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Low GWP Refrigerants for Air-conditioning and Chiller Applications

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ABSTRACT

Because of increasing concerns about climate change, various environmental regulations are being proposed to phase out high GWP refrigerants such as R410A and R134a. R410A refrigerant is used widely for residential and commercial air-conditioning, heat pump applications and air-cooled direct expansion chillers. This paper presents an evaluation of two low GWP refrigerants R447B (GWP=714) and R452B (GWP=675) as replacements for R410A. System simulations were carried out for a three Ton residential reversible heat pump at outdoor temperatures varying from 27.7°C to 46.1°C in cooling mode and 8.3°C in heating mode. R447B shows capacity within 5% of R410A and R452B shows a close match in capacity with R410A. For these simulations, both R447B and R452B show efficiency similar to R410A at ambient conditions below 35°C and show 3% to 4% higher efficiency at elevated temperatures. System simulations were also performed for a direct expansion R410A chiller at ambient temperature of 35°C. The simulations suggest that both R447B and R452B can show performance similar to R410A under the conditions and equipment simulated. This article also reports theoretical evaluations of replacements for R134a for medium pressure centrifugal chiller application. These evaluations suggest there may be low GWP refrigerant replacements available for chillers which can reduce the overall environmental emissions.

Keywords: Refrigerant, Air-Conditioning, Global Warming, Chillers

1. INTRODUCTION

Among high pressure blends, R410A is widely used in air-conditioning applications ranging from residential unitary air-conditioning, heat pump systems to large commercial chillers. R410A, however, is increasingly becoming a target of many environmental regulations due to its high GWP of 1924 (IPCC, 2013). In Europe, the new F-Gas regulations (European Union, 2014) limit the GWP to 750 in single split unitary air conditioning systems with refrigerant charge less than 3 kg. In all these applications, R410A will be banned in new systems. In the United States, the Environmental Protection Agency (EPA) has recently proposed a ruling to remove several high GWP refrigerants, such as R410A and R134a, from the list of acceptable refrigerant alternatives in various applications including chillers (U.S. EPA, 2016).

In this context, several low-GWP R410A replacements are under evaluation by the industry. This article focuses particularly on two of those alternatives, R447B (R32/R125/R1234ze 68%/8%/24%) and R452B (R32/R125/R1234yf 67%/7%/26%). Both these refrigerants have 2L flammability classification and have GWP less than 750 complying with the F-Gas regulation. Various performance evaluations have been carried out with these refrigerants. Abdelaziz and Shrestha (2016) conducted extensive experimental tests to assess low GWP R410A alternative refrigerants in 5.27 kW mini-split air conditioning unit designed for high-ambient conditions. They reported that R452B shows cooling capacity within 4% and Coefficient of Performance (COP) 2% to 3% higher than R410A over ambient temperatures ranging from 27.8°C to 55°C. Schultz et al. (2015) experimentally evaluated a 4 Ton R410A Rooftop Heat Pump under drop-in with R452B. The expansion device was replaced by adjustable thermostatic expansion valve (TXV) and variable speed compressor was used to evaluate refrigerants by matching cooling capacity. They reported that R452B 3% to 5% better COP than R410A for ambient temperatures ranging from 27.8°C to 35°C .
R1234ze is a very low GWP (<1) refrigerant that has been evaluated by industry to replace R134a in medium pressure screw and centrifugal chillers. Johnson and Kasai (2013) experimentally tested a 200 Ton R134a air-cooled

screw chiller with R1234ze under drop-in conditions. They reported that R1234ze shows 6% higher COP than R134a at 35°C ambient conditions. They observed 23% lower cooling capacity and suggested that a larger displacement compressor will be needed for R1234ze to match the capacity of R134a.

