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Evaluation of R-410A refrigerant alternatives in a residential reversible air-to-water heat pump

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ABSTRACT

Alternative refrigerants with low-GWP are under investigation for residential heat pumps and air-conditioners as R-410A has a GWP of 2088. In this paper, two promising alternative refrigerants, DR-5A (R-454B) and L41-2 (R-447A), both HFC-HFO mixtures with a GWP of 466 and 583 respectively, were tested in a residential reversible air-to-water heat pump. The results show that R-410A replacement by L41-2 and DR-5A does not raise any particular problem and the performance obtained is, aside from some few exceptions, almost equivalent (+/-10%) to that with R-410A. These experimental results provide better understanding and knowledge about R-410A replacement in heat pumps.

1. INTRODUCTION

Protocols and regulations such as the Montreal Protocol (1987), the Kyoto Protocol (1997), the European F-gas regulation (2006 revised 2014) cause a shift toward refrigerants with both zero Ozone Depletion Potential (ODP) and low Global Warming Potential (GWP) (Kedzierski *et al.,* 2015). These new limitations lead to the progressive phase-out of HFC and to their replacement by the 4th generation of refrigerants based on HFO mixtures. Alternative refrigerants with low-GWP are under investigation for residential heat pumps and air-conditioners as R-410A has a GWP of 2088 (Amrane, 2015). The objective of this work is to test two promising alternative refrigerants to R-410A, DR-5A (R-454B) and L41-2 (R-447A) (Amrane, 2015, Amrane and Wang, 2015, De Bernardi, 2014, Leck *et al.*, 2014). The refrigerants were selected upon the result analysis of the AHRI Low-GWP Arep Program (Amrane, 2015, Amrane and Wang, 2015). In the first section of this paper the refrigerant properties are presented, then, the experimental procedure is described, and finally, the experimental results are reported and analyzed.

2. REFRIGERANTS PROPERTIES

Table 1 presents the principal properties of the refrigerants used in this study. The data source for these refrigerant properties is the software NIST REFPROP Version 9.1 (a new file HMX.BNC has been supplied by the refrigerant suppliers to evaluate the refrigerant properties).

Table 1: Refrigerant properties

Refrigerant	Composition	GWP_{100}	Critical point	Normal boiling point	Safety class
R-410A	R-32/R-125 (50/50%w)	2088	T_c = 70.2°C P_c = 47. 7 bar ρ_c = 552 kg.m^{-3}	-51.6 to -51.1°C	A1
L41-2 (R-447A)	R-32/R-1234ze(E)/R-125 (68/28.5/3.5%w)	583	T_c = 80.2°C P_c = 52.7 bar ρ_c = 425 kg.m^{-3}	-49.3 to -44.2°C	A2L
DR-5A (R-454B)	R-32/R-1234yf (68.9/31.1%w)	466	T_c = 76.5°C P_c = 51.2 bar ρ_c = 415 kg.m^{-3}	-49.9 to -50.9°C	A2L

The GWP of the alternative refrigerants are considerably lower than the GWP of R-410A. The GWP of L41-2 is 28% of that of R-410A and for DR-5A this number is 23%. Both alternative mixtures are mainly composed of R-32 (~ 68 - 69%w) and of an HFO (~30%w). The major difference between L41-2 and DR-5A lies in the HFO used in the mixtures: R-1234ze(E) for L41-2 and R-1234yf for DR-5A. Both alternative refrigerants have a A2L safety class, which means they have a low flammability and are non-toxic.

3. EXPERIMENTAL INVESTIGATION

To assess and to compare the heat pump performance when using R-410A, DR-5A and L41-2, drop-in tests were carried out on a 10 kW air-to-water reversible heat pump. The heat pump characteristics are summarized in Table 2.

