LOW GLOBAL WARMING REFRIGERANTS FOR STATIONARY AIR CONDITIONING APPLICATIONS

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ABSTRACT

Due to the growing global concerns around the use of working fluids with relatively high global warming potential, new working fluids with the positive attributes of both high thermal performance and low environmental impact 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 unitary and 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.

Keywords: Refrigerants, Global Warming, Hydro-fluoro-olefins

1 INTRODUCTION

Two new low GWP refrigerant molecules (HFO-1234yf, HFO-1234ze) have been identified. These molecules are Hydro-Fluoro-Olefins (HFO) and Honeywell has discovered that these molecules 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 it 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 applications of potential refrigerant options in stationary air conditioning and heat pump systems.

Table 1. Working Fluid Properties

Refrigerant	GWP	PEL (ppm)	LFL / UFL (Vol%, 23°C)
R-134a	1430	1000	-
HFO-1234ze	6	1000	-
HFO-1234yf	4	500	6.2-12.3
HDR-14	<10	TBD	-
R-32	675	1000	14.4-29.3
R-600a	~5	800	1.8-8.5
R-290	~5	1000	2.1-10.0

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 fluids that do perform well in certain applications where R-134a is used doesn't necessarily imply that these same refrigerants will also

perform well in other applications, such as in heat pumps 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 heat pump and other applications are currently in development.
In addition to the refrigerant molecules listed above, another single component refrigerant, code named **HDR-14,** 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. Also blends with significantly lower GWP than current refrigerants are currently in development (depicted in Table 2). These blends have operating characteristics close to R-404A, R-22, and R-410A. Although blends can be formulated with a GWP below 150, trade-offs in performance are necessary to accomplish this. Blends with GWP greater than 150 can provide a better performance match with existing refrigerants, and still offer a GWP reduction of 75% to 95%.

Table 2.Honeywell's Refrigerants Options

Current Product	N-Series (Reduced GWP) (A1)	L-Series (Lowest GWP) (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
R-407C / HCFC-22 **GWP= 1774 / 1810**	**HFO Blend – GWP ~1000** N-20	**HFO Blend GWP <150** L-20 **HFO Blend GWP < 400** L-20+
HFC-134a **GWP=1430**	**HFO Blend – GWP ~600** N-13	**HFO-1234yf GWP = 4** L-YF **HFO-1234ze GWP = 6** L-ZE
R-410A **GWP=2088**		**HFO-Blend GWP <500** L-41

3. UNITARY HEAT PUMP R-410A APPLICATIONS

The R-410A system was a DC inverter ductless split (or RAC) reversible heat pump unit with a nominal cooling capacity of 4 kW and COP of 3.70. The nominal heating capacity was 5 kW with a COP of 4.33. The test conditions were based on ISO standard 5151 [1] and are shown in Table 3.

Table 3. RAC System Test Conditions

Operating Conditions (Cooling Mode)					
Test Condition	**Indoor Ambient**		**Outdoor Ambient**		**Compressor speed**
	DB (ºC)	**WB (ºC)**	**DB (ºC)**	**WB (ºC)**	
cool-01(T1 rating, **moderate** climate)	27	19	35	24	rated
cool-02(T1 Intermediate)	27	19	35	24	half
*cool-03(T2 rating, **cool** climate)*	*21*	*15*	*27*	*19*	*rated*
*cool-04(T3 rating, **hot** climate)*	*29*	*19*	*46*	*24*	*rated*

Operating Conditions (Heating Mode)					
Test Condition	**Indoor Ambient**		**Outdoor Ambient**		**Compressor speed**
	DB (ºC)	**WB (ºC)**	**DB (ºC)**	**WB (ºC)**	
Heat-01 (**High** Temp. rating)	20	<15	7	6	rated
Heat-02 (high Temp. intermediate)	20	<15	7	6	half
Heat-03 (**Low** Temp. rating)	20	<15	2	1	rated
*Heat-03 (**Extra Low** Temp. rating)*	*20*	*<15*	*-7*	*-8*	*rated*

3.1 Performance Results of Ductless Split (RAC) Heat Pump

This heat pump was tested at the conditions indicated above. All tests were performed inside environmental chambers equipped with instrumentation to measure both air-side and refrigerant-side parameters. Refrigerant flow was measured using a coriolis flow meter while air flow and capacity was measured using an air-enthalpy tunnel. All primary measurement sensors were calibrated to ±0.25ºC for temperatures and ±0.25 psi for pressure. Experimental uncertainties for capacity and efficiency were on average ±5%. Capacity values represent the air-side measurements, which were carefully calibrated using the reference fluid (R-410A).L-41 was also tested in this system along with R-32 and R-410A again as the baseline.