A reversible heat pump is a special vapor compression system which can work in both cooling and heating modes of operation. The refrigerant for this type of system has to be carefully selected since the system has dual modes of operation. Starting from this background, this paper aims to present performance of two low GWP R410A replacements, R447B and R452B, in a residential reversible heat pump and a direct expansion (DX) air cooled chiller. Further, centrifugal chillers are typically used for air conditioning applications for larger capacities (>150 Tons). This study will also discuss the performance of low GWP R134a replacements for centrifugal chiller applications.

2. REVERSIBLE HEAT PUMP APPLICATIONS

2.1 Thermodynamic Analysis

A thermodynamic analysis was performed to understand the impact of using a given refrigerant on the operating pressures, flow rate of refrigerant, cooling capacity, and efficiency in specific reversible heat pump. This type of analysis was performed at typical air conditioning conditions using thermodynamic data from the NIST database REFPROP 9.1 (Lemmon et al., 2013).

Table 1 shows the results of this analysis at an ambient temperature of 35°C. The performance of refrigerants R447B and R452B is compared to R410A. R447B shows capacity within 8% and 3% higher efficiency than R410A. R452B offers a closer match in performance to R410A with capacity within 3% and 2% higher efficiency than R410A. In this analysis, both these refrigerants have lower suction and discharge pressures than R410A while the compression ratios are very similar to R410A. The compressor discharge temperature for R447B is within 10°C and for R452B is within 5°C of R410A indicating that no discharge temperature mitigation may be required. In this study, both the refrigerants have about 18% to 20% lower mass flow rate than R410A which may lead to a lower pressure drop in the system. The GWP of these refrigerants is less than 750. The GWP was calculated based on the latest AR5 numbers as reported in (IPCC, 2013). Both the low GWP refrigerants are mildly flammable with ASHRAE flammability classification of "2L". Hence, further work on flammability risk assessments should be carried out in order to use these refrigerants commercially.

Table 1: Thermodynamic Analysis

Fluid Properties		Ambient Temperature 35°C						
Name	**GWP**	**Capacity**	**Efficiency**	**Flow Rate**	T_{disch} (°C)	$P_{suction}$	$P_{discharge}$	R_{comp}
R410A	1924	100%	100%	100%	76	100%	100%	100%
R447B	714	92%	103%	72%	85	86%	88%	103%
R452B	675	97%	102%	80%	81	93%	93%	100%

Condenser subcooling = 5.5°C; Condenser TD = 10°C; Evaporating temperature = +7°C; Evaporator exit superheat = 5.5°C; Suction line superheat = 0°C; η_{vol} = 100%; η_{isen} = 70%

2.2 SYSTEM SIMULATION

Another way to look at the performance of a given system with several different refrigerants is to use a detailed system model. The model employed for the simulations (Genesym™) represents a certain vapor compression cycle operating at steady-state conditions. The details of the simulation model, and its validation is described in Spatz and Yana Motta (2004).

System Description

Simulations were performed for a R410A reversible heat pump system. The system has a capacity of 9.6 kW at rating conditions, Seasonal Energy Efficiency Ratio (SEER) rating of 13 and Heating Seasonal Performance Factor (HSPF) of 8. Details of the unit are shown in Table 2.

Table 2: System Specifications

R410A Reversible Heat Pump	
Compressor	Scroll Compressor
Condenser	
Rows	1
Tubes per row	24
Tube Diameter (microfin)	0.375" (9.5 mm)
Fin Type	Louver
Fin Pitch	866 fins per meter
Air Flow	2000 cfm
Fan Power	265 W
Evaporator	
Rows	2
Tubes per row	20
Tube Diameter (microfin)	0.3125" (7.9 mm)
Fin Type	Louver
Fin Pitch	630 fins per meter
Air Flow	1200 cfm
Fan Power	422 W

A system with thermostatic expansion valve was simulated. Table 3 shows the AHRI conditions (AHRI, 2008) at which the simulations were performed. The system charge was optimized at AHRI B condition and was kept fixed at other simulation conditions. The evaporator superheat of 4.1°C at AHRI B condition for R410A. The superheat was taken from the mid-point temperature of evaporator for simulations with refrigerants that have an evaporator temperature glide.

