the usage of small diameter tubes can be compensated by large number of circuits.

Table 3: Performance of Optimized 5mm-Tube Heat Pump without Flow Control Device

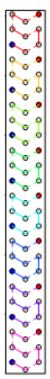
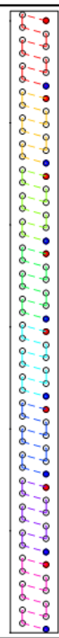
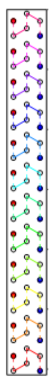
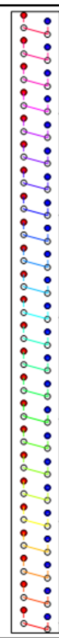
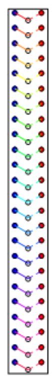
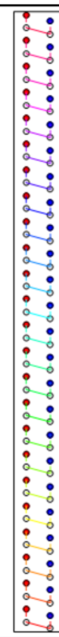
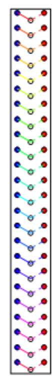
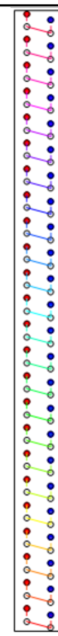
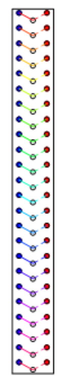
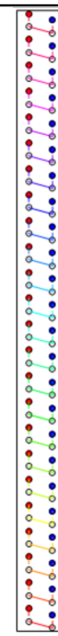
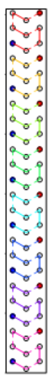
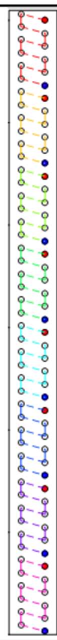
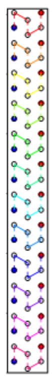
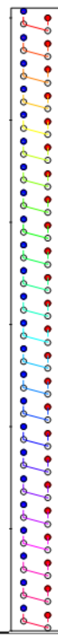
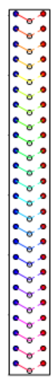
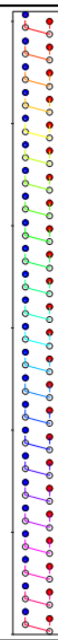
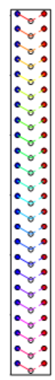
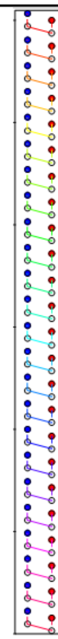
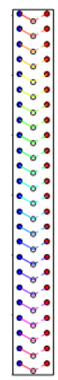
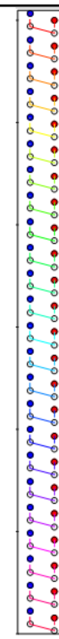
	R410A (Baseline)		R454A		R454C		ARM20A		ARM20B	
EER	12.02		11.31 (↓5.8%)		10.67 (↓11.2%)		10.85 (↓9.7%)		11.32 (↓5.7%)	
COP_{HP}	3.41		3.17 (↓1.9%)		2.87 (↓4.4%)		2.93 (↓3.8%)		3.01 (↓3.2%)	
System $Charge_{AC}$ [kg]	5.70		2.28		2.35		2.24		2.30	
System $Charge_{HP}$ [kg]	3.84		1.31		1.29		1.30		1.18	
HX	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Tube OD [mm]	9.52	9.52	5	5	5	5	5	5	5	5
Total tubes	72	96	72	96	72	96	72	96	72	96
NRows	3	2	3	2	3	2	3	2	3	2
NCircuits	8	8	12	24	24	24	24	24	24	24
Q_{ACMode} [W]	16118	19419	16118	19714	16118	19978	16118	19909	16118	19717
Q_{HPMode} [W]	15500	11912	15894	11754	15583	11242	15744	11492	15618	11458
Ref. DP_{AC} [kPa]	17.2	20.7	108.25	18.36	25.68	22.53	25.68	22.99	18.50	16.77
Air DP_{AC} [Pa]	109.8	23.9	81.9	13.1	81.9	13.1	81.9	13.1	81.9	13.1
Heat Exchanger Circuitry										

