Optimization of Residential Air Source Heat Pump using Low–Global Warming Potential Refrigerants

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Low–global warming potential refrigerants can significantly reduce the direct emissions of CO_2 originating from HVAC systems. However, high-efficiency systems are needed to reduce indirect CO_2 emissions. In this study, an R 410A residential 5-Ton heat pump was optimized using R 32, R 454A, R 454B, R 454C, and R 455A. Among these options, R 455A and R 454C have the lowest global warming potential but have lower volumetric capacity and high glide. Optimization results using 5 mm tube heat exchangers showed 12.4% to 19.1% efficiency improvements and 13% to 33% reduction in CO_2 emissions.

Environmental concerns have driven refrigerant changes since the 1980s. The Montreal Protocol (1987) affected chlorine-containing refrigerants, and the Kigali Amendment (2016) addressed global warming concerns by restricting the use of high–global warming potential (GWP) refrigerants.

The options to replace R-410A have been reduced by these measures, and replacements are mostly non-azeotropic blends with large temperature glide. Among the alternatives, R-32, R-454B, and R 454A are near-term options with GWP <750. Long-term options would likely have GWP <150, which requires the use of high-glide blends such as R-454C and R-455A (Table 1). These refrigerants have also lower volumetric capacity and pressure. Therefore, they will require significant changes to heat exchanger (HX) designs. Therefore, this study focuses on optimizing the whole system by employing HXs with smaller diameter (5 mm) and optimized circuitry.

System Model and Baseline Reversible Heat Pump

The US Department of Energy's Oak Ridge National Laboratory's Heat Pump Design Model [1] was used to simulate the performance of heat pumps. This model has been validated using experimental data [2]. REFPROP 10.0 [3] was used to calculate refrigerant properties. To ensure proper simulation of 5 mm tube HXs, air-side correlations that were developed for small-diameter tubes [4] were implemented. For the 9 mm R-410A baseline system, a model from Wang et al. [5] was used.

To compare the refrigerants, a residential 5-Ton R-410A reversible heat pump is used as a baseline. Table 2 lists the parameters of the baseline HXs, including airflow rate and fan power. The indoor HX is a 3-row/72-tube coil with 8 circuits. The outdoor HX is a 2-row/96-tube coil with 8 circuits.

Optimization Methodology

The particle swarm optimization algorithm implemented in GenOpt [6] was used to optimize the heat pump. This optimization has two objectives: the first is to maximize the efficiency at AHRI Standard cooling test A condition [7], and the second is to minimize the HX material cost. The number of circuits in indoor and outdoor HXs is a variable. The number of tubes is also a variable, which means that the number of circuits has a self-adaptive upper limit instead of a fixed upper limit.

Table 1. Characteristics of refrigerants investigated in this research

Refrigerant	GWP	Safety class	Composition and mass fraction (%)	Glide (°C)	Critical temperature (°C)
R-410A	2,088	A1	R32/R125: 50/50	0.1	72.8
R-32	675	A2L	R32: 100	0	78.1
R-454B	466	A2L	R32/R1234yf: 68.9/31.3	1.3	77
R-454A	238	A2L	R32/R1234yf: 35/65	6.2	78.9
R-454C	146	A2L	R32/R1234yf: 21.5/78.5	6.0	82.4
R-455A	139	A2L	R32/R1234yf/CO2: 21.5/75.5/3	6.9	90.2

Table 2. Parameters of indoor and outdoor heat exchangers of the baseline 5-Ton two-stage (staged at 100% and 67% compressor displacement volumes) heat pump.

Parameter	Indoor HX	Outdoor HX
Face area (ft2)	3.6	33.7
Number of tubes	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
Fan airflow rate (CFM)	1,770	4,215
Fan power (W)	478	181

In terms of operating conditions, the evaporator superheat was fixed. The condenser subcooling was automatically adjusted, but it was constrained between 1.1 °C and 8.3 °C. The cooling capacity matched the original 5-Ton R-410A heat pump by modifying the compressor volumetric displacement.

The HXs have the same frontal shapes as the baseline HX, so they can fit into the original indoor and outdoor fan-coil unit. The HX circuitry mimics a counter-flow configuration, which shows significant advantages for high-glide mixtures. The HX material cost was estimated by performing a material inventory for the copper and aluminium and multiplying them by the market price.

