Latest Developments of Low Global Warming Refrigerants for Chillers

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ABSTRACT

This paper will focus on the developments of new molecules that have low global warming potential, high thermal performance, and favorable safety characteristics, to name only a few required characteristics. Several new molecules that have very short atmospheric lifetimes, as well as refrigerant blends utilizing these molecules, have been developed and will be evaluated for use in various types of water chillers ranging from smaller capacity systems that currently use R-410A or R-407C refrigerants to larger centrifugal compressor chillers that have currently used R-134a or R-123. Thermodynamic and system simulations were carried out using low GWP refrigerant properties and compared against the baseline refrigerants. These new LGWP refrigerants show promise in these applications and warrants further development.
Keywords: Refrigerants, Global Warming, Hydro-fluoro-olefins

1. INTRODUCTION

Refrigerants that are in common use today, HFCs, have the benefits of high energy efficiency, safety in use, properties that enable the design of cost effective systems, and from an environmental perspective they have no impact on stratospheric ozone. Despite these attributes, the air conditioning and refrigeration industry is now looking for replacements due to the growing global concerns around climate change since many of these refrigerants have relatively high global warming potential. New molecules with the positive attributes of both high thermal performance and low environmental impact, not name a few necessary characteristics, are currently in development. These materials maintain the high level of system efficiency we are accustomed to with fluorocarbon refrigerants but with significantly lower global warming impact than current refrigerants. They also exhibit significantly lower flammability characteristics than the much more flammable hydrocarbons. Replacements for refrigerants used in chiller systems that employ DX heat exchangers as well as flooded ones will be discussed. Chemical and physical properties as well as experimental results in representative equipment will be presented. Two new low GWP refrigerant molecules (HFO-1234yf, HFO-1234ze) have been identified. These molecules are Hydro-Fluoro-Olefins (HFO) that due to their very short atmospheric life times of 11 and 18 days have an extremely low global warming potential (GWP) of only 4 to 6 (as compared to 1430 for R-134a). Also under development is another low global warming molecule (GWP < 10) that has properties that potentially enable its use in low pressure chillers. In addition, we are in the process of developing and evaluating refrigerant blends that balance the attributes of higher capacity and low global warming potential while maintaining the efficiency of present systems without significant increases in system cost. This study will discuss properties and performance of potential refrigerant options in positive displacement and centrifugal chiller systems often used in air conditioning applications.

2. WORKING FLUIDS

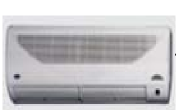
Depicted in Table 1 are potential low global warming molecules as well as a reference higher global warming molecule, R-134a. Also shown in Table 1 are Permissible Exposure Limits (PEL) and flammability limits (LFL and UFL). It should be noted that refrigerants that do perform well in certain applications where R-134a is used will not perform well in all applications, such as smaller capacity chillers where refrigerants with higher volumetric capacity, higher pressure, and other distinct properties are used. It is for this reason that refrigerant blends that are better suited for applications that use higher capacity/higher pressure refrigerants are currently in development.

Table 1: Certain Refrigerant Properties

Refrigerant	GWP	PEL (ppm)	LFL / UFL (Vol%, 23°C)
R-134a	1430	1000	-
HFO-1234ze	6	800	-
HFO-1234yf	4	400	6.2-12.3
R-32	675	1000	14.4-29.3
R-600a	~5	800	1.8-8.5
R-290	~5	1000	2.1-10.0

In addition to the refrigerant molecules listed above, another single component refrigerant, named **N-12**, is also under development for low pressure chillers and other applications. This molecule has a very low GWP of less than 10 and is non-flammable. Blends with significantly lower GWP than current refrigerants are currently in development and have been discovered to have performance characteristics close to R-404A, R-22, and R-410A and offer a GWP reduction of 75% to 95% relative to the refrigerant it replaces.

Table 2: Honeywell's Refrigerants Options



	N Series	L Series
Current Product	Reduced GWP Option (A1)	Lowest GWP Option (A2L)
R-404A GWP=3922	HFO Blend – GWP~1300 (retrofit) **N-40** HFO Blend – GWP~1000 (new equip) **N-20**	HFO Blend GWP~200-300 **L-40**
HCFC-22 GWP=1810	HFO Blend – GWP ~1000 **N-20**	HFO Blend GWP <350 **L-20**
R-410A GWP=2088		HFO-Blend GWP <500 **L-41**
HFC-134a GWP=1430	HFO Blend – GWP ~600 **N-13**	HFO-1234yf GWP = 4 **L-YF** HFO-1234ze GWP = 6 **L-ZE**
R-123 GWP= 77	HFO–GWP =7 **N-12**	

3. POSITIVE DISPLACEMENT CHILLER APPLICATIONS

A performance analysis was carried out for an air cooled 20 ton (70 kW) chiller using a lumped parameter modeling approach for the heat exchangers. The water inlet and outlet temperatures were assumed to be 12^{o}C and 7^{o}C respectively. The analysis was performed at an ambient air temperature of 35^{o}C. The evaporator superheat and condenser subcooling were set at 5.5^{o}C. An assumption was made that the volumetric and isentropic efficiencies were the same for all refrigerants. Performance results obtained for R-410A alternatives with our analysis are shown in Table 3. Performance results obtained for an alternative to R-407C with our analysis are depicted in Table 4.