Table 4: Performance of Optimized 5mm-Tube Heat Pump with Flow Control Device

Refrigerant	R410A (Baseline)		R454A		R454C		ARM20A		ARM20B	
EER	12.02		11.31 (↓5.8%)		10.67 (↓11.2%)		10.85 (↓9.7%)		11.32 (↓5.7%)	
COP_{HP}	3.41		3.40 (↓0.0%)		3.04 (↓3.0%)		3.11 (↓2.4%)		3.22 (↓1.5%)	
System $Charge_{AC}$ [kg]	5.70		2.28		2.35		2.24		2.30	
System $Charge_{HP}$ [kg]	3.84		1.45		1.36		1.38		1.38	
HX	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Tube OD [mm]	9.52	9.52	5	5	5	5	5	5	5	5
Total tubes	72	96	72	96	72	96	72	96	72	96
NRows	3	2	3	2	3	2	3	2	3	2
NCircuits	8	8	12	24	24	24	24	24	24	24
Q_{ACMode} [W]	16118	19419	16118	19714	16118	19978	16118	19909	16118	19717
Q_{HPMode} [W]	15500	11912	16594	12849	16107	12160	16255	12290	16466	12511
Ref. DP_{AC} [kPa]	17.2	20.7	108.25	18.36	25.68	22.53	25.68	22.99	18.50	16.77
Air DP_{AC} [Pa]	109.8	23.9	81.9	13.1	81.9	13.1	81.9	13.1	81.9	13.1
Heat Exchanger Circuitry										

5. Performance of 5 mm Tube Heat Pumps with Adding Tubes

The results in section 4 concludes that solely optimizing the refrigerant circuitry of 5 mm tube heat exchangers can not achieve the baseline performance. This section discusses the result obtained from the second group of the optimization runs, i.e. optimizing 5 mm tube heat exchanger with doubling tube rows. Figure 6(a) shows the EER of the optimized systems. After doubling tube rows, the optimized systems using all four low-GWP refrigerants can outperform baseline system. The maximum EER improvement is 9.9% obtained by R454A optimized system. Figure 6(b) shows the system charge of the baseline system and the optimized systems. Despite the increase of tubes, the refrigerant charge of optimized systems is lower than that of R410A baseline system. The maximum charge reduction is 56.3% from R454C system.

(a) (b)

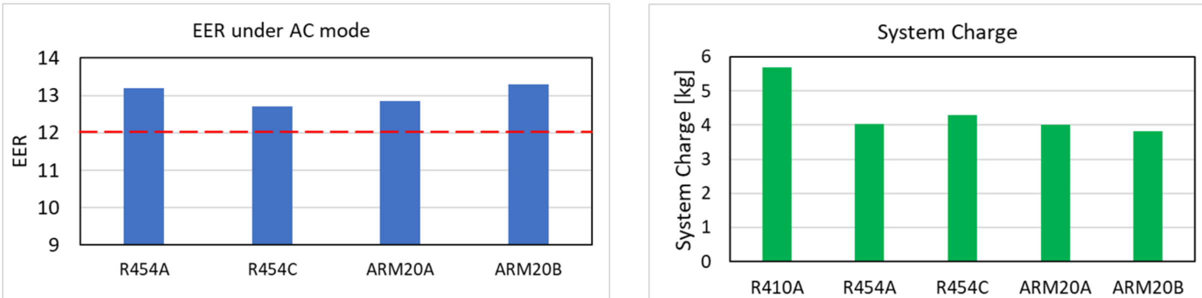


Figure 6: 5mm-Tube Heat Pumps with Added Tube Rows: (a) EER; (b) System Charge.

Figure 7(a) and Figure 7(b) show the COP of the optimized heat pumps under heating mode. Figure 7(a) shows the result without a smart flow device. Figure 7(b) shows the result with flow control device. Without flow control device (Figure 7(a)), optimized systems using R454A and ARM20A tie the baseline system, and systems using R454C and ARM20B outperforms baseline system. In contrast, the flow control device can make the optimized systems with all low-GWP refrigerants outperform the baseline. Figure 8 shows the airside pressure drop for the added tube row indoor and outdoor HXs. For both heat exchangers, the air side pressure drop is smaller than that of the R410A baseline due to the large free flow area between tubes and fins of the 5 mm tube HXs.

(a) (b)

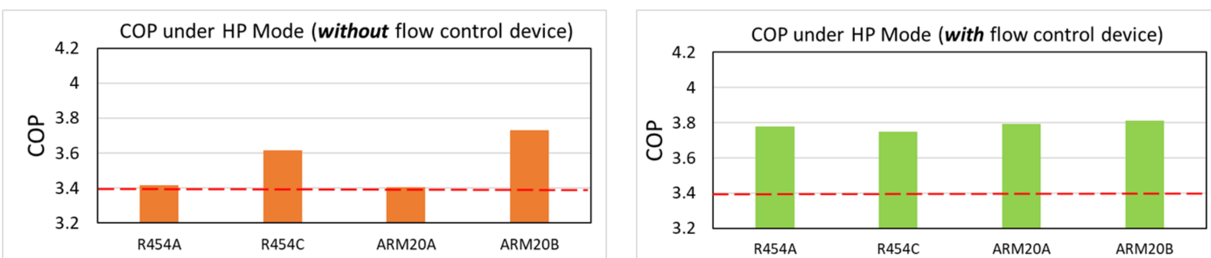


Figure 7: Heating COP of 5mm-Tube Added Tubes Heat Pumps: (a) No Flow Control Device; (b) Flow Control Device Installed.

