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Evaluation of lower GWP alternatives to R410A in AC and HP applications

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Abstract

R410A is a refrigerant commonly used in air conditioning and heat pump applications that has become the target to be replaced by lower global warming potential (GWP) alternatives. R-454B with a GWP of 466 has been proposed as a lower GWP replacement for R-410A with similar performance and operating characteristics. Long-term refrigerant solutions are required to provide similar to improved efficiency with comparable capacity while having a GWP of less than 300. This threshold has been identified as an industry-wide average in line with global climate commitments.
This paper investigates alternative refrigerant options to replace R-410A including R-454B, as well as DR-4 and R-479A with a GWP of less than 300 and less than 150 respectively. Thermodynamic simulations followed by an investigation using a component system model of a 3-ton unitary heat pump are performed. Varying ambient temperatures in cooling operation as well as standard rating conditions for both heating and cooling operation for each candidate are considered, to compare refrigerant performance and to determine their viability as a replacement option. Drop-in performance and adjusted compressor speeds are used to compensate for the capacity penalty the lower GWP options experience to achieve relative COP and capacity within 5% of R-410A for investigated heating and cooling conditions.

Keywords: R-410A; Low GWP; Air conditioning; Heat pump, R-479A, DR-4

1. Introduction

Global climate change has brought the scientific community together through the research performed within the Intergovernmental Panel for Climate Change (IPCC, [1]). The reports that document the findings of experts confirm mankind's impact on ever increasing carbon dioxide emissions that drive temperature rise. Refrigerants with high global warming potential (GWP) are estimated to potentially contribute an average global temperature rise of 0.5˚C if no action was to be taken with reducing the GWP of fluorinated hydrocarbons in use today in HVACR equipment. Air conditioning and heat pump applications are hereby an important factor for which R410A is one of the leading refrigerants with a GWP of 2088 [2].

Multiple studies have been performed to investigate refrigerant options with a lower GWP to replace R-410A. The reduction of refrigerant GWP requires in many cases a blend design which contains lower GWP hydrofluoroolefin (HFO) refrigerant components that are often, ASHRAE Standard 34 flammability Class 2L [3]. For example, R-410A is a blend of R-32 which has a flammability classification of 2L and R-125 (Class 1) is added only to render the blend non-flammable. An industry wide test program that evaluated lower GWP R-410A replacements included R-744 as a nonflammable option along with nine lower flammability options with classification of 2L based on R-1234yf and R-1234ze(E) in combination with R-32 in most cases [4]. The GWP of the investigated 2L candidates offered hereby significant reduction compared to R-410A in a range from a GWP of about 200 to 1500 as described in [5]. Another lower flammability candidate with a GWP of 466 is the binary blend R-454B formulated with 68.9% R32 and 31.1% R-1234yf as presented by Hughes et

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al. [6]. This blend provides similar capacity with slight improvements in efficiency while having higher compressor discharge temperatures compared to R-410A. Considering a weighted average approach of GWP of refrigerants being used today throughout the industry, the GWP will need to be less than 300 to meet the phase-down targets of the Kigali Amendment to the Montreal Protocol as described by Schultz et al. [7]. Schultz describes the potential blend development opportunity by using newly introduced low GWP molecules CF3I, R-1123, R-1132a. Candidate blends were identified to have suitable properties to be considered as R410A replacement candidates. However, the expectable capacity would be 10 to 15% lower compared to R410A. Additional challenges remain in chemical and material compatibility considerations of these new molecules that need to be investigated for a successful implementation in air conditioning and heat pump applications. Recently another low GWP (GWP<1) molecule has been introduced with R-1132(E) as described by Rydkin et al. [8]. This molecule which has a safety classification of B2 by ASHRAE Standard 34 [3] has been formulated in the blend R-479A with 21.5% R32 and 50.5% R1234yf.

For the investigation performed in this study R410A is compared to R-454B and the binary blend option DR-4 as evaluated by Schultz et al. in [9] with a GWP of less than 300 and R-479A with a GWP of less than 150 as summarized in Table 1. All the investigated replacement blend candidates are of lower flammability and provide significant GWP reduction potential. The normal boiling point temperatures as well as the critical properties of the replacement candidates are similar while their temperature glide increases with decreasing GWP.