Optimization Results

Figure 1 shows the results for R-410A and all alternative refrigerants. The horizontal axis depicts the Energy Efficiency Ratio (EER), while the vertical one shows the material cost of the heat exchangers. The optimal R-410A 5 mm tube design shows good performance, as expected. This performance point is also plotted on other Pareto fronts as a solid black hexagon.

R-32 results (Figure 1b) show good performance, as expected, because of its good thermal properties. On the other plots (Figure 1c–3f), reference points were set. The red triangle represents the baseline R-410A system using 9 mm tube HXs. The yellow hollow circle represents a drop-in simulation using the baseline system. The green diamond symbol represents a drop-in simulation replacing the 9 mm tubes with 5 mm tubes. The purple rectangle symbol represents a design in which the 9 mm tubes are replaced with 5 mm tubes but doubling the number of tubes.

The drop-in comparison (red triangle with yellow hollow circle) shows decreased efficiency for all alternative refrigerants. Replacing the 9 mm tubes with the 5 mm tubes (yellow circle with green diamond) shows an even greater decrease, as expected by the reduced heat transfer area. Furthermore, doubling the number of tubes (purple rectangle with green diamond) shows that increasing the HX area without optimization also fails to deliver a satisfactory solution. This analysis demonstrates the excellent sensitivity of the heat pump design model and emphasizes the need to perform optimization of the 5 mm tube system for all low-GWP alternatives.

Finally, the optimized systems (blue circle with red triangle) show significant HX cost savings and efficiency improvement compared with the baseline R-410A 9 mm tube system. The maximum efficiency improvements for low-GWP systems range from 11.7% to 14.1%, and the optimized HX design can save material costs by at least 62%, depending on the choice of refrigerants.

Performance of Optimized Heat Pump Designs

The seasonal energy efficiency ratio (SEER) and heating seasonal performance factor (HSPF) were calculated for the optimized systems, according to AHRI 210/240 test standards [8]. In all cases, the volumetric displacement was adjusted to match the baseline cooling capacity. The performance degradation owing to frost accumulation was considered by applying performance degradation factors (0.91 for heating capacity and 0.985 for power consumption). Figure 2 shows performance for the R-410A baseline system and low-GWP optimized systems with SEER over 16 and HSPF over 9.5.

Figure 3a shows the optimized systems charges with reductions ranging from 13% to 50%, likely because of the use of optimized 5 mm tube HXs. However, compressor displacements are larger than in the baseline, indicating the need for further development.

Life Cycle Climate Performance Analysis

Life cycle climate performance (LCCP) evaluation [8] was performed to analyze the direct and indirect greenhouse gas emissions of the system. To evaluate the annual energy consumption, each system was evaluated two cooling conditions and three heating conditions according to AHRI 210/240 test standards [8]. Other values used