(a) (b)

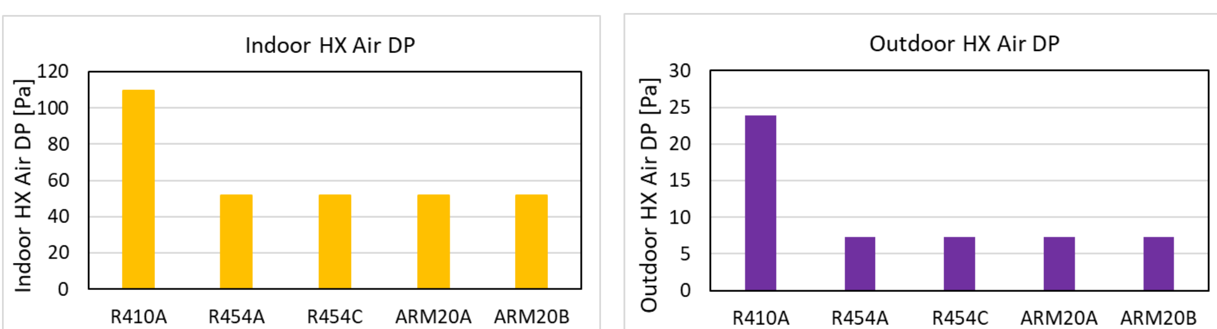


Figure 8: Air Side Pressure Drop of 5mm-Tube Heat Pumps with Added Tube Rows: (a) Indoor HX; (b) Outdoor HX.

Table 5 and Table 6 details the performance of the optimized 5mm-tube heat pumps without and with the flow control device, respectively. For indoor HXs, the number of circuits increases from 8 to 24. For outdoor HX, the number of circuits increases from 8 to 24 (or 48). Similar as the results in section 4, the large number of circuits can reduce the refrigerant pressure drop by reducing the refrigerant mass flux in each circuit and shortening the flow path length.

Table 5: Performance of Optimized Added Tube Rows 5mm-Tube Heat Pump without Flow Control Device by Using Different Refrigerants