Table 3: AHRI Conditions for simulation

Test Conditions	Indoor Ambient		Outdoor Ambient	
	DB	WB	DB	WB
	°C	°C	°C	°C
AHRI B	26.7	19.4	27.8	18.3
AHRI A	26.7	19.4	35.0	23.9
AHRI MOC	26.7	19.4	46.1	23.9
AHRI H1	21.1	15.6	8.3	6.1

Overall System Performance

Figure 1 shows the results of the simulation performed under drop-in conditions. The condition AHRI A is the rating condition for capacity and AHRI B is the rating condition for efficiency. The results for capacity and efficiency for the equipment and conditions simulated are presented relative to the performance R410A. The theroretical results indicate that R447B may show a capacity of 95% at condition A and efficiency of 104% at condition B. For this simulation R447B may show an improvement in performance compared to R410A at MOC condition with capacity of 97% and efficiency of 106%. At the heating rating condition simulated, R447B may show a capacity of 95% and efficiency of 102%. The theroretical results indicate that for the equipment and conditions simulated, R452B may show a closer match in capacity of 98% at condition A and efficiency of 103% at condition B. R452B may also show an improvement in performance compared to R410A at MOC condition with a capacity of 100% and efficiency of 104%. At the heating rating condition, R452B may show a capacity of 97% and efficiency of 102%.

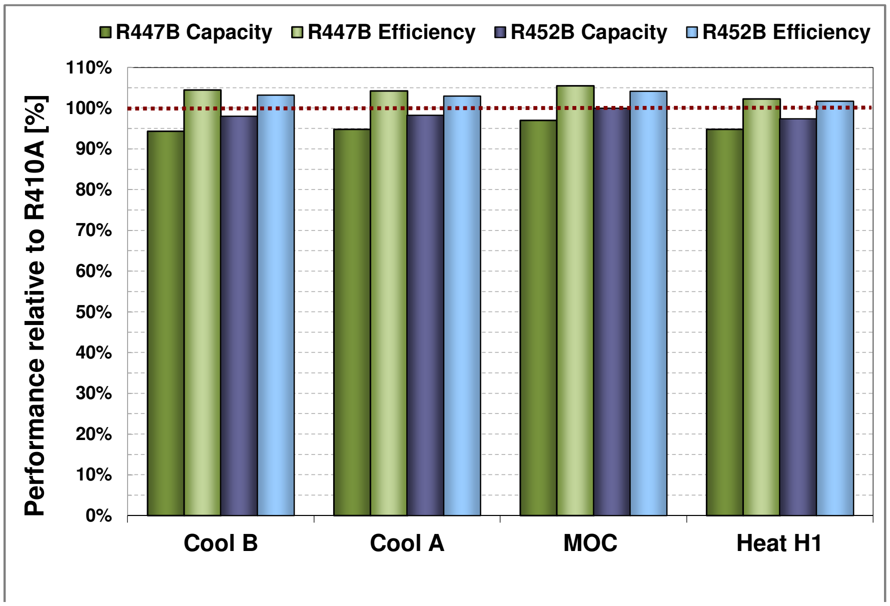

Figure 1: Simulation of R410A heat pump

System Parameters

Table 4 shows some key parameters of the system for ambient temperatures of 35°C and 46°C. It can be observed from the table that the theoretical results indicate that for the equipment and conditions simulated R447B may have slightly higher evaporating temperatures and lower condensing temperatures compared to R410A under drop-in conditions. For this study, the evaporating and condensing temperatures for R452B may be very similar to R410A. The discharge temperature for R447B may be 7°C higher and R452B may be 4°C higher than R410A at ambient temperature of 46°C. The drop of saturation temperature in the condenser is about 30% lower and in the suction line is about 12% lower than R410A for both the refrigerants. The drop of saturation temperature in the evaporator in this study is similar for all the refrigerants. This could be due to 15% to 25% lower mass flow rates of the alternative refrigerants.