Table 2: Heat pump description

Heating capacity at 7(6)°C-30/35°C	10 kW
Operation modes	Reversible (Four-way valve)
Type	packaged, non-ducted - outdoor installation
Compressor technology	Scroll – fixed capacity
Expansion device	Calibrated orifice (Not adjustable)
Initial R-410A charge	2.35 kg

For each refrigerant, the heat pump performance was assessed for 2 rating conditions and 2 operating limit conditions in cooling mode and for 6 rating conditions and 3 operating limit conditions in heating mode. The tests were carried out in the CETIAT climatic room, CLIM 1, according to EN 14511 standard. The test conditions in cooling mode and in heating mode are described in Table 3 and Table 4, respectively.

Table 3: Rating (C) and operating limit conditions (CL) in cooling mode

	Air temperature (°C)	**Inlet water temperature (°C)**	**Outlet water temperature (°C)**
C1	35	12	7
C2	35	23	18
CL1	18	*	5
CL2	42	*	25

* Inlet water temperature obtained with the C1 water flow.

Table 4: Rating (H) and operating limit conditions (HL) in heating mode

	Dry air temperature (wet bulb) (°C)	**Inlet water temperature (°C)**	**Outlet water temperature (°C)**
H1	7(6)	30	35
H2	7(6)	40	45
H3	7(6)	47	55
H4	-7(-8)	*	35
H5	2(1)	*	35
H6	12(11)	*	35
HL1	-15	*	22
HL2	-10	*	42.5
HL3	24 (20)	*	54.8

* Inlet water temperature obtained with the H1 water flow.

The operating limit conditions (in grey) were fixed by the heat pump manufacturer and they correspond to the boundary conditions of operation of the heat pump with R-410A.

In the first phase, the heat pump performance using R-410A was evaluated. Then, in phases 2 and 3, both alternative refrigerants, DR-5A and L41-2, were tested. For each, a refrigerant charge optimization was done, then the rating and operating limit condition tests were performed, and finally, a performance verification using R-410A was carried out to detect any anomaly after the use of one or the other alternative. During all the tests, measurements allowed the determination of thermal capacities, electric energy consumptions, efficiencies (EER or COP), as well as the pressures and discharge temperature on the refrigerant circuit. According to the uncertainty of measurement on the laboratory's instrumentation, capacities were determined with a maximal uncertainty of 5% and electric energy consumptions with a maximal uncertainty of 1%.

4. RESULTS

4.1 Heat pump performance evaluation with R-410A

Table 5 and Table 6 present the heat pump performance evaluation when using R-410A in cooling mode and in heating mode, respectively. These results are the baseline for all the performance comparisons of this study.

Table 5: Heat pump performance with R-410A in cooling mode

	Power input [kW]	Cooling capacity [kW]	EER [-]
C1	2.96	8.01	2.71
C2	3.00	8.80	2.93
CL1	2.46	9.30	3.78
CL2	3.50	8.87	2.53

Table 6: Heat pump performance with R-410A in heating mode

	Power input [kW]	Heating capacity [kW]	COP [-]
H1	2.60	10.10	3.88
H2	3.17	10.44	3.30
H3	3.73	9.95	2.67
H4	2.05	4.33	2.11
H5	2.05	6.21	3.03
H6	2.65	10.86	4.10
HL1	1.62	3.50	2.16
HL2	2.35	3.71	1.58
HL3	4.04	12.33	3.05

4.2 Alternative refrigerant charge optimization

To perform charge optimization, the initial alternative refrigerant charge loaded into the heat pump was about 1,65 kg (corresponding to 70% of the initial R-410A charge). Charge optimization was carried out at C1 rating condition (see Table 3). When refrigerant charge was added (~ + 50 g every 30 minutes), four parameters were followed: EER, cooling capacity, superheating and subcooling. The objective was to identify the performance curve inflexion point to determine the optimal charge. Particular attention was paid to the fact that superheating and subcooling have to be comprised between 4 and 7 K. The charge optimization results are reported in Table 7.

Table 7: Charge optimization results (at C1 rating condition)

	R-410A (baseline)	DR-5A	L41-2
Charge [kg]	2.35	2.00	1.86
Cooling capacity [kW]	8.01	8.25	7.44
Electrical power absorbed [kW]	2.96	2.78	2.63
EER [-]	2.71	2.97	2.83
Superheating [K]	9.4	4.1	6.4
Subcooling [K]	7.7	4.5	5.5

Both alternative refrigerant charges are lower than the R-410A charge: -15% for DR-5A and -21% for L41-2. These results are consistent with the literature (Amrane and Wang, 2015, De Bernardi, 2014, Leck *et al.*, 2014).