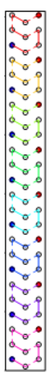
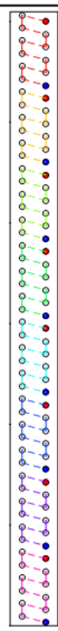
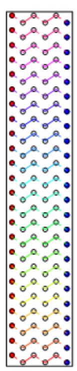
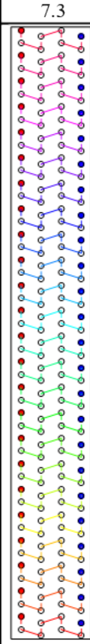
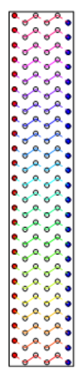
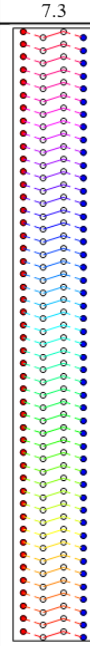
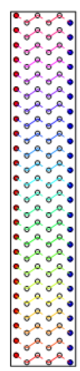
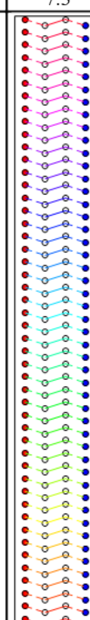
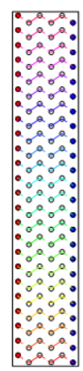
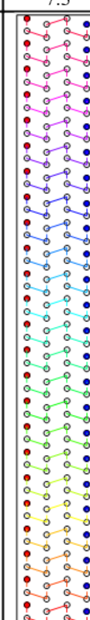
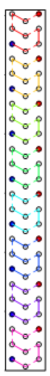
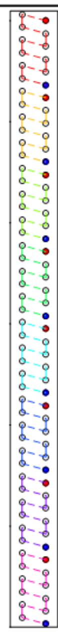
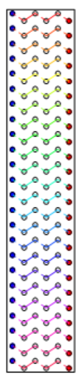
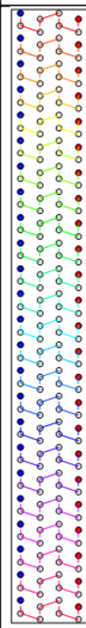
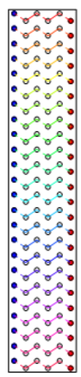
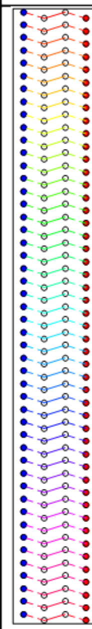
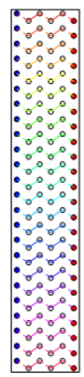
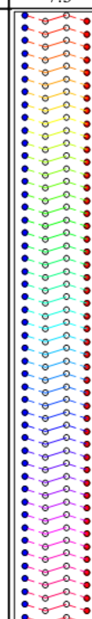
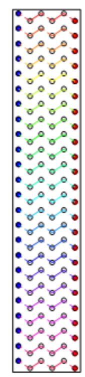
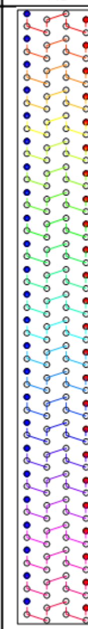
Refrigerant	R410A (Baseline)		R454A		R454C		ARM20A		ARM20B	
EER	12.02		13.19 (↑9.9%)		12.71 (↑5.9%)		12.85 (↑7.0%)		13.29 (↑10.7%)	
COP_{HP}	3.41		3.42 (↑0.1%)		3.62 (↑1.8%)		3.40 (↑0.0%)		3.73 (↑2.7%)	
System $Charge_{AC}$ [kg]	5.70		4.03		4.28		4.01		3.83	
System $Charge_{HP}$ [kg]	3.84		2.23		1.68		1.93		1.94	
HX	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Tube OD [mm]	9.52	9.52	5	5	5	5	5	5	5	5
Total tubes	72	96	144	192	144	192	144	192	144	192
NRows	3	2	6	4	6	4	6	4	6	4
NCircuits	8	8	24	24	24	48	24	48	24	24
Q_{ACMode} [W]	16118	19419	16118	19116	16118	19259	16118	19224	16118	19096
Q_{HPMode} [W]	15500	11912	13624	10560	14029	11015	13992	10790	13815	11006
Ref. DP_{AC} [kPa]	17.2	20.7	25.3	34.9	33.6	6.1	33.6	6.3	24.6	33.9
Air DP_{AC} [Pa]	109.8	23.9	51.7	7.3	51.7	7.3	51.7	7.3	51.7	7.3
Heat Exchanger Circuitry										

Table 6: Performance of Optimized Added Tube Rows 5mm-Tube Heat Pump with Flow Control Device by Using Different Refrigerants

Refrigerant	R410A (Baseline)		R454A		R454C		ARM20A		ARM20B	
EER	12.02		13.19 (↑9.9%)		12.71 (↑5.9%)		12.85 (↑7.0%)		13.29 (↑10.7%)	
COP_{HP}	3.41		3.78 (↑3.1%)		3.75 (↑2.9%)		3.79 (↑3.3%)		3.81 (↑3.4%)	
System $Charge_{AC}$ [kg]	5.70		4.03		4.28		4.01		3.83	
System $Charge_{HP}$ [kg]	3.84		2.54		2.36		2.35		2.41	
HX	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Tube OD [mm]	9.52	9.52	5	5	5	5	5	5	5	5
Total tubes	72	96	144	192	144	192	144	192	144	192
NRows	3	2	6	4	6	4	6	4	6	4
NCircuits	8	8	24	24	24	48	24	48	24	24
Q_{ACMode} [W]	16118	19419	16118	19116	16118	19259	16118	19224	16118	19096
Q_{HPMode} [W]	15500	11912	14420	11647	15116	12054	15108	12110	14396	11653
Ref. DP_{AC} [kPa]	17.2	20.7	25.3	34.9	33.6	6.1	33.6	6.3	24.6	33.9
Air DP_{AC} [Pa]	109.8	23.9	51.7	7.3	51.7	7.3	51.7	7.3	51.7	7.3
Heat Exchanger Circuitry										

As a conclusion, the results from section 5 demonstrates that with doubling tube rows, the optimized heat pump using low-GWP refrigerants and 5 mm tubes can offer equivalent or improved performance under cooling and heating modes compared with the baseline system. And usage of the flow control device to always maintain counter-flow circuitry pattern of heat exchanger regardless of mode switching can furtherly improve the system performance under heat pump mode.