Table 4: System parameters in the original system at 35°C ambient

Ambient Temperature	35.0°C						46.1°C
Refrigerant	T_{evap} (°C)	T_{cond} (°C)	$\Delta T_{sat,cond}$ (°C)	$\Delta T_{sat,evap}$ (°C)	$\Delta T_{sat,sl}$ (°C)	Mass Flow (%)	T_{disch} (°C)
R410A	10.6	47.7	0.46 (100%)	0.72 (100%)	0.17 (100%)	100%	92
R447B	11.5	47.0	0.31 (67%)	0.69 (96%)	0.15 (88%)	75%	99
R452B	11.0	47.2	0.33 (72%)	0.72 (100%)	0.15 (88%)	84%	96

3 POSITIVE DISPLACEMENT CHILLER APPLICATIONS

A theoretical performance analysis of certain equipment and conditions was carried out for an air cooled 20 tons (70 kW) chiller using a lumped parameter modeling approach for the heat exchangers. The water inlet and outlet temperatures were assumed to be 12°C and 7°C respectively. The analysis was performed at an ambient air temperature of 35°C. The evaporator mid-point superheat and condenser subcooling were set at 5.5°C. An assumption was made that the volumetric and isentropic efficiencies were the same for all refrigerants. Performance of refrigerants R447B and R452B was compared with R410A. Performance results obtained for R447B are shown in Table 5 and for R452B are shown in Table 6.

Table 5: Performance of R447B

	T_{evap} (°C)	T_{cond} (°C)	$P_{suction}$ (kPa)	P_{disch} (kPa)	T_{disch} (°C)	dP_{cond} (kPa)	dP_{evap} (kPa)	Mass Flow (kg/h)	Q (kW)	COP
R410A	4.4	46.4	880.0	2846.4	79.9	50.0	70.0	1554	69.8	3.60
R447B (Drop In)	4.5	47.2	759.7	2564.3	89.3	40.2	54.8	1143	64.8	3.62
Comparison	**0.1**	**0.8**	**86.3%**	**90.1%**	**9.4**	**80.4%**	**78.3%**	**73.5%**	**93.0%**	**100.7%**
R447B (Circuits mod.)	4.7	46.6	756.1	2538.3	88.8	51.2	72.1	1138.0	64.9	3.7
Comparison	**0.3**	**0.3**	**85.9%**	**89.2%**	**8.9**	**102.4%**	**103.0%**	**73.2%**	**93.0%**	**101.7%**
R447B (Comp. mod.)	4.4	46.9	753	2557.6	89.4	51.6	64.8	1245.24	70.8	3.607
Comparison	**0.1**	**0.5**	**85.6%**	**89.9%**	**9.5**	**103.2%**	**92.6%**	**80.1%**	**101.4%**	**100.3%**

The theoretical results indicate that for the equipment and conditions studied, R447B may show 7% lower capacity with matching efficiency under drop-in conditions. Since, R447B could show a significantly lower mass flow rate and pressure drop under drop-in conditions, the number of circuits in the evaporator was decreased by 10% and in the condenser by 8% to increase the mass velocity for R447B. Based on the theroretical results, the capacity was fully recovered when the compressor displacement was increased by 10% and the number of circuits in evaporator was kept the same as R410A and reduced by 3% in the condenser. Also, the theoretical results indicate that for the equipment and conditions studied, the COP of R447B may be similar to R410A when the capacity is fully recovered and the discharge temperature of R447B may be within 10°C of R410A.

