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Low GWP Refrigerants for Air Conditioning Applications

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ABSTRACT

Refrigerants with low environmental impact have been developed as replacements for R22 and R410A in stationary air conditioning applications. Two low global warming potential (GWP) refrigerants, L-20 and L-41 have been evaluated in representative residential equipment. This study discusses the performance of R22 replacements at high ambient temperatures (warm climate) and potential design changes. Replacements of a common HFC refrigerant R410A are discussed for use in water heating heat pumps. In addition, replacements for R22 and R410A are also discussed for positive displacement chiller applications. Theoretical and experimental results are discussed in detail showing the benefits of using these new fluids
Keywords: Low GWP Refrigerants, Water Heating Heat Pumps, Positive Displacement Chiller

1. INTRODUCTION

Refrigerants that are in common use today, hydro fluorocarbons (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 potentials. New molecules with the positive attributes of both high thermal performance and low environmental impact, in addition to a mosaic of other essential characteristics, are currently in development. These materials maintain the high level of system efficiency we are accustomed to with HFC refrigerants but with significantly lower global warming impact than current refrigerants. They also exhibit significantly lower flammability characteristics than the much more flammable hydrocarbons.

Since 2013, there has been strong push towards the phase out of hydro chlorofluorocarbons (HCFCs) like R22 in the Middle East countries due to the directives of the Montreal Protocol phase out plan for Article 5 countries. Along with this certain Gulf Countries like Saudi Arabia have implemented new stringent efficiency requirements for residential air conditioners. HFC refrigerants like R407C and R410A are being evaluated as R22 replacements in these countries. However, performance of these refrigerants deteriorates at high ambient temperatures which are observed in these countries for a significant part of the year. Since there are no such immediate alternatives available, there has been a heightened focus on evaluating refrigerants with low GWP. Utilizing these refrigerants can help these countries to directly move on to the low GWP platform without going through HFCs. In light of these developments, this paper will discuss the experimental results for replacements for R22 in a ductless mini-split air conditioner with focus on performance at high ambient temperatures. Evaluation of two refrigerants, a HFC R407C and a low global warming refrigerant L-20 is presented. Air to water heat pumps (hydronic systems) are very commonly used in Europe for domestic hot water. A large proportion of hydronic systems in Europe use R410A as a refrigerant. The latest F-gas directives provide indication on restricting the use of refrigerants having high global warming potential. Hence, there is a keen interest in low GWP R410A replacements suited for these systems. A theoretical analysis of the replacements of R410A in hydronic systems is presented. Positive displacement chillers are often used in air conditioning applications. This study will discuss properties and performance of potential replacements for refrigerants R22 and R410A in positive displacement chillers employing DX heat exchangers.

2. STATIONARY AIR CONDITIONING FOR HIGH AMBIENT CONDITIONS

2.1 Testing of Mini-Split Air Conditioner

An experimental investigation of a ductless split (mini-split) cooling only system was carried to evaluate R22 replacements for high ambient conditions. The system was originally designed to operate with R22. The system has a nominal capacity of 7.0 kW and nominal COP of 3.0. The test conditions were based on ISO standard 5151 [1] and are shown in Table 1.The system has a fixed speed rotary compressor with fin-tube heat exchangers as outdoor and indoor coils with internally micro-finned tubes. A capillary tube is used as an expansion device. Two R22 replacements, R407C and a HFO based low GWP blend L-20 were evaluated. L-20 is a refrigerant blend with a GWP under 300 that is mildly flammable with a provisional ASHRAE flammability classification of “2L”.

Figure 1 shows a schematic of the test facility. 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 [2],[3]. The humidity of the air was measured using dew point meters with an accuracy of ±0.2 ºC. All primary measurement sensors were calibrated to ±0.15ºC for temperatures and ±0.04 kpa for pressure.

2.2 Performance

A drop-in test was performed for both L-20 and R407C with a capillary tube resized for each refrigerant. L-20 had a drop-in capacity and efficiency of 97% and 96% respectively compared to R22. The indoor and outdoor heat exchangers were modified without addition of any heat transfer area in order to obtain improved performance with L-20. Table 2 shows some key properties of refrigerants at ISO T1 condition. L-20 offers more than 80% reduction in GWP over R22 and R407C. The suction and the discharge pressures and the discharge temperature of L-20 are similar to R22 indicating it to be a suitable replacement. The mass flow rate of L-20 is 20% lower than R407C leading to lower pressure drop in the heat exchangers and thereby improving system efficiency.