6. LCCP Calculation

Life Cycle Climate Performance (LCCP) is an evaluation method by which heating, ventilation, air conditioning and refrigeration systems can be evaluated for their global warming impact over the course of their complete life cycle. It is calculated as the sum of direct and indirect emissions generated over the lifetime of the system "from cradle to grave". Direct emissions include all effects from the release of refrigerant into the atmosphere during the lifetime of the system as shown in Eq. (2). Direct emissions include:

1. Annual refrigerant loss from gradual leaks.
2. Losses at the end of life disposal of the unit.
3. Large losses during operation of the unit.
4. Atmospheric reaction products from the breakdown of the refrigerant in the atmosphere.

$$Direct\ emissions = C \times (L \times ALR + EOL) \times (GWP + Adp.GWP) \quad (1)$$

In Eq. (2), C refers refrigerant charge (kg); L refers average life of the equipment (yr); ALR refers annual leakage rate (percentage of refrigerant charge); EOL refers End of Life refrigerant leakage (percentage of refrigerant charge); GWP refers Global Warming Potential (kg CO2e/kg); Adp. GWP refers GWP of Atmospheric Degradation Product of the Refrigerant (kg CO2e/kg).

The indirect emissions as shown in Eq. (3) include:

1. Emissions from electricity generation
2. Emission from the manufacturing of materials
3. Emissions from the manufacturing of refrigerants
4. Emissions from the disposal of the unit

$$\begin{aligned} Indirect\ emissions = {} & L \times AEC \times EM + \sum (m \times MM) + \sum (mr \times RM) \\ & + C \times (1 + L \times ALR) \times RFM + C \times (1 - EOL) \times RFD \end{aligned} \quad (2)$$

Where AEC refers Annual Energy Consumption (kWh); EM refers CO_2 produced/kWh (kg CO2e/kWh); m refers mass of unit (kg); MM refers CO_2 Produced/Material (kg CO2e/kg); mr refers mass of recycle material (kg); RM refers CO2 produced/ recycled material (kg CO2e/kg); ALR refers Annual leakage rate (percentage of refrigerant charge); RFM refers refrigerant manufacturing emission (kg CO2e/kg); RFD refers refrigerant disposal emissions (kg CO2e/kg); L, C, and EOL have the same meaning as the ones in Eq. (2).

To evaluate the annual energy consumption of the baseline and optimized heat pump systems, each system needs to be evaluated in 5 operating conditions: 2 cooling conditions and 3 heating conditions from AHRI 210/240 test standards. Table 7 lists the test conditions for the heat pump performance evaluation.

Table 7: AHRI 210/240 Test Conditions used in LCCP Calculation

Test	Indoor		Outdoor		Operation
	Dry bulb [°F]	Wet bulb [°F]	Dry bulb [°F]	Wet bulb [°F]	
A	80	67	95	NA	Cooling
B	80	67	82	NA	Cooling
H1	70	≤ 60	0	0	Heating
H2	70	≤ 60	62	58.5	Heating
H3	70	≤ 60	47	43	Heating

In addition to the performance evaluation results, other input values used for evaluating the LCCP (illustrated by the baseline system) are shown in Table 8. In Table 8, cut off temperature is a low outdoor temperature at which the heat pump stop operating. The T_{on} is the temperature that heat pump starts to run again after the outdoor falls below the cut off temperature.

Table 8: Input Values for Baseline System LCCP Calculation

Item	**Value**
Refrigerant	R410A
Refrigerant Charge [kg]	5.7
Unit Weight [kg]	190
Annual refrigerant leakage [%]	4
EOL leakage [%]	15
Lifetime [years]	15
Manufacturing emission type	Virgin
Cut off temperature [°C]	-17.8
T_{on} [°C]	-12.2

Figure 9 (a) and Figure 9 (b) shows the detailed LCCP calculation in 5 different climate zones represented by five typical US cities for the R410A baseline system and the ARM20A small diameter tube optimized system, respectively. Comparing the limit of y-axis, ARM20A system has 9%-12% lower total CO_2 emission. For R410A system (Figure 9 (a)), energy consumption and refrigerant leakage are the main contributors of LCCP. However, for low-GWP systems (Figure 9 (b)), energy consumption is the dominant contributor (>98%) of LCCP.