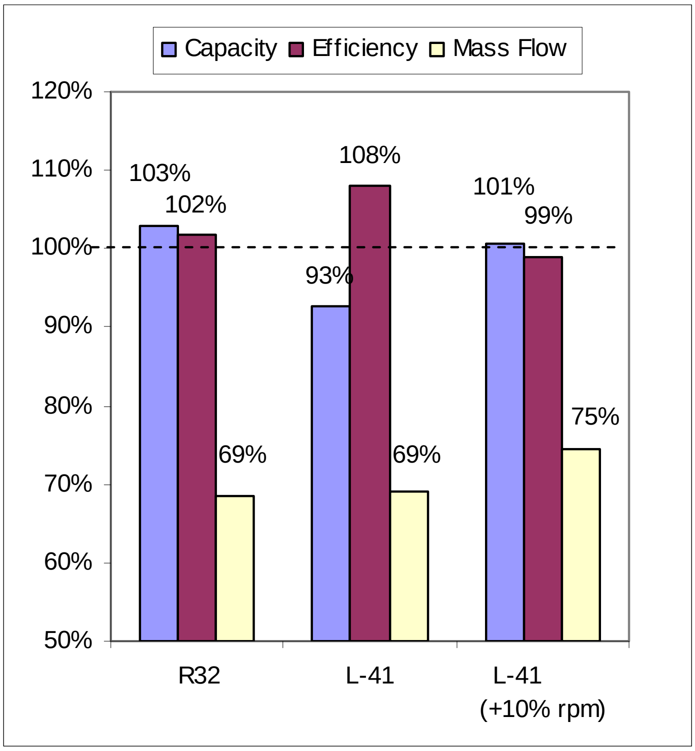

Figure 1. Cooling Mode Results (35^{o}C ambient)

Figures 1 and 2 shows the results of the ductless split heat pump tests at two representative conditions: 35^{o}C ambient for cooling and 7^{o}C ambient for heating.

The L-41 results show improved efficiency in both cooling and heating relative to the baseline refrigerant however the capacity at the nominal compressor speed was lower. Slightly increased compressor displacement would be needed for capacity to match the baseline refrigerant. To evaluate the performance with a larger displacement compressor the compressor speed was increased approximately 10% and the tests were repeated. Capacity and efficiency results are shown and indicate that performance now nearly matches that of R-410A. Although the capacity and efficiency of R-32 does match that of R-410A, the discharge temperature of this refrigerant is considerably higher than that of the baseline refrigerant, or L-41, as depicted in Figure 3. These particular temperatures may not be a significant concern, but these tests were not run at very high ambient conditions. Temperatures at extreme ambient temperatures can be a concern. Another consideration is the condition of the condenser as all these tests were run with a new condenser. Typical fouling of the condenser will exacerbate the situation leading to potential system reliability concerns.