Table 1. Properties of investigated refrigerants

Refrigerant	**R-410A**	**R-454B**	**DR-4**	**R-479A**
Composition	R-32/R-125, (50/50)	R-32/R-1234yf, (68.9/31.1)	R-32/R-1234yf, (43.5/56.5)	R-1132(E)/R-32/R-1234yf, (28/21.5/50.5)
ASHRAE	A1	A2L	A2L	A2L
GWP_{100} AR4	2088	466	299	148
NBP [°C]	-51.7	-50.8	-49.0	-50.7
NDP [°C]	-51.6	-49.8	-44.9	-44.9
Glide [K]	0.1	1.0	4.1	5.8
Pcrit [MPa]	4.9	5.3	4.8	4.8
Tcrit [°C]	71.3	78.1	80.1	79.7

Figure 1 shows the property diagrams for all four compared blends visualizing their similarity in terms of heat of vaporization for R-410A, DR-4 and R-479A (pressure-enthalpy) as well as compressor discharge temperature (temperature -entropy). R-454B has a wider two-phase dome due to its larger R-32 blend fraction causing higher compressor discharge temperatures at the same time. The larger glide of DR-4 and R-479A compared to R-410A and R-454B becomes noticeable in the condenser and evaporator.

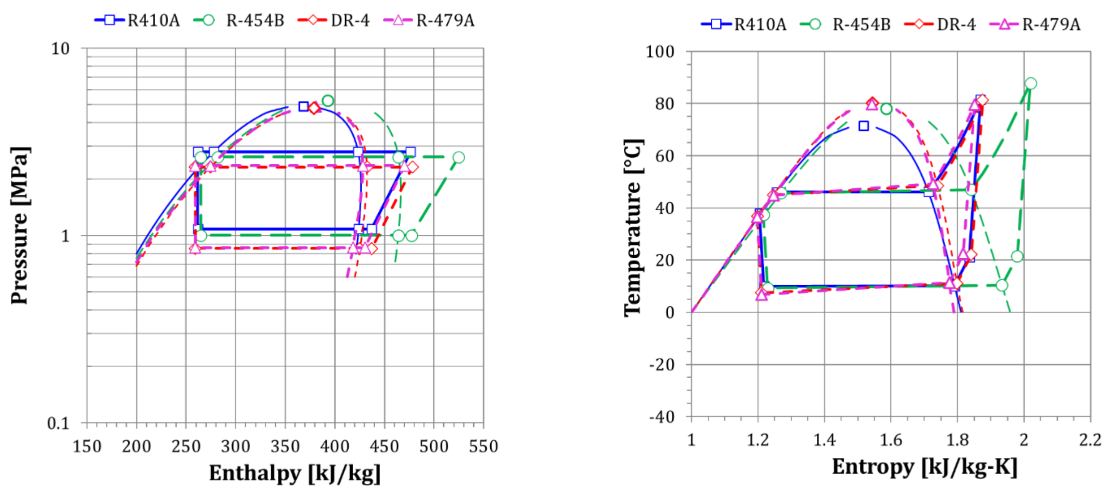


Figure 1. Pressure- Enthalpy and Temperature- Entropy property comparison of evaluated refrigerants

A thermodynamic model was set up using REFPROP 10 [10] refrigerant properties to evaluate the R-410A lower GWP alternatives in terms of expected performance and operating characteristics as outlined in Petersen et al. [11]. Pressure drops are hereby not accounted for in the heat exchangers and connecting lines. AHRI 210/240 A test point [12] conditions were used for the study with an evaporation temperature of 10°C considering 8.3K superheat and an approach of 8.4K based on an indoor air side temperature of 26.7°C. Similarly, the condensing temperature was set at 46.1°C with 8.3K subcooling and an approach temperature difference of 2.8K based on 35°C air temperature entering the outdoor unit. A heat exchanger weighting of 0.7 is applied for the evaporator and the condenser as a weighted average of the dew point and bubble point temperatures. Figure 2 summarizes the relative COP (COP*), relative capacity (CAP*) and relative compressor discharge temperature difference (ΔCDT) compared to R-410A.