(a) (b)

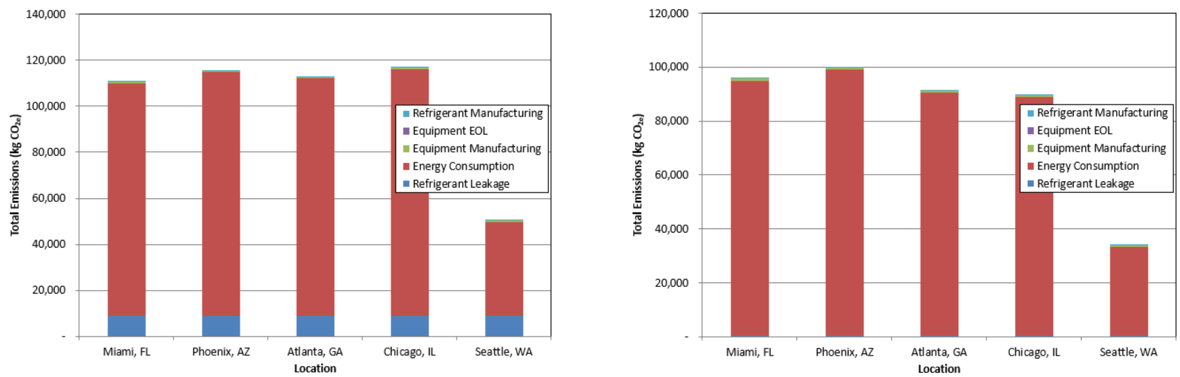


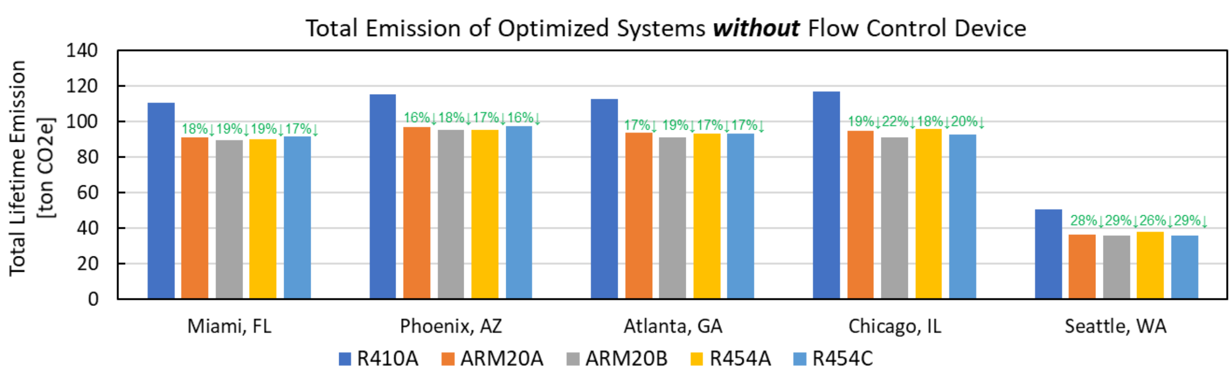
Figure 9: LCCP Calculation: (a) Baseline R410A Unit; (b) Optimized System for ARM20A without Flow Control Device.

7. Comparison of Total, Direct and Indirect Emissions

This section performs a detailed comparison of LCCP, in terms of total emission, direct emission and indirect emission. It also compares the difference between systems with and without flow control device.

Figure 10 shows the comparison of the total emissions. Figure 10 (a) shows the total emissions of optimized system without flow control device. Figure 10 (b) shows the total emissions with flow control device. In difference cities R410A system always has the highest total emissions, ARM20B has the lowest total emission. The total emission in Seattle is about 48% smaller than the total emission in Miami, because Seattle requires much less cooling capacity than any other regions. The hours in temperature bins are mostly developed in mild conditions (relatively high temperature bins at heating season). By comparing the numbers in Figure 10 (a) with Figure 10 (b), it can be seen that adding flow control device can furtherly reduce total emission by 3%-5%.