The performance of L-20 and R407C in the improved system was compared to the baseline R22 at different ambient temperatures as shown in Table 3. The performance of L-20 matches R22 across the entire range of ambient temperatures. At high ambient conditions, the performance of L-20 is similar to R22 due to similar critical temperatures. L-20 reduces the direct emissions substantially due to lower GWP (295) and lower charge (85%). Hence, L-20 should be considered a low GWP refrigerant option for systems like the one tested that are designed to use either R22 or R407C and applied in locations that can safely use a mildly flammable refrigerant.

2.3 System Design for L-20

In order to obtain better performance with L-20 several changes were made in the system originally designed for R22. The circuitry of indoor and outdoor heat exchangers was modified, without addition of any additional heat exchange area, to account for the glide of L-20 and obtain better matching of temperature profiles of the air and the refrigerant. Figure 2 shows the evaporator circuitry in the original system and the modified system. A more restrictive capillary tube is needed for L-20 compared to the R22 system to obtain improved performance. Since, the mass flow rate of L-20 is about 80% of R22, further improvement in system performance is possible by using smaller diameter tubes or by reducing the number of circuits.

Table 1: Mini-Split AC Test Conditions

Test Condition	Cooling Mode			
	Indoor Ambient		Outdoor Ambient	
	Db	WB	DB	WB
	C	C	C	C
T1	27	19	35	24
T3	29	19	46	24
T3 max	32	13	52	31

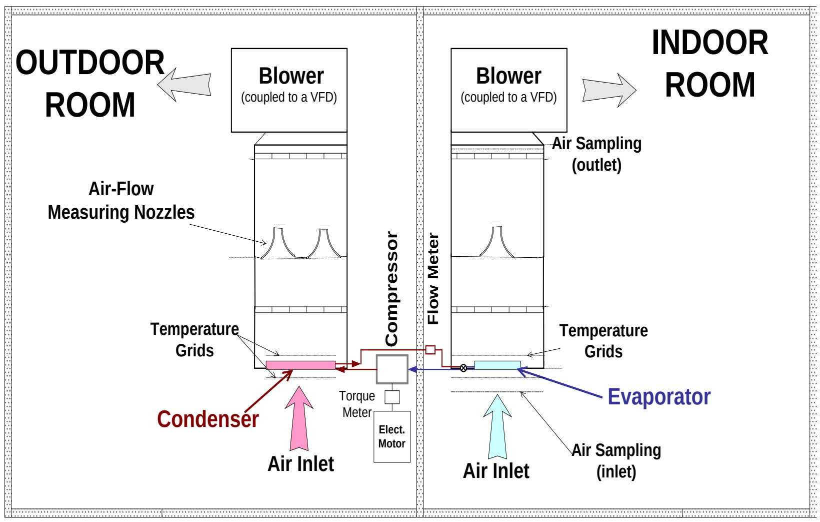

Figure 1. Schematic of Test Facility

Table 2: Refrigerant Properties at ISO T1 condition

Refrigerant	GWP	T_{crit} (°C)	$P_{suction}$	$P_{discharge}$	Pres. Ratio	$T_{dis.}$	dP_{cond}	dP_{evap}	Mass Flow
R22	1760	96	100%	100%	100%	82	100%	100%	100%
L-20	295	90	100%	107%	107%	83	66%	88%	81%
R407C	1624	86	97%	110%	113%	76	82%	123%	99%

Table 3: Performance comparison of R22 alternatives

Refrigerant	Condition	Capacity % of R22	COP % of R22	Charge % of R22
L-20	T1 (35/27)	99%	98%	85%
	T3 (46/29)	100%	100%	
	T3(H) (52/32)	101%	100%	
R407C	T1 (35/27)	97%	93%	94%
	T3 (46/29)	98%	95%	
	T3(H) (52/32)	99%	96%	