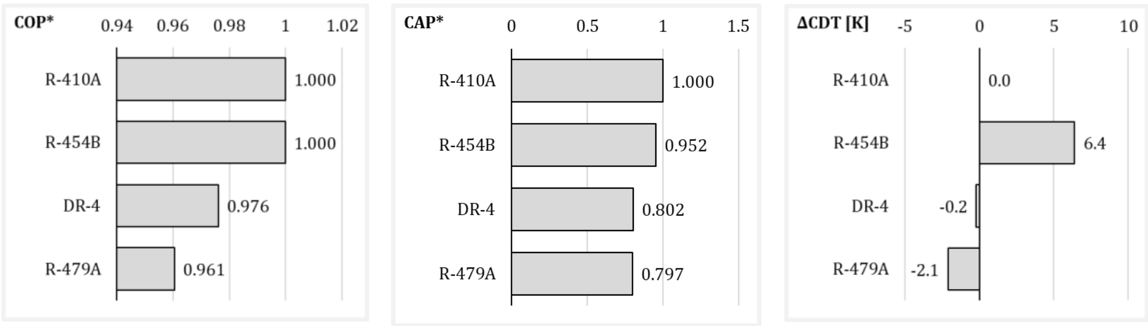


Figure 2. Relative COP (COP*), capacity (CAP*) and compressor discharge temperature difference (ΔCDT)

The relative COP of the alternative candidates are all within 5% of R-410A making them viable options, whereas the only R-454B provides this margin for relative capacity. The lower GWP alternatives DR-4 and R-479A both have a roughly 20% lower capacity compared to R-410A as well as similar to lower compressor discharge temperatures. Both lower GWP options provide similar performance characteristics whereas R-479A has a GWP below 150 or half of DR-4 with a GWP of less than 300. To better understand the relative performance and operating characteristics of the refrigerants exhibiting pressure drop and utilize their transport properties in the heat exchanger a system model was developed and investigated.

2. System and model description

A unitary packaged rooftop heat pump unit was chosen for the refrigerant system modeling. The unit is rated with a cooling capacity of 3 RT or 10.6kW while operating at 60 Hz. The nameplate R-410A refrigerant charge is 7.7 lbm or 3.5 kg. The unit is driven by a scroll compressor and uses indoor and outdoor heat exchangers with aluminum-fin/copper-tube construction with fixed speed fans. The Modelica platform with TiL suite library [13] has been used to create the heat pump unit system model. The system comprises of a physics based refrigerant independent compressor model which is developed using the R-410A test data. The compressor model parameters can then be used to predict the performance with other refrigerants over the entire operating map. Both the indoor and outdoor coils used have fin and tube heat exchanger configurations. The heat transfer (Shah [14],[15], [16] for two-phase and Dittus-Boelter [17] for Single-phase) and pressure drop (Konakov [18]) correlations from the literature are used both on the refrigerant side and air side (Haaf, [19]), while a discretized calculation method is applied for the heat exchangers. Correction factors are then applied to these correlations to accurately represent the test data in both cooling and heating modes for the baseline R-410A resulting in a match of the experimental data within 3%. Pressure-drop and heat transfer is also calculated for the refrigerant lines which are used to connect the above components and a 4-way reversing valve which enables switching between cooling and heating modes. NIST REFPROP 10.0 [10] has been used to generate the refrigerant properties lookup table for each of the refrigerant mixtures simulated here. Moist air properties are sourced from TiL Media [13]. The refrigerant R-410A is used as a baseline for relative performance as well as R-454B as a baseline for matching capacity in AHRI 210/240 [12] A condition for adjusting the compressor speed for the low GWP alternative refrigerant options DR-4 and R-479A. The baseline compressor speed hereby set at 50Hz with higher adjusted speed for DR-4 and R-479A to accommodate the lower relative capacity of around 20% as determined in the thermodynamic model in the previous paragraph. The system model design in Dymola/ Modelica is shown in Figure 3.