(a)



(b)

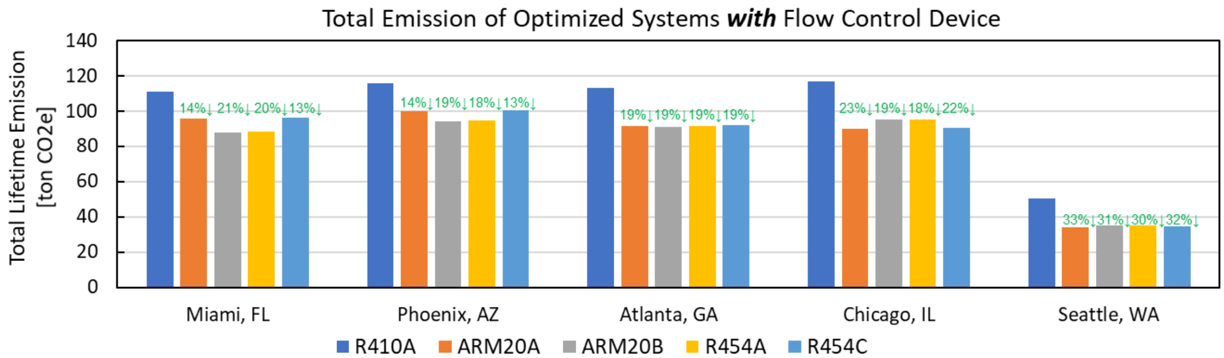
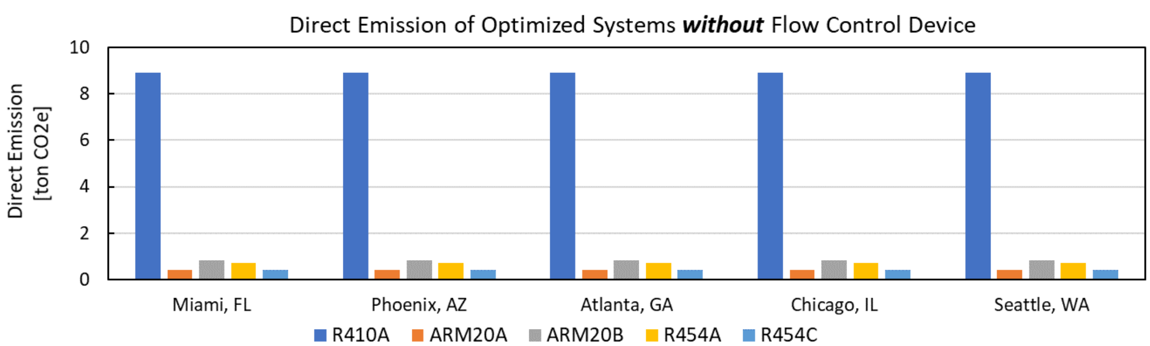


Figure 10: Total Emision of Baseline and Low-GWP Refrigerants Optimized Systems: (a) No Flow Control Device; (b) Flow Control Device Installed.

Figure 11 shows the comparison of the direct emissions. Figure 11 (a) shows the direct emissions of optimized system without flow control device. Figure 11 (b) shows the direct emissions with flow control device. The optimized systems have significantly lower direct emissions than the baseline system. This attributes to the much lower GWP value of alternative refrigerants and the reduced system charge as shown in Figure 6 (b).

(a)



(b)

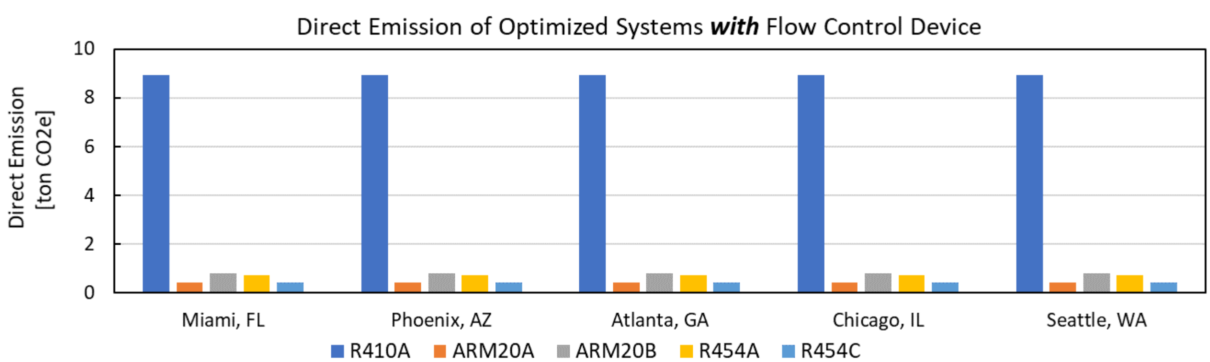
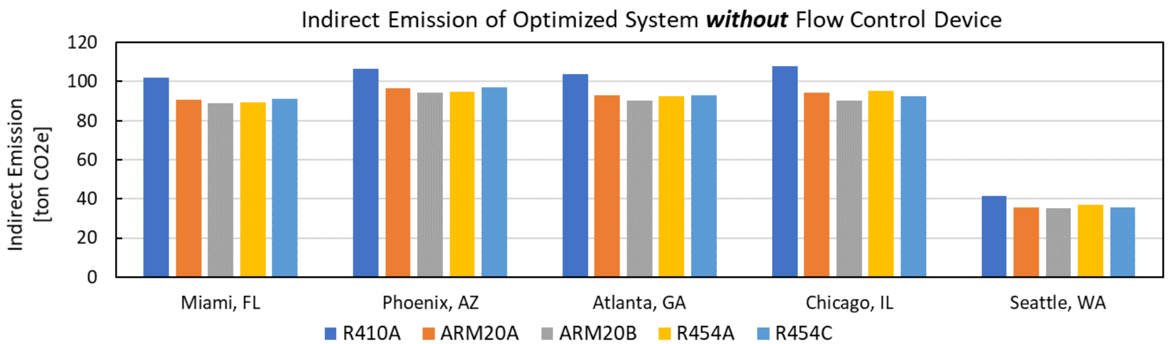