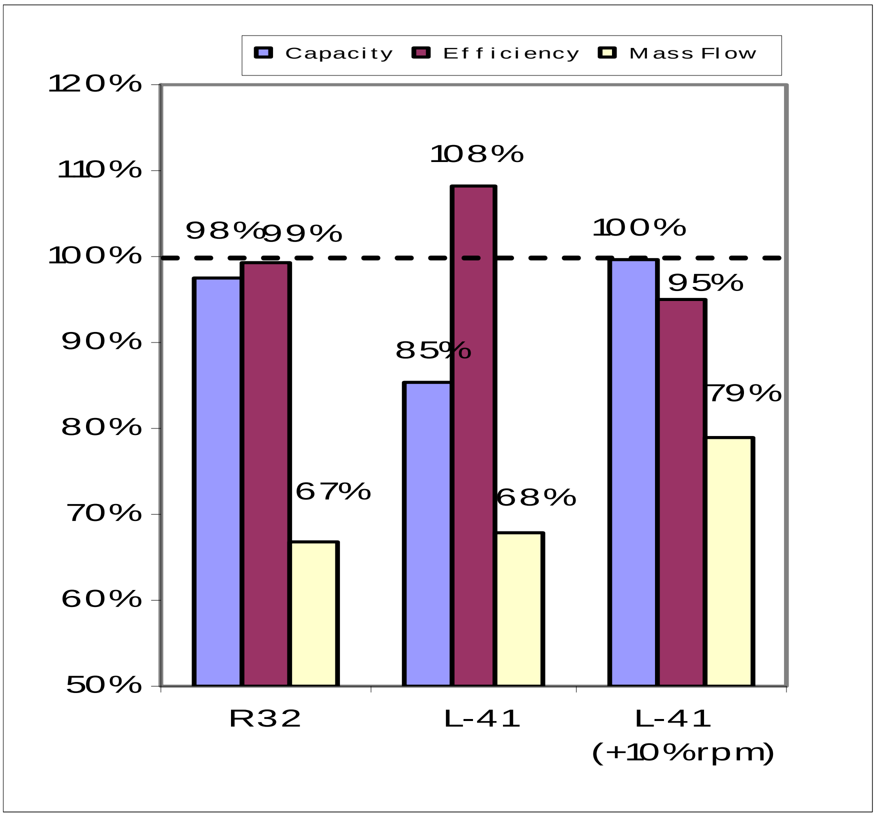

Figure 2. Heating Mode Results (7^{o}C ambient).

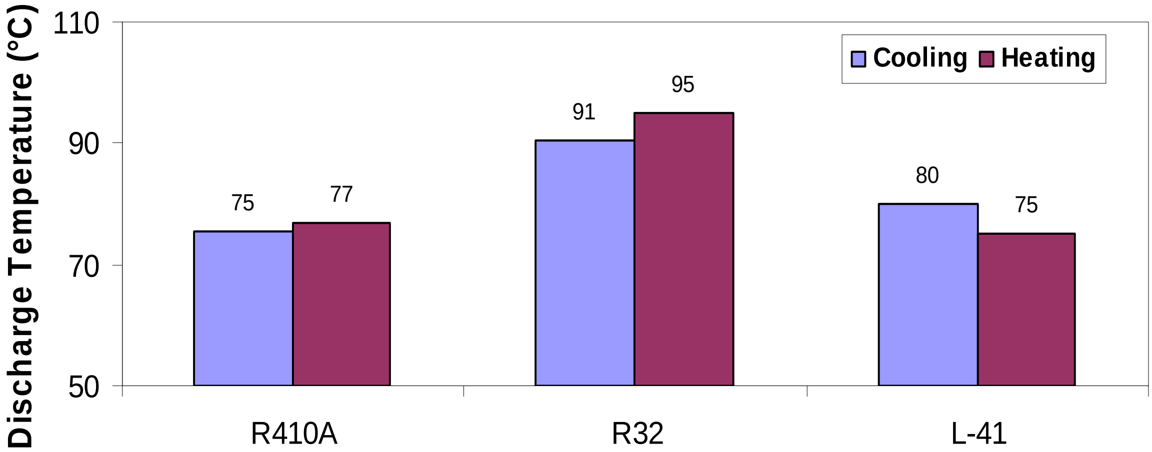

Figure 3. Discharge Temperature Comparisons

3.2 Discussion of R-410A Alternatives Evaluation

Overall, L-41 shows potential to replace R-410A as its performance is close to that of R-410A. Any slight differences seen can be reduced or eliminated with minor system changes. This performance can be achieved without concern of high discharge temperature, and with a GWP of less than 500; this is a considerable reduction in GWP as compared to R-410A (more than 75%).

4 UNITARY HEAT PUMP R-407C EVALUATIONS

A ducted reversible heat pump with a 3-ton (10.5 kW) cooling capacity, an efficiency rating of 13 SEER (3.8 seasonal COP), a heating capacity of 10.1 kW and an HSPF of 8.5 was used for this evaluation. This system was originally designed for R-22 but was converted to R-407C, which serves as the baseline refrigerant. R-407C was selected since R-22 has already been phased out for new equipment in many countries and R-407C is used in many types of equipment that formerly utilized R-22.

In addition to R-407C, three alternative refrigerants were evaluated. L-20 and N-20 that were identified in Table 1 along with another option, L-20+. N-20 is a non-flammable refrigerant blend with a GWP under 1000, while L-20 has mild flammability with an expected flammability classification of “2L” but has a GWP under 150. L-20+ is another “2L” option that has a GWP under 400 (>80% reduction from R-407C) with performance characteristics nearly identical to that of R-407C.

Table 4. Test Conditions for R-407C Evaluations [2].