The investigated conditions for cooling and heating operations include both standard test conditions as defined in AHRI 210/240 for cooling (A, B) and heating (H1, H3) as well as ambient temperature sweeps in cooling operation to investigate the performance at varying ambient temperatures. The investigated conditions are summarized in Table 2.

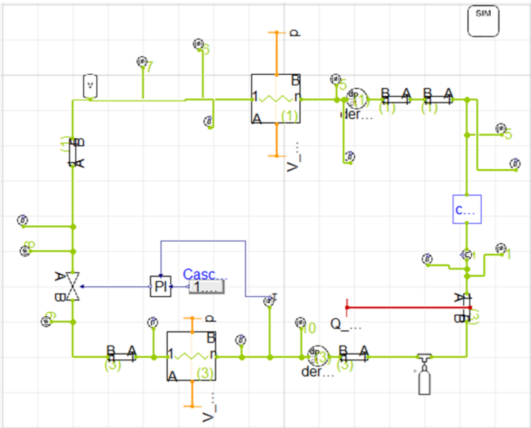


Figure 3. Schematic diagram of the system model developed

Table 2. Cooling and heating modeling conditions

Mode	**Description**	**Indoor**		**Outdoor**	
		Dry bulb temperature [˚C]	Wet bulb temperature [˚C]	Dry bulb temperature [˚C]	Wet bulb temperature [˚C]
Cooling	A	26.7	19.4	35.0	n/a
	B			26.7	
	Sweep			18.3	
				23.9	
				27.8	
				29.4	
				35.0	
				40.6	
				46.1	
				51.7	
Heating	H1	21.1	<15.6	8.3	6.1
	H3			-8.3	-9.4

3. Modeling results

In cooling condition “A” the baseline capacity was established with R-454B at a compressor frequency of 50Hz. The determined cooling capacity was then matched with the low GWP alternatives DR-4 and R-479A and the compressor speed at this adjusted condition was maintained for the temperature sweep and heating conditions to obtain both performance results at drop in compressor speeds of 50Hz and adjusted compressor speeds. The results for relative COP compared to R-410A are shown in Figure 4.

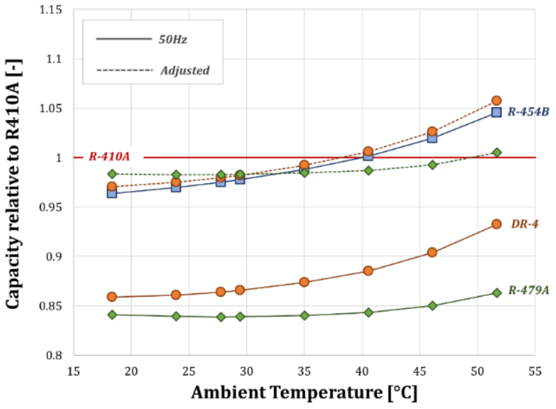


Figure 4. Capacity relative to R-410A for baseline and adjusted compressor speed

R-454B has similar capacity compared to R-410A at a rating ambient temperature of 29.4˚C. The low GWP alternative refrigerants DR-4 and R-479A have approximately 15% lower capacity compared to R-410A and have therefore been investigated at adjusted compressor speeds to match the higher capacity of R-454B. These adjusted compressor speeds were then used in the following conditions. DR-4 at baseline compressor speed of 50Hz provides a relative capacity of roughly 0.86 to 0.94 compared to R-410A with R-479A achieving 0.84 to 0.86. With adjusted compressor speeds both low GWP alternatives remain within ±5% of relative capacity compared to R-410A with slightly more improvement for DR-4 at elevated temperatures of 51.7˚C exceeding 5% relative capacity. The adjustment of compressor speed therefore confirms a viable option to match relative capacity requirements. However, the increase in refrigerant flow rate while maintaining the rest of the system design unchanged has an impact on the system COP as shown in Figure 5.