Table 3: Positive Displacement Chiller Analysis – R-410A Alternatives Results

	Tevap (^{o}C)	Tcond (^{o}C)	$P_{suction}$ (kPa)	$P_{discharge}$ (kPa)	dP_{cond} (kPa)	dP_{evap} (kPa)	Mass Flow (kg/s)	Capacity (kW)	COP
R410A	3.2	50.85	871.8	3165.4	70	20	0.454	69.7	3.5
L-41 (Drop in)	2.9	51.6	731.9	2823.2	52.5	14.4	0.310	64.2	3.6
Comparison	**-0.30**	**0.75**	**84.0%**	**89.2%**	**75.0%**	**72.0%**	**68.3%**	**92.1%**	**100.9%**
L-41 (Circuits mod.)	3.4	50.85	737.3	2787.9	77.7	27.9	0.313	65.4	3.7
Comparison	**0.20**	**0.00**	**84.6%**	**88.1%**	**111.0%**	**139.5%**	**68.9%**	**93.9%**	**103.5%**
L-41 (Comp. mod.)	3.2	51.4	731.4	2820.2	76.5	27.9	0.333	69.2	3.6
Comparison	**0.00**	**0.55**	**83.9%**	**89.1%**	**109.3%**	**139.5%**	**73.2%**	**99.3%**	**101.3%**

Since drop-in performance of L-41 into the R-410A system showed a significant drop in mass flow rate and pressure drops, the number of circuits in the evaporator was decreased by 23% and in the condenser by 13% to increase the mass velocity for L-41. This led to increase in capacity and COP of the system due to improvements in heat transfer. The capacity was fully recovered when the compressor displacement was increased by 8% and the number of circuits was decreased by 18% in the evaporator and by 11% in the condenser.

Table 4: Positive Displacement Chiller Analysis – R-407C Alternatives Results

	Tevap (^{o}C)	Tcond (^{o}C)	$P_{suction}$ (kPa)	$P_{discharge}$ (kPa)	dP_{cond} (kPa)	dP_{evap} (kPa)	Mass Flow (kg/s)	Capacity (kW)	COP
R407C	3.3	50.6	545.7	2173.0	70	20	0.461	70.78	3.745
L-20	3.0	50.85	532.1	2133.4	57.9	16.1	0.355	72.44	3.754
Comparison	**-0.30**	**0.25**	**97.5%**	**98.2%**	**82.7%**	**80.5%**	**77.0%**	**102.3%**	**100.2%**

Table 4 shows drop-in evaluation of L-20 as replacement of R407C in a air-cooled chiller. Results show L-20 as having slightly larger capacity and similar efficiency. Moreover, L-20's flow rate is 77% of R407C, which indicate potential for further improvements in the design of the heat exchangers.

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):

$$N = 0.76 \frac{H^{0.75}}{\sqrt{Q}} \quad (1)$$

$$D = 3.4 \frac{\sqrt{Q}}{H^{0.25}} \quad (2)$$

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 two sets of refrigerants, medium pressure refrigerants that are potential replacements for HFC-134a and low pressure refrigerants that are more suited for chillers that ran CFC-11 or HCFC-123. For both applications, a refrigerant capacity of 500 tons (1760 kW) was selected assuming evaporation and condensation temperatures of 5^oC and 35^oC, respectively. An evaporator superheat of 3^oC was selected. 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 a 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

Table 5 shows the results for medium pressure refrigerants.

Table 5: Compressor Sizing for Medium Pressure Refrigerants

		Refrigerant				
Parameter	Units	R-12	R-134a	R1234ze(E)	R1234yf	N-13
Delta hevap	kJ/kg	122.84	155.24	142.29	121.72	145.92
Delta hs,comp	kJ/kg	15.34	19.64	18.04	15.94	18.59
Head	m	1563	2002	1839	1625	1895
mdot	kg/s	14.31	11.33	12.34	14.45	12.04
density	kg/m^3	20.54	16.86	13.74	20.41	15.56
Vdot	m^3/s	0.70	0.67	0.90	0.71	0.77
N (Impeller Speed)	rpm	11983	14691	11919	12236	13131
D (Impeller Dia.)	m	0.255	0.235	0.278	0.255	0.256
u2 (tip speed)	m/s	160	181	174	163	176
Pr (Pressure Ratio)	-	2.34	2.54	2.57	2.40	2.55
COP	-	8.01	7.90	7.91	7.64	7.85
COP Rel to R134a		**101.3%**	**100.0%**	**100.1%**	**96.6%**	**99.3%**

Based on our analysis, all three alternative refrigerants can possibly be used with a centrifugal compressor designed for R-134a with only minor changes. For example, if the same speed and diameter were used, the specific speed and diameter will 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 a particular chiller would see. In addition, our analysis suggests that the non-flammable near-azeotropic blend, N-13 has the potential for use in existing machines and yet still reduces the GWP by close to 60% from that of R-134a. Likewise, R-1234ze(E) can possibly be used in R-134a adapted machines with some loss in capacity but at or above efficiency level of R-134a. Tables 6 and 7 show the potential gains in efficiency that are possible by using multiple stage compression processes that are not normally seen in this type of machine.

