LATEST DEVELOPMENTS IN LOW GLOBAL WARMING REFRIGERANTS FOR HEAT PUMP APPLICATIONS

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Abstract New refrigeration system 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. The evaluation of potential replacements for common heat pump refrigerants such as R-410A, R-407C, and R-22 will be discussed for several heat pumps applications. Chemical and physical properties for the new molecules, as well as experimental results for the heat pump applications using these developmental refrigerants are compared and contrasted.

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) 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). 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 to replace R-410A, R-407C, and R-22 in stationary heat pump systems.

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 applications where R-134a is used doesn't imply that these same refrigerants will also perform well in other applications such as 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.

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
R-32	675	1000	14.4-29.3
R-600a	~5	800	1.8-8.5
R-290	~5	1000	2.1-10.0

Blends with significantly lower GWP than current refrigerants are currently in development. 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 R-410A APPLICATIONS

Two representative air-to-air reversible heat pumps designed for R410A were tested. The ducted unit was tested in Honeywell's Buffalo, New York application laboratory while the ductless split unit was tested in Honeywell's Shanghai application laboratory.

The ducted unit is a 3-ton (10.5 kW) 13 SEER (3.8 seasonal COP) with a heating capacity of 10.1 kW and an HSPF of 8.5, equipped with a scroll Compressor. This system has tube-and-fin heat exchangers, reversing valves and thermostatic expansion valves for each operating mode. Due to the different pressures and densities of the refrigerants tested, some of the tests required the use of Electronic Expansion Valves (EEV) as expansion devices to reproduce the same degrees of superheat observed with the original refrigerants.

The other R-410A system was a DC inverter ductless split (or RAC) 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 5151

3.1 Performance Results of Ducted Heat Pump

Tests shown in table 6 were performed using standard [AHRI, 2008] operating conditions. 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 designed according to industry standards (ASHRAE, 1992). 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). The developmental blend, L-41 was tested in this heat pump in both cooling and heating modes along with the baseline refrigerant R-410A.

Table 6 – Operating Conditions

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

3.1.1 Cooling Mode Results

Table 7 shows performance results in cooling mode. L-41 shows efficiency comparable to R410A with capacities ranging from 92% to 95%. Due to the lower mass flow rates than R410A , there may be potential improvements of the heat exchangers. Evaporating temperature is 5 to 6% higher than what is seen with R-410A indicating improved heat transfer process and/or reduced pressure drop while the slightly higher (~3%) condensing temperature indicates the opposite effect in this heat exchanger. Discharge temperatures are just slightly higher than that of R-410A but remain at acceptable levels.

Table 7 – Cooling Mode Results

Cooling Mode								
Refrigerant	**AHRI-Std**	**Cap.**	**EER**	**mass flow**	**Tcd**	**Tev**	**Tdisch**	**Pd/Ps**
		% of R410A	% of R410A	% of R410A	% of R410A	% of R410A	°C	% of R410A
R410A	A	100%	100%	100%	100%	100%	77	100%
	B	100%	100%	100%	100%	100%	67	100%
	C	100%	100%	100%	100%	100%	71	100%
	MOC(46)	100%	100%	100%	100%	100%	94	100%
L-41	A	**92%**	100%	68%	103%	105%	88	100%
	B	93%	**101%**	69%	103%	106%	76	99%
	C	95%	104%	75%	104%	114%	77	96%
	MOC(46)	94%	104%	67%	103%	105%	108	102%

3.1.2 Heating Mode Results

Table 8 shows performance results in heating mode. The trends seen in the cooling mode test results are also seen with heating results. L-41 shows efficiency comparable to R410A with capacities ranging from 91% to 93%. Mass flow rates are approximately 30% lower than R410A. Discharge temperatures remain at an acceptable level though marginally higher than that of R-410A.

Table 8 – Heating Mode Results

Heating Mode								
Refrigerant	**AHRI-Std**	**Cap.**	**EER**	**mass flow**	**Tcd**	**Tev**	**Tdisch**	**Pd/Ps**
		% of R410A	% of R410A	% of R410A	% of R410A	% of R410A	°C	% of R410A
R410A	H1 (8.3/21)	100%	100%	100%	100%	100%	79	100%
	H2 (1.6/21max)	100%	100%	100%	100%	100%	80	100%
	H2(1.6/21 avg)	100%	100%	100%	100%	100%	76	100%
	H3 (-8.3/21)	100%	100%	100%	100%	100%	90	100%
L-41	H1 (8.3/21)	**91%**	**102%**	71%	101%	108%	84	96%
	H2 (1.6/21max)	93%	102%	74%	102%	119%	85	95%
	H2(1.6/21 avg)	84%	95%	69%	97%	120%	83	99%
	H3 (-8.3/21)	84%	95%	68%	99%	115%	98	97%

3.2 Performance Results of Ductless Split (RAC) Heat Pump

This heat pump was tested at the conditions indicated on Table 9 using similar techniques and instrumentation employed in the ducted heat pumps tests. L-41 was also tested in this system along with R-32 and R-410A again as the baseline. Figures 1 and 2 show the results of the ductless split heat pump at representative conditions of 35°C ambient for cooling and 7°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 match 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 on 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.