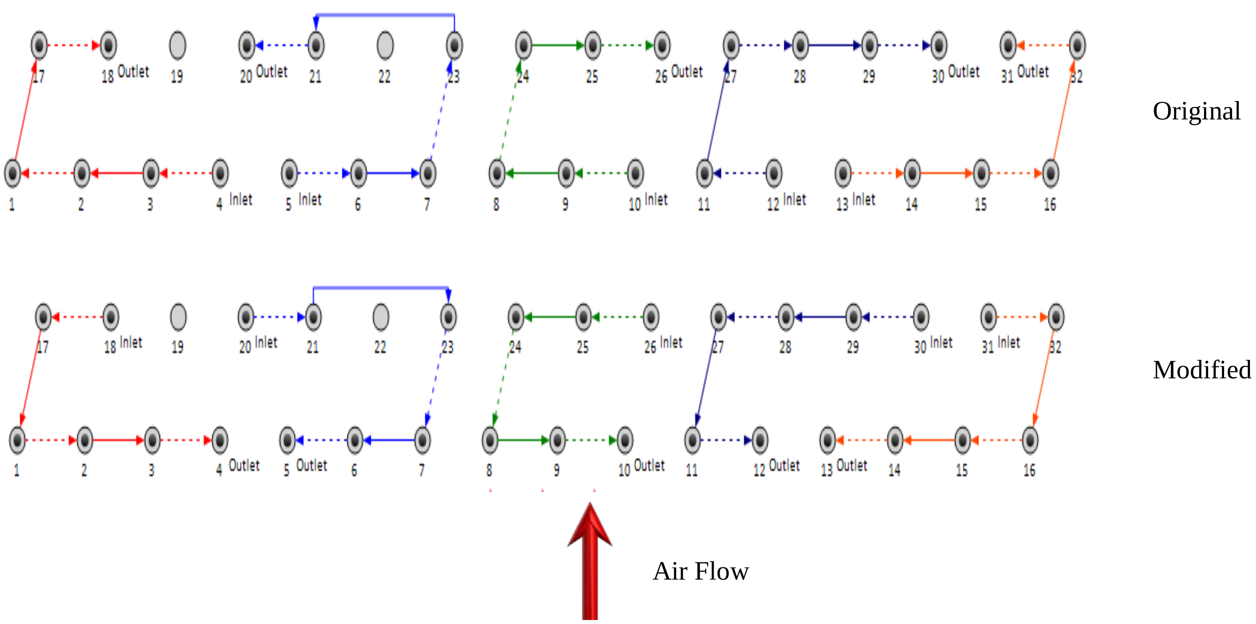

Figure 2. Evaporator Circuitry

3. AIR-TO-WATER HEAT PUMP APPLICATIONS (HYDRONIC SYSTEMS)

These types of heat pumps are used for floor heating or similar applications. Current systems employ R410A as refrigerant. Typical operating conditions [1] require the water delivered at 35ºC (standard rating) with a temperature difference of 5ºC after passing through the floor heating system. Outdoor ambient temperature varies from 7ºC (standard rating) to -15ºC (lowest rating value).