Operating Conditions (Cooling Mode)				
Test Condition	Indoor Ambient		Outdoor Ambient	
	DB(ºC)	WB(ºC)	DB(ºC)	WB(ºC)
AHRI Std. A	26.7	19	35	24
AHRI Std. B	26.7	19	27.8	18
AHRI Std. C	26.7	14	27.8	-
AHRI Std. MOC	26.7	19	46.1	24

Operating Conditions (Heating Mode)				
Test Condition	Indoor Ambient		Outdoor Ambient	
	DB(ºC)	WB(ºC)	DB(ºC)	WB(ºC)
AHRI Std. H1	21.1	15.6	8.3	6.1
AHRI Std. H2	21.1	15.6	1.7	0.6
AHRI Std. H3	21.1	15.6	-8.3	-9.4

All tests were performed inside environmental chambers equiped with instrumentation to measure both air-side and refrigerant-side parameters. Refrigerant flow was measured using a coriolis flow meter while air flow and capacity was measured using an air-enthalpy tunnel designed according to industry standards [2],[3]. All primary measurement sensors were calibrated to ±0.27ºF (0.15ºC) for temperatures and ±0.25 psi for pressure. Overall system uncertainties (capacity and efficiency) were in average ±5%.

4.1 Cooling Mode Results

Table 5 shows the results of this heat pump operating in cooling mode tested at conditions reported in Table 4. All three alternatives operate with cooling efficiencies at or slightly above that of R-407C with acceptably low discharge temperatures. L-20+ also matches the cooling capacity of R-407C. L-20 would need a slightly larger compressor displacement to make up for the 10% lower capacity while N-20 comes closer to meeting the capacity of R-407C.

Table 5. Cooling Mode Results.

Cooling Mode								
Refrigerant	AHRI-Std	Capacity	EER	mass flow	Tcd	Tev	Tdisch	Pd/Ps
		% of R-407C	% of R-407C	% of R-407C	% of R-407C	% of R-407C	°C	% of R-407C
R-407C	A	100%	100%	100%	100%	100%	76	100%
	B	100%	100%	100%	100%	100%	66	100%
L-20	A	90%	105%	84%	100%	103%	70	99%
	B	88%	101%	84%	100%	103%	62	98%
L-20+	A	101%	101%	77%	101%	99%	82	101%
	B	100%	100%	77%	102%	99%	71	100%
N-20	A	93%	104%	106%	98%	104%	65	94%
	B	94%	104%	105%	98%	103%	57	94%

4.2 Heating Mode Results

Heating mode results are depicted on Table 6 with basically very similar results as those seen in cooling mode. L-20+ again shows nearly identical heating capacity and efficiency performance to R-407C with the other candidates matching efficiency but with somewhat lower capacity.

Table 6. Heating Mode Results

Heating Mode								
Refrigerant	AHRI-Std	Capacity	COP	mass flow	Tcd	Tev	Tdisch	Pd/Ps
		% of R-407C	% of R-407C	% of R-407C	% of R-407C	% of R-407C	°C	% of R-407C
R-407C	H1 (8.3/21.1)	100%	100%	100%	100%	100%	75	100%
L-20	H1 (8.3/21.1)	87%	104%	84%	104%	97%	66	93%
L-20+	H1 (8.3/21.1)	102%	101%	77%	100%	103%	85	102%
N-20	H1 (8.3/21.1)	97%	99%	106%	95%	102%	68	105%

4.3 Discussion of R-407C Alternatives Evaluation

Three low global warming refrigerant candidates were evaluated with promising results. L-20 with a GWP less than 150 (>90% reduction from R-407C) achieved comparable efficiency and with minor system changes would likely achieve the same capacity as the baseline refrigerant. Another refrigerant option, L-20+ matches both the capacity and efficiency of R-407C with a greater than 80% reduction in GWP. N-20, a non-flammable option with a GWP reduction of more than 45%, achieves comparable efficiency and only sees a slight reduction in capacity.

5 CENTRIGUGAL 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) [4], 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:

$$N = 0.76\frac{H^{0.75}}{\sqrt{Q}} \quad \text{(1a)} \qquad\qquad D = 3.4\frac{\sqrt{Q}}{H^{0.25}} \quad \text{(1b)}$$

Where H = Isentropic enthalpy rise in J/kg or "Head" in m 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 and 35°C, respectively. The cycle analyses yielded the values for isentropic enthalpy rise and volumetric flow rate needed to determine the speed and compressor impeller diameters using equations 1a and 1b.