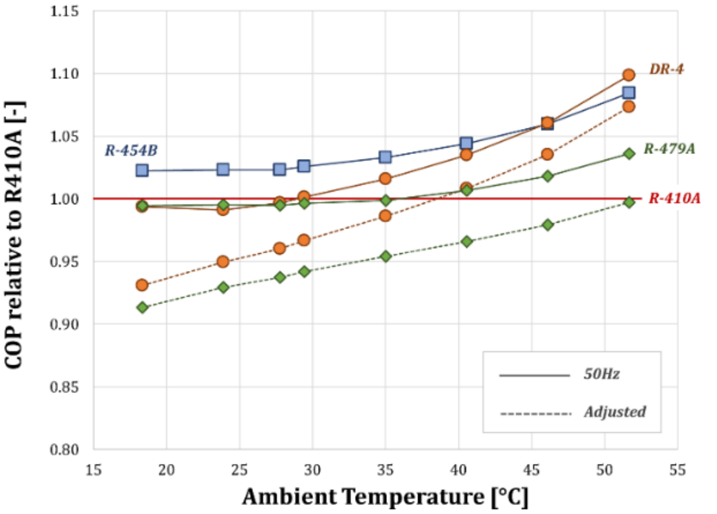


Figure 5. COP relative to R-410A for baseline and adjusted compressor speed

The baseline system efficiency for R-454B shows improvement over R-410A throughout the investigated ambient temperature range within 2% to 8%. DR-4 has similar COP at lower ambient temperatures up to 30˚C with benefits at higher ambient temperatures up to 10% at 51.7˚C. R-479A has a similar response with comparable COP up to 40˚C and improved values up to 4% at high ambient temperatures for the drop-in compressor speed of 50Hz. Adjusting the compressor speed to match relative capacity penalizes the achievable COP leading to a maximum penalty of approximately 8% at low ambient temperatures which decreases with increasing ambient temperatures up to parity with R-410A at 51.7˚C. Another important system operating parameter is the compressor discharge temperature which needs to be evaluated closely to ensure compressor operation throughout the operating map is not affected. The compressor discharge temperature difference compared to R-410A is shown in Figure 6.

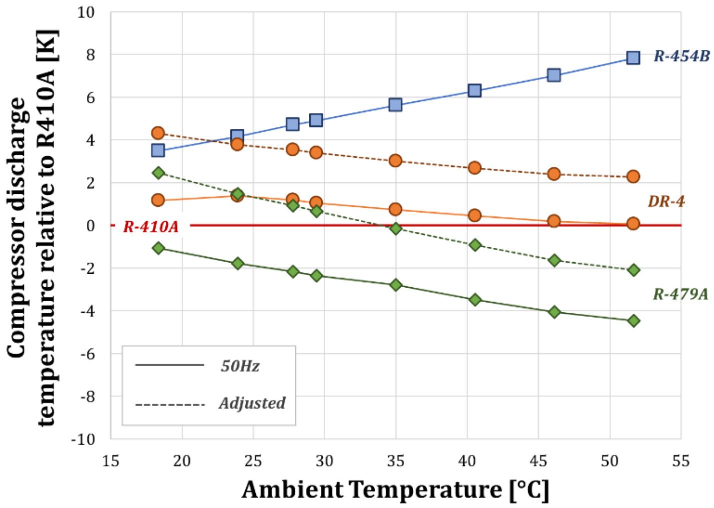


Figure 6. Relative compressor discharge temperature for baseline and adjusted compressor speed

R-454B shows higher compressor discharge temperatures compared to R-410A between roughly 4K at low ambient temperatures increasing to around 8K for high ambient temperatures. For drop in compressor speeds of 50Hz DR-4 shows similar CDT with slightly elevated values within 2K. R-479A provides lower compressor discharge temperatures ranging from 1K at low ambient temperatures to 4.5K at high ambient temperatures. With adjusted compressor speeds to match R-454B capacities at "A" condition the relative compressor discharge temperature difference increases for both low GWP options by approximately 2K to 3K. R-479A still provides lower relative temperatures compared to DR-4 and maintains lower temperatures compared to R-410A at ambient temperatures above 35˚C.