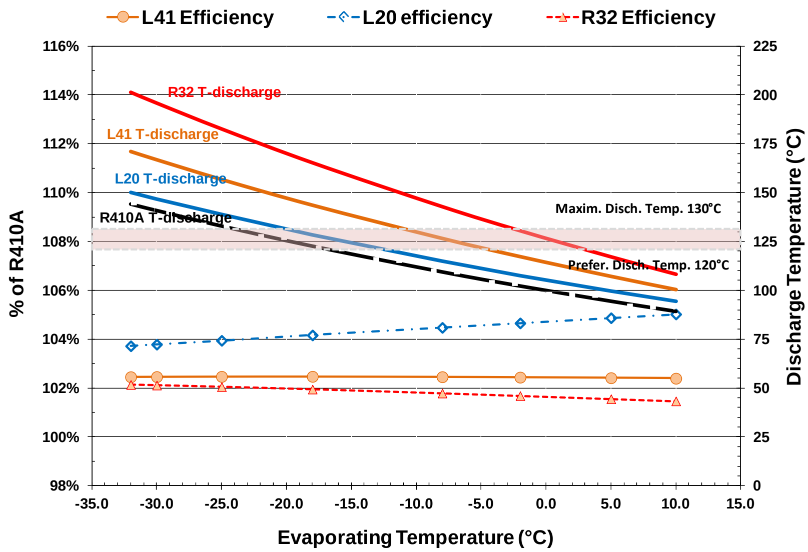

Figure 3. Standard system results

Low ambient temperatures represent a challenge for the performance (capacity, efficiency) and reliability (discharge temperature) of the system. Most compressor manufacturers have a maximum temperature limit of 130ºC with a preferred value of 120ºC. [4]

A thermodynamic evaluation was carried out for two types of systems: 1) A typical system with a standard compressor, 2) An advanced system equipped with a vapor injected compressor. A vapor injected compressor is used in a system to extend the operating envelope by improving efficiency and reducing discharge temperature. Refrigerants considered were R410A as baseline, R32, L-41 and L-20.

Figure 3 shows results for a standard compressor system. Condensing temperature was kept constant at 45ºC to represent a standard rating of 35ºC with 10ºC TD. Evaporating temperatures were varied from 10ºC to -30ºC which with a 6ºC TD would represent outdoor ambient temperatures of 16ºC to -24ºC. Compressor isentropic efficiency was assumed as 60%. The results show all refrigerants providing reasonable efficiency with an advantage for L-20 (4% better than R410A) over L-41 and R32 (2% better than R410A) in that order. Further examination of discharge temperature shows R32 limited to an evaporation temperature of -2ºC (4ºC outdoor), while L-41 goes down top -10ºC (-4ºC outdoor) and L-20 follows closely R410A with -20ºC (-14ºC outdoor). L-20 seems to be a choice that would extend significantly the operating envelope.

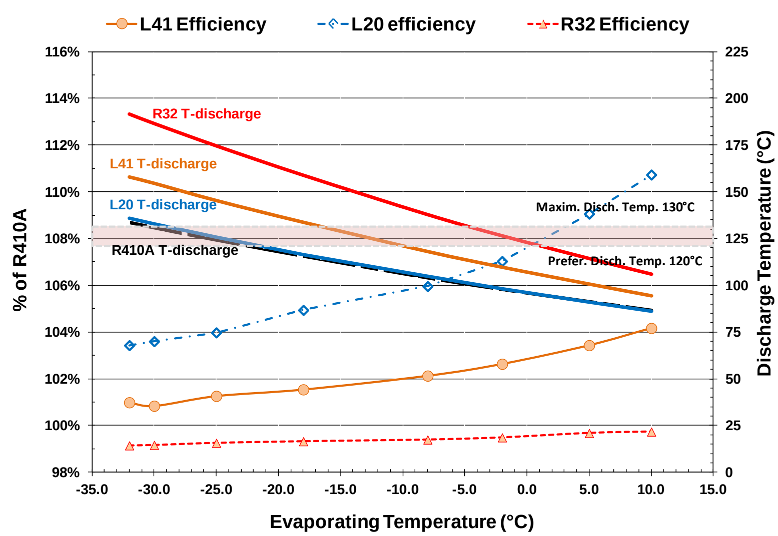

Figure 4. Evaluations for a vapor injected system

Further evaluations of a vapor injected system are shown in figure 4. Additional assumptions were needed so we used compressor isentropic efficiencies of 60% for each stage, while the heat exchanger effectiveness was of 80%. The performance of L-20 is significantly better than R410A and any other alternative (4% to 8%), while L-41 is better than R410A (1% to 4%), and R32 matches R410A. Additional examination of discharge temperature shows R32 limited to an evaporation temperature of -5ºC (1ºC outdoor), while L-41 goes down to an evaporation temperature of -16ºC (-10ºC outdoor). L-20 follows closely R410A with evaporation temperature limited to -28ºC (-22ºC outdoor). These initial evaluations show L-20 as having the largest potential not only to match operating envelope but to give superior performance.

4. 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 R410A alternatives with our analysis are shown in Table 4. Performance results obtained for an alternative to R407C with are depicted in Table 5.