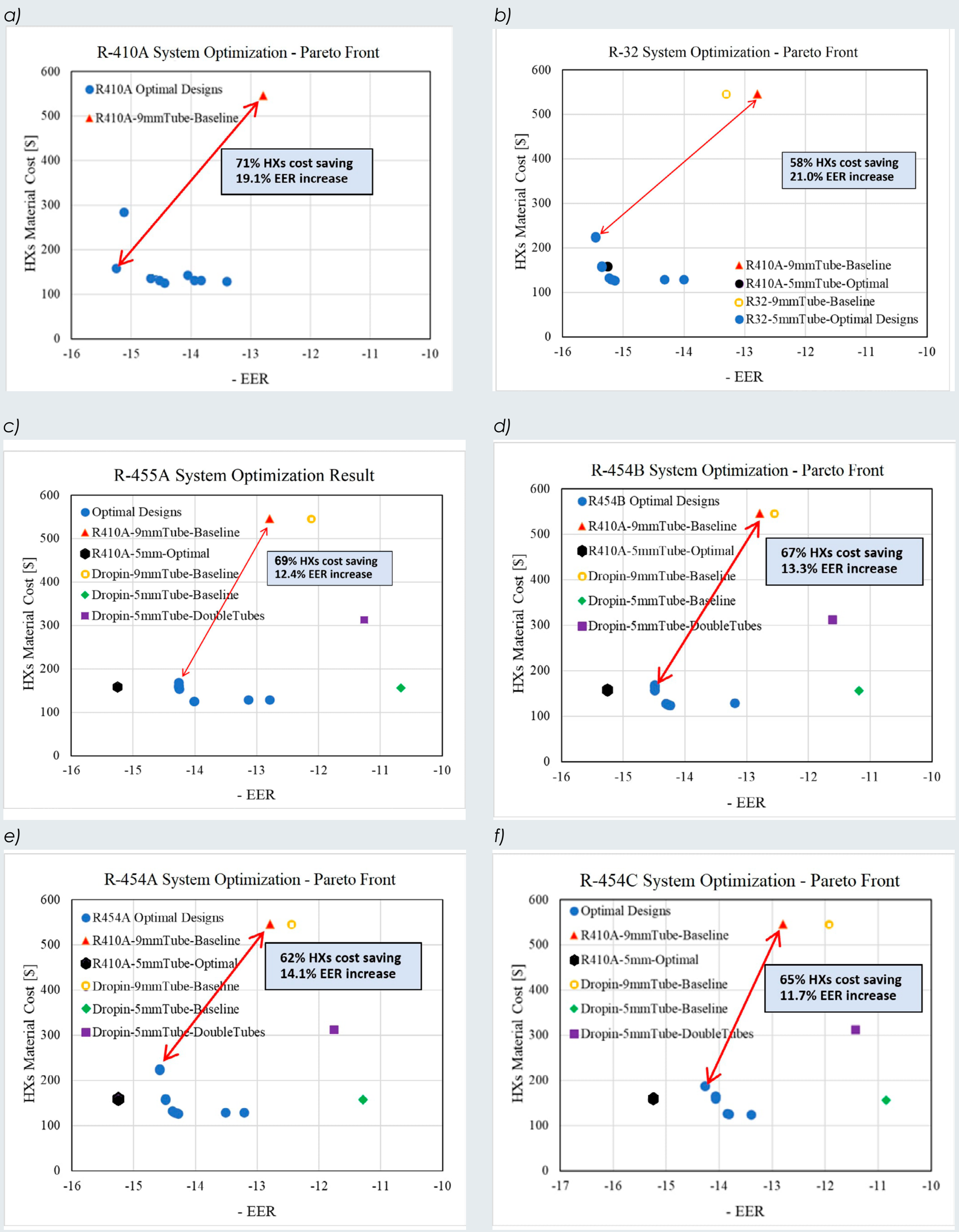

Figure 1. Pareto Fronts for 5 mm diameter tube heat pump system optimization using (a) R-410A, (b) R-32, (c) R-455A, (d) R-454B, (e) R-454A, and (f) R-454C.

for evaluating the LCCP are shown in Table 3. The cut-off outdoor temperature and the temperature at which the heat pump starts are also shown.

Figure 4 shows LCCP results for five cities representing all climate zones in the United States. The optimized systems using low-GWP refrigerants reduced total lifetime greenhouse gas emissions by 13% to 33%, depending on the refrigerant and climate zone.

Conclusions

This study presents heat exchanger and system development technologies to support the transition to refrigerants with GWP lower than 150. High-efficiency levels in cooling (SEER over 16.0) and heating modes (HSPF over 9.5) were achieved by a model-based design optimization approach for low-GWP refrigerants using 5 mm tube heat exchangers. The potential to reduce the overall lifetime emissions of CO_2 by 13% to 33% was also shown.

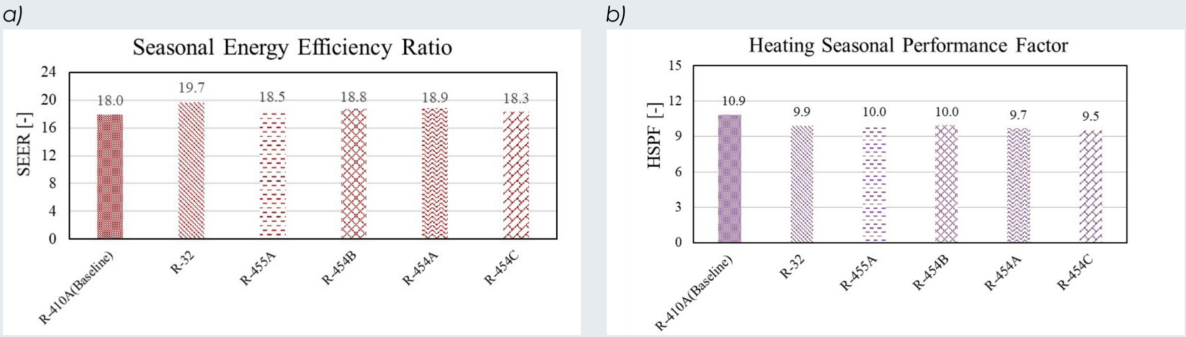

Figure 2. Performance of sampled optimized heat pump systems using different refrigerants: (a) SEER and (b) HSPF.