Table 9 – RAC System Test Conditions

Operating Conditions (Cooling Mode)					
Test Condition	Indoor Ambient		Outdoor Ambient		Compressor
	DB (C)	WB (C)	DB (C)	WB (C)	speed
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
	DB (C)	WB (C)	DB (C)	WB (C)	speed
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-04 (Extra Low Temp. rating)	*20*	*<15*	*-7*	*-8*	*rated*

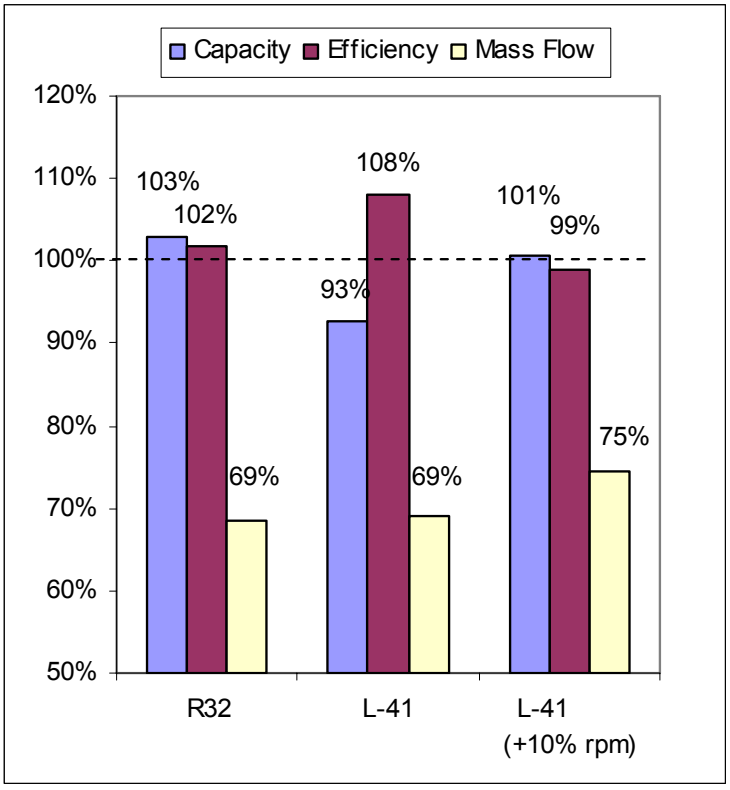


Figure 1 Cooling Mode Results (35°C ambient)

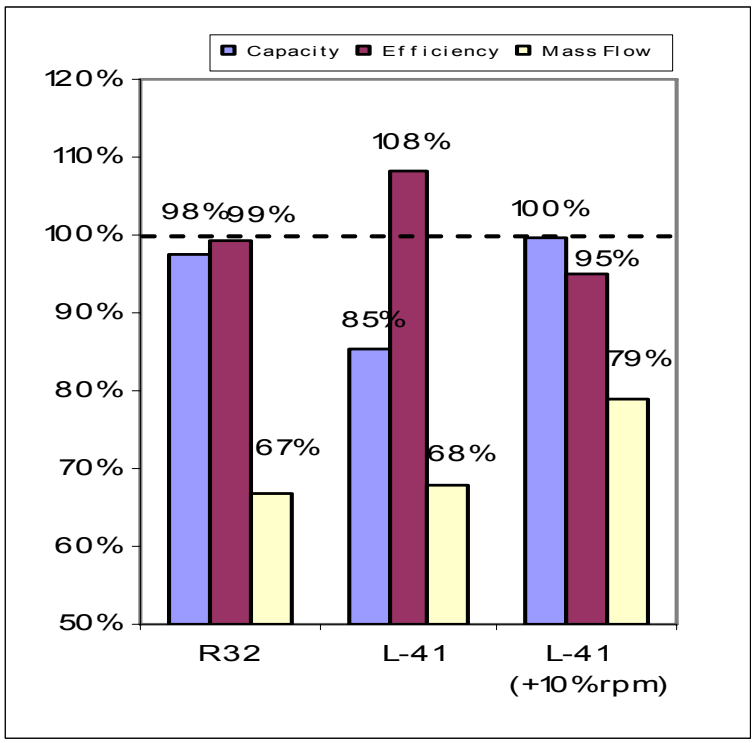


Figure 2 Heating Mode Results (7°C ambient)