Figure 11: Direct Emision of Baseline and Low-GWP Refrigerants Optimized Systems: (a) No Flow Control Device; (b) Flow Control Device Installed.

Figure 12 shows the comparison of the indirect emissions. Figure 12 (a) shows the indirect emissions of optimized system without flow control device. Figure 12 (b) shows the indirect emissions with flow control device. It can be seen the optimized systems have 10%-16% lower indirect emissions than the baseline system. This attributes to improved EER (Figure 6(a)) and COP (Figure 7) from the system design.

(a)



(b)

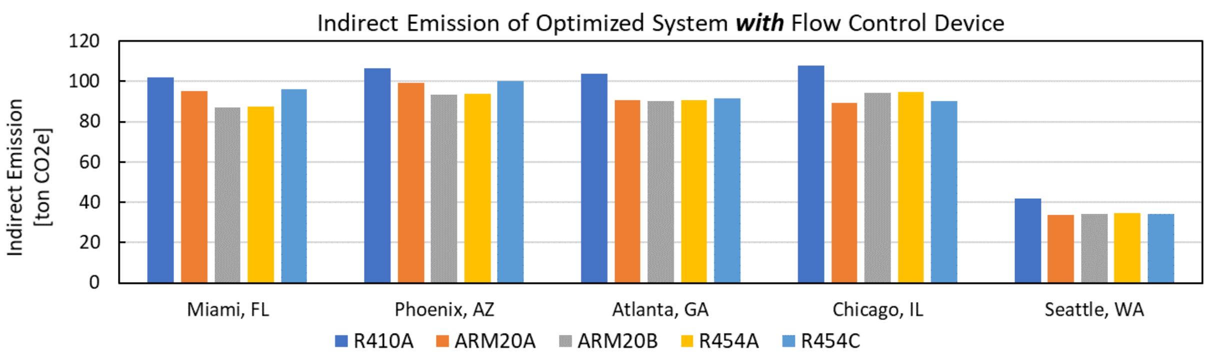


Figure 12: Indirect Emision of Baseline and Low-GWP Refrigerants Optimized Systems: (a) No Flow Control Device; (b) Flow Control Device Installed.

8. Summary

This report investigates the efficacy of a new design method for heat pump systems using low-GWP refrigerants and 5 mm diameter tubes. A simulation-based design method is used to optimize the refrigerant circuitries of a 5-ton heat pump system whose indoor and outdoor heat exchangers adopt 5 mm tubes.

- Systems using four commercially available low-GWP refrigerants (R454A, R454C, ARM20A, ARM20B) are optimized in this study.
- Directly replacing 9 mm tubes into 5mm tubes in the baseline systems induces heat pump performance degradation.
- By optimizing the 5 mm tube heat pumps with added tube rows, the system refrigerant charge is reduced up to 33% compared with the baseline R410A system.

- The optimized low-GWP 5 mm tube heat pumps offer the equal or higher performance under both cooling and heating mode. Under cooling mode, the EER improvement is up to 10.7% and under heating mode the COP improvement is up to 3.4%.
- Flow control device to maintain counter-flow circuitry pattern on both operating modes can improve the heating performance of the low-GWP 5 mm tube optimized system by up to 3.0%.
- Life Cycle Climate Performance analysis shows the optimized systems using 5mm tubes and low-GWP refrigerants can reduce life-cycle CO_2 emission significantly. And improving system efficiency is the most effective way to reduce the emission of low-GWP refrigerant systems.

This report shows that using 5 mm diameter tubes in heat exchangers is a feasible approach to develop heat pumps with low-GWP refrigerants. Using the proposed design approach can yield higher system efficiency with lower environmental impact.