In heating operation, the investigation was done in a similar way with a drop-in situation using a compressor speed of 50Hz as well as the adjusted speed as determined in cooling "A" condition. The results for relative COP at condition H1 are summarized in Figure 7.

Both low GWP refrigerant blend options show relative COP compared to R-410A within 5% with similar results for both 50Hz and adjusted compressor speeds. R-454B due to its larger R-32 blend fraction has a match in heating efficiency compared to R-410A. The relative capacity results in Figure 8 show the impact of increased compressor speed to make up the inherent lower capacity of the low GWP blends due to their properties.

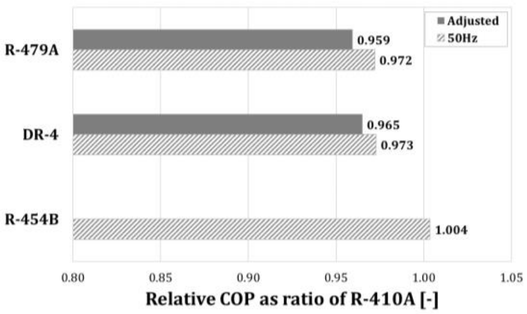


Figure 7. Relative heating COP of R454B and low GWP options compared to R-410A at H1 condition

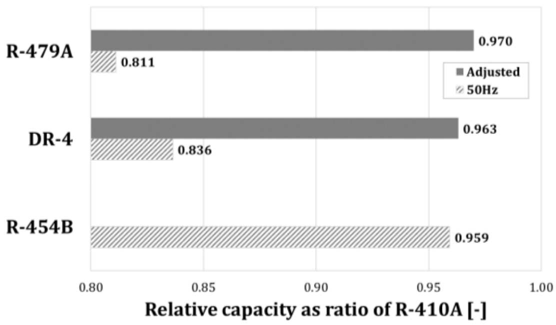


Figure 8. Relative heating capacity of R454B and low GWP options compared to R-410A at H1 condition

R-454B shows slightly lower capacity compared to R-410A at H1 condition with an ambient temperature of 8.3˚C. DR-4 and R-479A have about 18% lower heating capacity at drop in compressor speed of 50Hz. This can be recovered with the adjusted compressor speed and brings it within 5% of R-410A and slightly above R-454B. The effect on compressor discharge temperature can be seen in Figure 9. Similar to cooling operation R-454B shows higher compressor discharge temperature with 4.5K over R-410A. Both DR-4 and R-479A provide lower CDT with 2K and 6.7K respectively. Adjusting the compressor speed reduces this benefit of lower compressor discharge temperature by about 4K for both candidates which results in about 2K lower CDT for R-479A and 2.2K higher CDT compared to R-410A for DR-4.

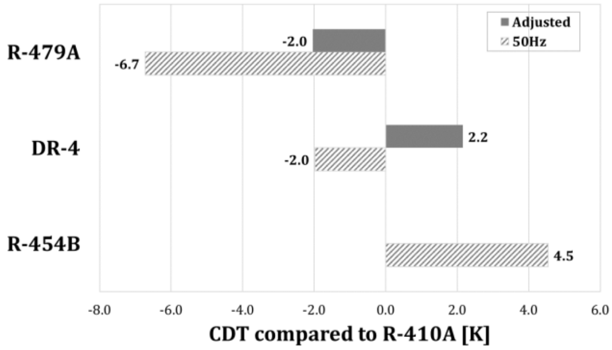
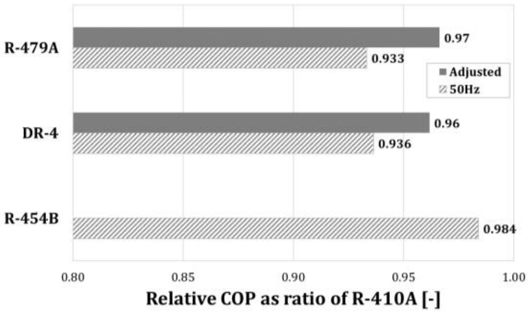


Figure 9. Compressor discharge temperature of R454B and low GWP options compared to R-410A at H1 condition

At even lower ambient temperatures of -8.3˚C at H3 condition the relative performance of all investigated refrigerants decreases compared to R-410A as shown in Figure 10.