5.1 Medium Pressure Chiller Applications:
Table 7 shows the results for medium pressure refrigerants:

Table 7. Compressor Sizing for Medium Pressure Refrigerants

		Refrigerant				
Parameter	**Units**	**R-12**	**R-134a**	**1234ze(E)**	**1234yf**	**N-13**
Delta hevap	**kJ/kg**	**120.92**	**152.49**	**140.01**	**118.26**	**138.95**
Delta hs,comp	**kJ/kg**	**15.1**	**19.31**	**19.13**	**18.73**	**17.80**
Head	**m**	**1540**	**1969**	**1743**	**1910**	**1815**
mdot	**kg/s**	**14.56**	**11.54**	**12.57**	**14.88**	**12.67**
density	**kg/m3**	**20.84**	**17.13**	**13.64**	**20.74**	**17.34**
Vdot	**m3/s**	**0.70**	**0.67**	**0.92**	**0.73**	**0.73**
N (Impeller Speed)	**rpm**	**11828**	**14485**	**11296**	**13600**	**13090**
D (Impeller Dia.)	**m**	**0.256**	**0.237**	**0.286**	**0.248**	**0.251**
u2 (tip speed)	**m/s**	**159**	**180**	**169**	**177**	**172**
Pr (Pressure Ratio)	**-**	**2.34**	**2.54**	**2.60**	**2.40**	**2.52**
COP	**-**	**8.01**	**7.90**	**7.87**	**7.58**	**7.80**
COP Rel to 134a		**101.4%**	**100.0%**	**99.6%**	**95.9%**	**98.7%**

Where,

Delta hevap: Change in enthalpy in the evaporator (kJ/kg)
Delta hs, comp: Change in enthalpy in the compressor (kJ/kg)
Head: Pressure rise in compressor (m)
mdot: Mass flow rate (kg/s)
Vdot: Volume flow rate (m3/s)
N: Impeller speed (rpm)
D: Impeller diameter (m)
u2: Tip speed (m/s)
Pr: Pressure Ratio (-)

These results show that all three alternative refrigerants could be applied to a centrifugal compressor designed for R-134a with only minor changes. If the same speed and diameter were used, the specific speed and diameter will for the most part stay in the optimum range for these parameters. The operating envelop would have to be evaluated to ensure reliable operation over the expected conditions a particular chiller would see. Efficiency would be very close to the baseline refrigerant.

5.2 Low Pressure Chiller Applications:
Table 8 shows the results of this analysis for low pressure refrigerants.

Table 8. Compressor Sizing for Low Pressure Refrigerants

		Refrigerant			
Parameter	**Units**	**R-11**	**R-123**	**R-245fa**	**HDR-14**
Delta hevap	**kJ/kg**	**161.71**	**149.04**	**162.32**	**165.44**
Delta hs,comp	**kJ/kg**	**19.02**	**18.09**	**20.19**	**19.85**
Head	**m**	**1939**	**1844**	**2058**	**2023**
mdot	**kg/s**	**10.88**	**11.81**	**10.84**	**10.64**
density	**kg/m3**	**3.01**	**2.76**	**3.96**	**3.44**
Vdot	**m3/s**	**3.61**	**4.28**	**2.74**	**3.09**
N (Impeller Speed)	**rpm**	**6186**	**5475**	**7423**	**6902**
D (Impeller Dia.)	**cm**	**55.0**	**60.6**	**47.2**	**50.4**
u2 (tip speed)	**m/s**	**178**	**174**	**184**	**182**
Pr (Pressure Ratio)	**-**	**3.00**	**3.20**	**3.20**	**3.06**
COP	**-**	**8.50**	**8.24**	**8.04**	**8.34**
COP Rel to R123		**103.2%**		**97.6%**	**101.2%**

The results for HDR-14 (Honeywell Developmental Refrigerant 14) show that this refrigerant could be used in these applications without significant modifications. Larger capacity with comparable, if not superior, energy efficiency could be obtained using this refrigerant. Not part of this analysis is the evaluation of 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).

6 CONCLUSIONS

Recently developed low global warming molecules may have potential applications in systems that currently employ medium pressure refrigerants, such as commercial refrigeration and stationary A/C systems. Unlike CO2, comparable performance to existing refrigerants can be achieved in applications investigated to date without significant hardware modification.
Preliminary evaluations of higher pressure blends show promise, 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 would include additional performance evaluations as well as conducting flammability risk assessments where appropriate.

REFERENCES

1- ISO 5151:2010(E), Non-ducted Air Conditioners and Heat Pumps – Testing and Rating for Performance, 2010.

2-AHRI Standard 210/240-2008, Performance Rating of Unitary A/C and Air Source Heat Pump Equipment, Arlington, VA, 2008.

3- ASHRAE Standard 41.2, Standard Methods for Laboratory Airflow Measurements, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1992.

4- Biederman, B.P., Mulugeta, J, Zhang, L, Chen, Y, Brasz, J, Cycle Analysis and Turbo Compressor Sizing with Ketone C6F as Working Fluid for Water-Cooled Chiller Applications, International Compressor Engineering Conference at Purdue, July, 2004.