Table 4: Positive Displacement Chiller Analysis – R410A Alternatives Results

	Tevap (^oC)	Tcond (^oC)	$P_{suction}$ (kPa)	$P_{discharge}$ (kPa)	dP_{cond} (kPa)	dP_{evap} (kPa)	Mass Flow (kg/h)	Capacity (kW)	COP
R410A	3.2	50.9	871.8	3165.4	70	20	1634	69.7	3.50
L-41 (Drop In)	2.9	51.5	717.5	2774.1	52.7	14.5	1130	62.6	3.60
Comparison	**-0.3**	**0.6**	**82.0%**	**87.6%**	**75.2%**	**72.5%**	**69.0%**	**89.8%**	**102.9%**
L-41 (Circuits mod.)	3.1	50.9	719.5	2747.7	72.3	19.5	1130	63.4	3.60
Comparison	**-0.1**	**0.0**	**82.5%**	**86.8%**	**103%**	**97.5%**	**69.0%**	**91.0%**	**102.9%**
L-41 (Comp. mod.)	2.7	51.8	710.1	2804.4	68.8	20.6	1256	69.7	3.5
Comparison	**-0.5**	**0.9**	**81.4%**	**88.6%**	**98.2%**	**103.0%**	**76.9%**	**100%**	**100%**

Since drop-in performance of L-41 into the R410A system showed a significant drop in mass flow rate and pressure drops, the number of circuits in the evaporator was decreased by 10% and in the condenser by 8% to increase the mass velocity for L-41. This led to increase in capacity and COP of the system due to improvements in the heat transfer. The capacity was fully recovered when the compressor displacement was increased by 13% and the number of circuits was decreased by 5% in the evaporator and by 3% in the condenser.

Table 5: Positive Displacement Chiller Analysis – R407C Alternatives Results

	Tevap (^oC)	Tcond (^oC)	$P_{suction}$ (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	1660	70.78	3.70
L-20 (Drop In)	2.9	50.8	519.9	2103.3	59.3	16.7	1332	69.84	3.70
Comparison	**-0.40**	**0.20**	**95.2%**	**96.7%**	**84.7%**	**83.5%**	**80.2%**	**99.0%**	**100.0%**
L-20 (Circuits mod.)	3.0	50.5	521.5	2093.7	71.2	19.9	1336	70.44	3.80
Comparison	**-0.30**	**-0.10**	**95.6%**	**96.3%**	**101.7%**	**99.5%**	**80.5%**	**99.5%**	**102.7%**

Table 5 shows the evaluation of L-20 as replacement of R407C in a air-cooled chiller. Results show that as a drop-in replacement for R407C, L-20 has similar capacity and efficiency. Since, L-20's flow rate is 80% of R407C, the number of circuits in the evaporator and the condenser was decreased by 5% to increase the mass velocity for L-20. This led to increase in capacity and COP of the system due to improvements in heat transfer. Re-circuiting the coils to obtain better matching of temperature profiles between air and refrigerant may lead to additional benefits for L-20.

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. Our present analysis indicates that comparable performance to existing refrigerants may possibly be achieved in applications investigated in this paper without significant hardware modification.

- Experimental results suggest that without significant system modifications, L-20 can match the performance of R22 across the range of ambient temperatures observed in various countries in the Middle East. Hence, L-20 is a promising low global warming replacement for R22 in cooling-only systems designed to work in regions.

- Theoretical results indicate that in hydronic systems, L-20 would be expected to have reasonable efficiency with an operating envelope very similar to R410A. Hence, L-20 seems to be an attractive R410A replacement in hydronic systems.
- Preliminary evaluations of higher pressure and medium pressure blends also show promise in positive displacement chiller applications, 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.

Nomenclature			
COP	Coefficient of Performance	T_{cond}	Condensing temperature
dP_{cond}	Pressure drop in condenser	T_{dis}	Compressor discharge temperature
dP_{evap}	Pressure drop in evaporator	TD	Temperature difference between air and refrigerant saturation temperature
$P_{discharge}$	Compressor discharge pressure	T_{evap}	Evaporating temperature
$P_{suction}$	Compressor suction pressure		
T_{crit}	Critical temperature of refrigerant		

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