Table 6: Performance of R452B

	T_{evap} (°C)	T_{cond} (°C)	$P_{suction}$ (kPa)	P_{disch} (kPa)	T_{disch} (°C)	dP_{cond} (kPa)	dP_{evap} (kPa)	Mass Flow (kg/h)	Q (kW)	COP
R410A	4.4	46.4	880.0	2846.4	79.9	50.0	70.0	1554	69.8	3.60
R452B (Drop In)	4.4	46.5	823.6	2664.6	85.6	44.1	59.1	1267.6	68.4	3.7
Comparison	**0.1**	**0.1**	**93.6%**	**93.6%**	**5.7**	**88.2%**	**84.4%**	**81.6%**	**97.9%**	**102.0%**
R452B (Comp. mod.)	4.4	46.5	818.6	2667.7	85.8	47.7	64.3	1324.4	71.4	3.6
Comparison	**0.0**	**0.1**	**93.0%**	**93.7%**	**5.9**	**95.4%**	**91.9%**	**85.2%**	**102.3%**	**101.3%**

The theoretical results indicate that for the equipment and conditions studied, R452B may show 2% lower capacity with 2% higher efficiency under drop-in conditions. The capacity was fully recovered when the compressor displacement was increased by 5%. The COP of R452B is similar to R410A when the capacity is fully recovered. Additionally, for the equipment and conditions studied, the discharge temperature of R452B may be within 6°C of R410A.

4 CENTRIFUGAL CHILLER APPLICATIONS

A compressor design analysis was conducted for both medium-pressure and low-pressure refrigerants using specific speed and diameter approach as discussed in Biederman et al. (2004), in order to size single-stage compressors for alternative low global warming refrigerants. Using the same specific speed (0.76) and specific diameter (3.4), the resulting compressor speed N and diameter D is given by equation (1) and equation (2):

$$N = 0.76\frac{H^{0.75}}{\sqrt{Q}} \tag{1}$$

$$D = 3.4\frac{\sqrt{Q}}{H^{0.25}} \tag{2}$$

Where H = Isentropic enthalpy rise or "Head" in J/kg and
Q = Volumetric flow rate in m^3/s.

Cycle analyses and compressor sizing were conducted for medium-pressure refrigerants that are potential replacements for R134a. For both applications, a refrigerant capacity of 500 tons (1760 kW) was selected assuming evaporation and condensation temperatures of 5°C and 35°C, respectively. An evaporator superheat of 0°C was selected since most of the centrifugal chillers have flooded evaporators. The cycle analyses yielded the values for isentropic enthalpy rise and volumetric flow rate needed to determine the speed and compressor impeller diameters using equation (1) and equation (2). Further two-stage and three-stage cycle analyses were carried out to compare the performance of various fluids. The thermodynamic cycle conditions were same as those chosen for single stage analysis. The intermediate pressure was chosen to be the optimum pressure.

4.1 Medium Pressure Chiller Applications

This theoretical analysis was performed for fixed capacity. Refrigerants R1234ze, R1234yf and R515A (R1234ze/227ea 88%/12%) were chosen for this analysis. The GWP values reported here are based on the latest AR5 numbers. Table 7 shows the results for medium-pressure refrigerants.

Table 7: Compressor Sizing for Medium Pressure Refrigerants

		Refrigerant				
Parameter	Units	R12	R134a	R515A	R1234ze	R1234yf
ASHRAE Claasification	-	A1	A1	A1	A2L	A2L
GWP*	-	10,200	1300	387	1	1
Delta hevap	kJ/kg	120.92	152.49	133.15	139.75	118.88
Delta hs,comp	kJ/kg	15.10	19.31	16.99	17.76	15.65
Head	m	1539	1969	1732	1810	1595
mdot	kg/s	14.54	11.53	13.21	12.58	14.79
density	kg/m^3	20.84	17.13	14.46	13.92	20.74
Vdot	m^3/s	0.70	0.673	0.913	0.904	0.713
N	rpm	11836	14492	11305	11745	12023
D	m	0.256	0.237	0.285	0.280	0.257
u2 (tip speed)	m/s	159	180	168	172	162
Pr (Pressure Ratio)	-	2.34	2.54	2.57	2.57	2.40
COP	-	8.01	7.90	7.84	7.87	7.60
COP Rel to R134a		**101.4%**	**100.0%**	**99.2%**	**99.7%**	**96.2%**