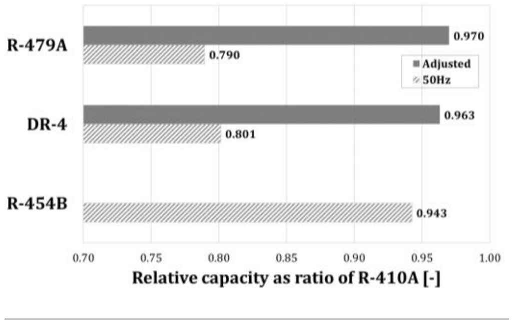


Figure 10. Relative heating COP of R454B and low GWP options compared to R-410A at H3 condition

Figure 11. Relative heating capacity of R454B and low GWP options compared to R-410A at H3 condition

For adjusted compressor speeds DR-4 and R-479A achieve similar capacity to R-454B within 5% of R-410A. The relative capacity as shown in Figure 11 confirms the trends seen for cooling operation with drop-in capacity of about 80% compared to R-410A. By adjusting the compressor speed the relative capacity is recovered to within 5% with slight improvement for R-479A over DR-4. R-454B shows slightly lower relative capacity compared to R-410A while operated at the same compressor speed of 50Hz. The impact of compressor discharge temperature is shown in Figure 12 confirming the offsetting impact of necessary compressor speed increase to accommodate for the lower capacity of low GWP blends DR-4 and R-479A.

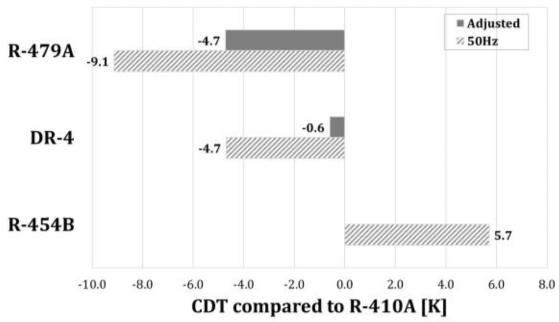


Figure 12. Compressor discharge temperature of R454B and low GWP options compared to R-410A at H3 condition

For the drop-in compressor speed lower compressor discharge temperatures of 9.1K to 4.7K are achieved for R-479A and DR-4 respectively compared to R-410A. When adjusting the compressor speed to make up the lower capacity of the blends the CDT increases to 4.7K and 0.6K lower values compared to R-410A.

4. Conclusions

This paper described the investigation of low GWP alternatives to R-410A for new system designs due to their flammable characteristics. The three investigated alternatives represent different GWP levels ranging from around 450 with R-454B as well as 300 (DR-4) and 150 for R-479A. R-479A is hereby utilizing the recently classified molecule R-1132(E) that provides a GWP<1. The thermodynamic model showed good agreement with the modeling results of a detailed system model of a unitary heat pump under standard rating conditions. The drop in case with same compressor speed confirmed the lower relative capacity for the low GWP options DR-4 and R-479A with approximately 17% lower capacity as seen in the initial thermodynamic model. Increasing the compressor speed allowed for recovery of relative capacity within 5% for all investigated conditions for both heating and cooling. The lower compressor discharge temperature that can be achieved with DR-4 and R-479A is offset when increasing the compressor speed but remains lower compared to R-410A and R-454B which can be beneficial to avoid limitations of the compressor operating map due to compressor discharge temperature limitations. The evaluation of a detailed system model that considers a physical compressor model as well as heat transfer and pressure drop provides good insight and indication of expectable performance. However, experimental evaluations are needed to validate these findings. In conclusion R-479A has been found to provide comparable to superior performance and operating characteristics to DR-4 while having approximately half the GWP. Further improvement of the system design is expected to improve the overall efficiency from the drop-in situation that was evaluated in this study.

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