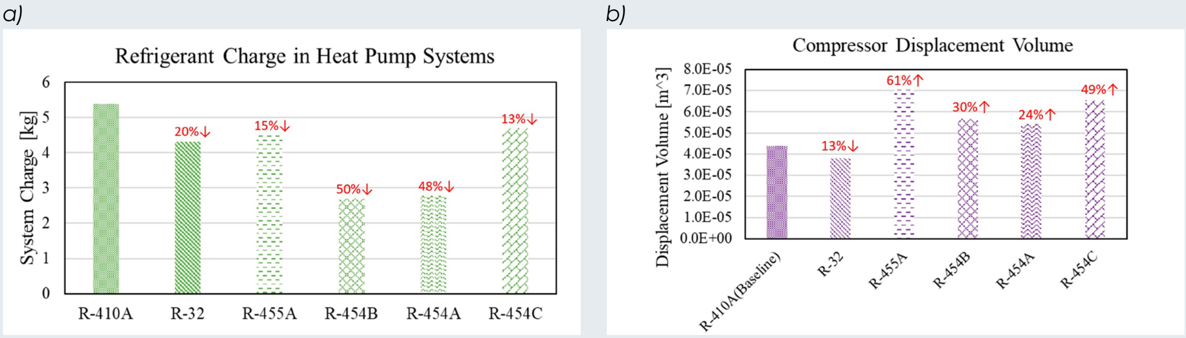

Figure 3. (a) System refrigerant charge and (b) designed compressor displacement volume.

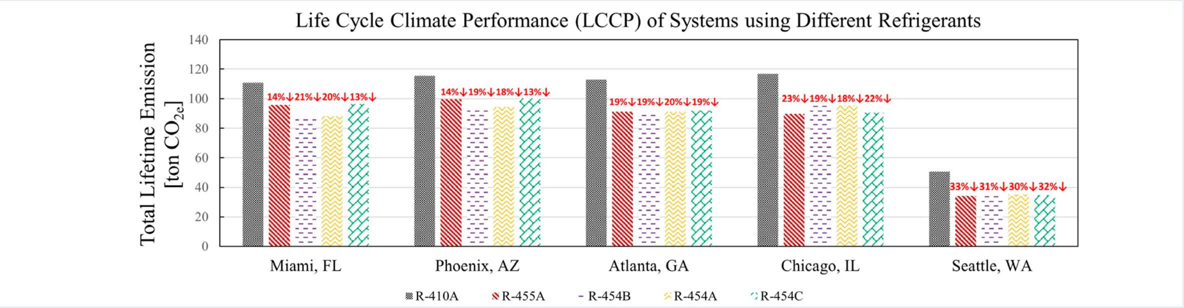

Figure 4. Total greenhouse gas emissions of the baseline system and low-GWP optimized systems.

The optimal 5 mm tube heat exchangers obtained from this research can fit into the original R-410A system frame, which helps to minimize changes in manufacturing and installation, thus reducing impacts on manufacturers and end-users. The proposed approach establishes a production and installation path to produce cost-effective low-GWP reversible heat pumps.

Table 3. Input values for baseline system LCCP calculation

Factor	Value
Refrigerant	R-410A or its alternatives
Refrigerant charge (kg)	From Figure 3 (a)
Unit weight (kg)	190
Annual refrigerant leakage (%)	4
EOL leakage (%)	15
Lifetime (years)	15
Cut-off temperature (°C)	−17.8
Temperature at which the heat pump starts (°C)	−12.2

This study has clearly shown the usefulness of Artificial Intelligence, i.e., optimization, in designing the next generation A/C systems. Still, significant challenges remain as other components like the compressor will also need to be properly designed for the new low-GWP refrigerants.

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