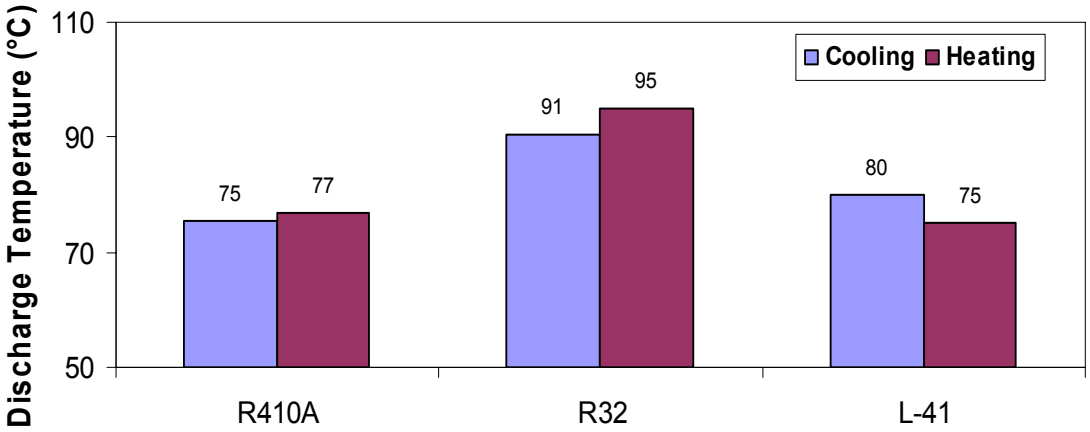


Figure 3 Discharge Temperature Comparisons

3.3 Discussion of R-410A Alternatives Evaluation

Overall, L-41 shows potential to replace R-410A due to its performance 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; it offers a considerable reduction from R-410A (more than 75%).

4 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 for new equipment in many countries and R-407C is used in many types equipment that formerly utilized R-22.

In addition to R-407C, three alternative refrigerants were evaluated. L-20 and N-20 that were identified on 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

4.1 Cooling Mode Results

Table 10 shows the results of this heat pump operating in cooling mode. 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 10 – 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 11 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 11 – 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.

It should be noted that the heat pump used for the R-407C evaluations is noticeably larger in size (primarily the outdoor heat exchanger) than the previous unit used for the R-410A so it is difficult to compare the two series of tests. R-407C and its alternatives discussed here are likely to perform worse in the smaller R-410A unit even if measures were taken to make it function with R-407C using the correct compressor and other minor components.

5 GWP Impact on Life Cycle Climate Performance (LCCP)

An evaluation was conducted on the contribution of the direct impact of refrigerant GWP on overall system contribution to global warming. LGWP refrigerants with GWPs of 500 and 150 were compared to R-410A.
Calculations were performed using 5% annual leak rate, 15 year life and 15% end-of-life loss. A Southern EU climate was used. The units are reversible (heat/cool) with no efficiency loss relative to R-410A for LGWP-500. There is an assumption of an 8% lower COP for LGWP-150 and it would be an R-407C-like refrigerant. In addition, the heat exchanger size was the same as it is for R-410A and its alternative. This last assumption was made since the analysis should assume that the equipment costs are comparable.
Results show minimal gain in direct impact when reducing GWP below 500 (figure 4). Any decrease in efficiency would more than offset any reduction in direct impact
This analysis is based on paper presented at Earth Technology Forum [Spatz, 2004] and heat pump results obtained in the present study.

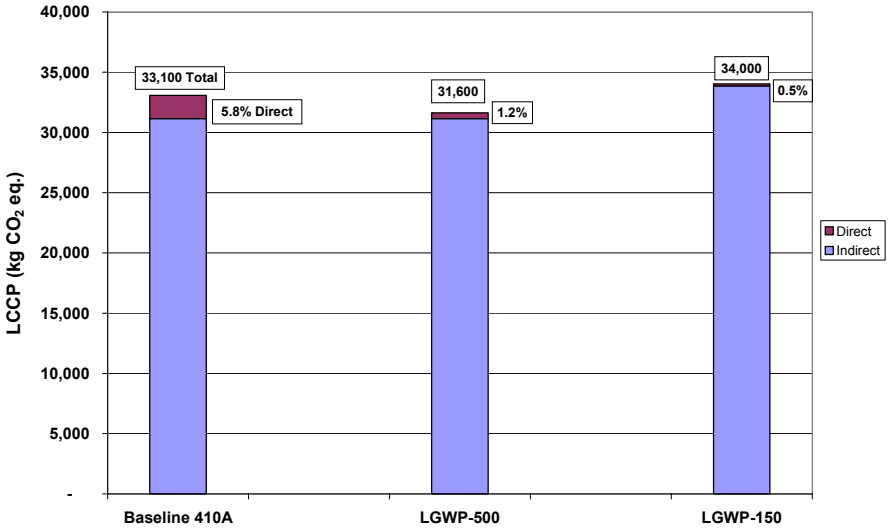


Figure 4 – LCCP Analysis

CONCLUSIONS

Recently developed low global warming molecules may have potential applications in systems that currently employ medium pressure refrigerants such as commercial refrigeration and AC 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.

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