The theoretical results indicate that for the equipment and conditions studied R1234yf may show the closest match in capacity while showing efficiency within 5% of R134a. This theoretcial analysis suggests that the non-flammable azeotropic refrigerant, R515A, may have about 25% to 30% loss of capacity while showing efficiency similar to R134a along with close to 70% reduction of GWP from that of R134a. This capacity loss may be recovered by using a compressor with larger displacement. Likewise, R1234ze may possibly be used in R134a adapted machines with some loss in capacity but at or above efficiency level of R134a. Kenji et al. (2012) reported that R1234ze can show performance similar to R134a by redesigning the impeller diameter and blade shape. They also estimated a 30% reduction in overall CO_2 emissions with R1234ze compared to R134a. Due to these benefits, centrifugal chillers for R1234ze are already comercially available from some manufacturers. The table shows the design of centrifugal chiller may be very similar for R515A and R1234ze. Therefore, R515A may be used as an interim non-flammable replacement for R134a in medium-pressure chillers, while the safety standards and building codes are being modified to make it easier to use mildly flammable (A2L) refrigerants like R1234ze. Based on this theoretical analysis for the equipment and conditions studied, all three alternative refrigerants may possibly be used with a centrifugal compressor designed for R134a with some small design changes. For example, if the same speed and diameter were used, the specific speed and diameter may most likely, for the most part, stay in the optimum range for these parameters, but the operating envelop would have to be further evaluated to ensure reliable operation over the expected conditions under which a particular chiller would operate.

5. CONCLUSIONS

Recently developed low global warming molecules may have potential applications in systems that currently employ high to medium-pressure refrigerants, such as stationary air-conditioning systems and chillers. The present analysis indicates that for the equipment and conditions studied comparable performance to existing refrigerants can be achieved in applications investigated in this paper.

- Theoretical system simulations in a R410A reversible heat pump indicate that both R447B and R452B can match the performance of R410A without significant system modifications for ambient temperature below 35^{o}C and can show 3% to 4% higher efficiency at elevated ambient temperatures. Therefore, both these refrigerants are promising low global warming replacements for R410A for residential reversible heat pump applications.
- Theoretical results indicate that, in positive displacement chillers and the conditions studied, R447B and R452B may match the performance of R410A by making minor system modification like larger displacement compressor.
- Evaluations of low GWP refrigerants R1234yf, R1234ze and R515A in medium pressure centrifugal chiller applications indicate that that for the equiment and conditions studied, they may match the efficiency of R134a while providing siginficant reduction in direct emissions . R515A offers a non-flammable, low GWP solution to replace R134a and can be used an interim option while the safety standards and building codes are being modified to make it easier to use mildly flammable (A2L) ultra-low GWP refrigerants like R1234ze. R1234ze has been accepted by the industry as a long term solution and chillers designed for R1234ze are already commercially available from some manufacturers.

The low GWP replacements discussed in this paper may be useful in reducing the environmental emissions in heat pump systems and chillers. Further, existing and upcoming standards should be considered to address the mild flammability of these refrigerants.

Nomenclature			
COP	Coefficient of Performance	$P_{suction}$	Compressor suction pressure
D	Impeller Diameter (m)	Q	Cooling Capacity
DB	Air Dry Bulb Temperature	R_{comp}	Compression Ratio
dP_{cond}	Pressure drop in condenser	T_{cond}	Condensing temperature
dP_{evap}	Pressure drop in evaporator	T_{disch}	Compressor discharge temperature
MOC	Maximum operating condition	T_{evap}	Evaporating temperature
N	Impeller Speed	WB	Air Wet Bulb Temperature
$P_{discharge}$	Compressor discharge pressure		
Greek Symbols			
$\Delta T_{sat,cond}$	Drop of Saturation Temperature Condenser	$\Delta T_{sat,evap}$	Drop of Saturation Temperature Evaporator
$\Delta T_{sat,sl}$	Drop of Saturation Temperature Suction Line		

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