Table 6: Two-Stage Performance Medium Pressure Refrigerants

	Refrigerant				
Parameter	R-12	R-134a	R1234ze(E)	R1234yf	N-13
Single Stage COP	8.01	7.90	7.90	7.64	7.88
Two Stage COP	8.48	8.42	8.46	8.27	8.49
% Improvement	5.9%	6.6%	7.1%	8.2%	7.7%
Two Stage Comparison	**100.7%**	**100.0%**	**100.5%**	**98.2%**	**100.8%**
Second Stage Comp. Inlet Superheat ^oC	4.6	4.2	2.2	1.7	3.0

Table 7: Three-Stage Performance Medium Pressure Refrigerants

	Refrigerant				
Parameter	R-12	R-134a	R1234ze(E)	R1234yf	N-13
Single Stage COP	8.01	7.90	7.90	7.64	7.88
Three Stage COP	8.65	8.61	8.66	8.49	8.68
% Improvement	8.0%	9.0%	9.6%	11.1%	10.2%
Three Stage Comparison	**102.7%**	**102.3%**	**102.9%**	**100.8%**	**103.1%**
Second Stage Comp. Inlet Superheat ^oC	4.2	3.9	2.5	2.1	3.1
Third Stage Comp. Inlet Superheat ^oC	5.1	4.5	1.9	1.2	3.0

4.2 Low Pressure Chiller Applications

Table 8 shows the results of our analysis for low pressure refrigerants.

Table 8: Compressor Sizing for Low Pressure Refrigerants

		Refrigerant			
Parameter	Units	R-11	R-123	R-245fa	N-12
Delta hevap	kJ/kg	163.46	151.02	164.97	167.76
Delta hs,comp	kJ/kg	19.25	18.06	20.11	20.13
Head	m	1962	1841	2050	2052
mdot	kg/s	10.75	11.64	10.66	10.48
density	kg/m^3	2.98	2.73	3.94	3.38
Vdot	m^3/s	3.61	4.27	2.71	3.10
N (Impeller Speed)	rpm	6241	5474	6450	6966
D (Impeller Dia.)	m	0.550	0.607	0.468	0.503
u2 (tip speed)	m/s	179	174	183	183
Pr (Pressure Ratio)	-	3.00	3.20	3.20	3.07
COP	-	8.49	8.36	8.21	8.33
COP Rel to R123		**101.6%**	**100.0%**	**98.1%**	**99.6%**

Based on our analysis of N-12, we believe that larger capacity with comparable energy efficiency may be obtained using this refrigerant without significant system modifications. We did not evaluate operating pressures, and due to somewhat higher pressure than HCFC-123, pressure code vessels would be required if this refrigerant were used (similar to HFC-245fa). Significant gains in efficiency is seen when typical multiple staging in used in this type of compressor.

Table 9: Two-Stage Performance Low Pressure Refrigerants

	Refrigerant			
Parameter	R-11	R-123	R-245fa	N-12
Single Stage COP	8.49	8.37	8.19	8.33
Two Stage COP	8.85	8.80	8.70	8.77
% Improvement	4.2%	5.1%	6.2%	5.3%
Two Stage Comparison	**100.6%**	**100.0%**	**98.9%**	**99.7%**
Second Stage Comp. Inlet Superheat ^{o}C	5.9	3.1	1.9	2.6

Table 10: Three-Stage Performance Low Pressure Refrigerants

	Refrigerant			
Parameter	R-11	R-123	R-245fa	N-12
Single Stage COP	8.49	8.37	8.19	8.33
Three Stage COP	8.96	8.94	8.87	8.92
% Improvement	5.5%	6.8%	8.3%	7.1%
Three Stage Comparison	**100.2%**	**100.0%**	**99.2%**	**99.8%**
Second Stage Comp. Inlet Superheat ^{o}C	5.1	3.2	2.4	2.9
Third Stage Comp. Inlet Superheat ^{o}C	6.7	2.9	1.3	2.3

5. CONCLUSIONS

Recently developed low global warming molecules may have potential applications in systems that currently employ low to medium pressure refrigerants, such as stationary commercial A/C systems and commercial refrigeration. Our present analysis indicates that comparable performance to existing refrigerants may possibly be achieved in applications investigated to date without significant hardware modification. Both the low and medium pressure refrigerants show considerable promise in providing high energy efficiency in chiller systems that employ these refrigerants.

Preliminary evaluations of higher pressure blends also show promise in a system that uses these refrigerants, however there are trade-offs in performance, flammability, and GWP that need to be made.

This initial work is encouraging but further work is needed to more fully explore these applications. This work would include, among other things, additional performance evaluations as well as conducting flammability risk assessments where appropriate.

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