4.3 Heat pump performance evaluation using the alternative refrigerants

Figure 1 presents the results obtained in cooling mode as a ratio of performance (alternative refrigerant / R-410A).

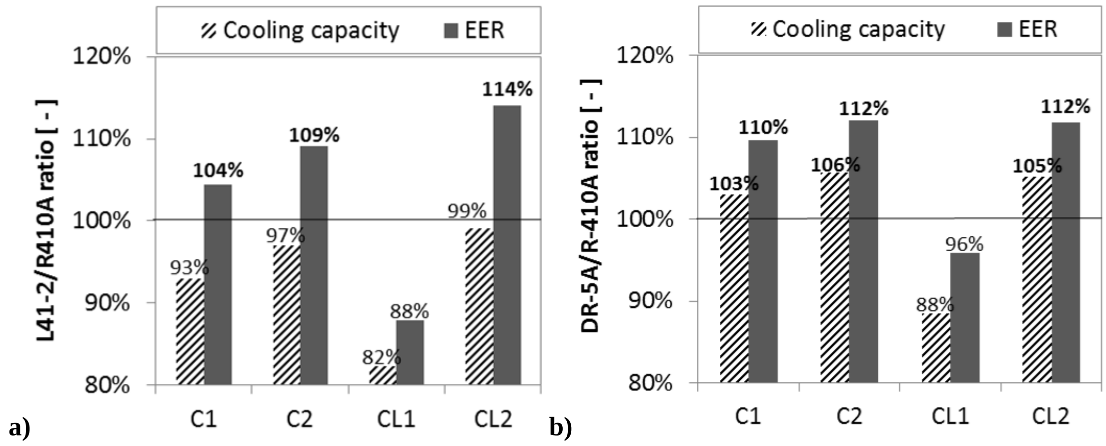

Figure 1: Heat pump performance using the alternative refrigerants in cooling mode: a) L41-2; b) DR-5A

For the operating conditions C1, C2 and CL2, greater performance is achieved with DR-5A than that with R-410A, from +3 to +6% for the cooling capacity and from +10 to +12 % for the EER. With L41-2, greater EER is obtained, from +4 to +14%, but cooling capacities are slightly lower, between -1% to -7%, compared to those with R-410A. For both alternative refrigerants, performance at the CL1 operating limit condition is lower than that with R-410A.

Figure 2 shows the discharge temperatures obtained by the refrigerants in cooling mode.

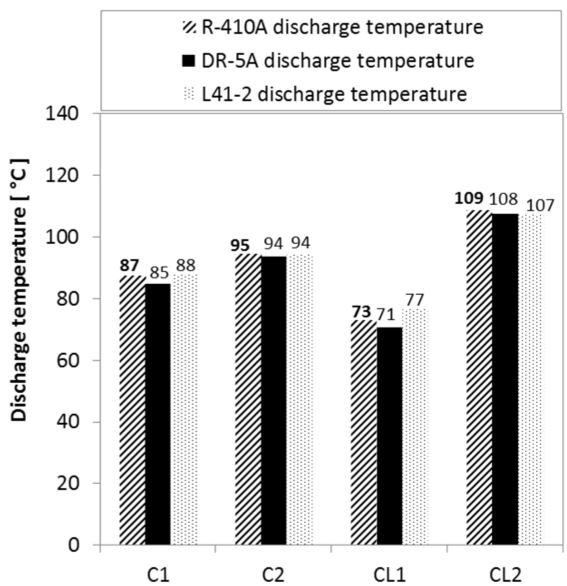

Figure 2: Discharge temperatures in cooling mode

The discharge temperatures observed for the three refrigerants are very close. According to these results, we can conclude that both alternatives might be used in drop-in for all cooling mode conditions tested in this work.

Figure 3 presents the results obtained in heating mode as a ratio of performance (alternative refrigerant / R-410A).

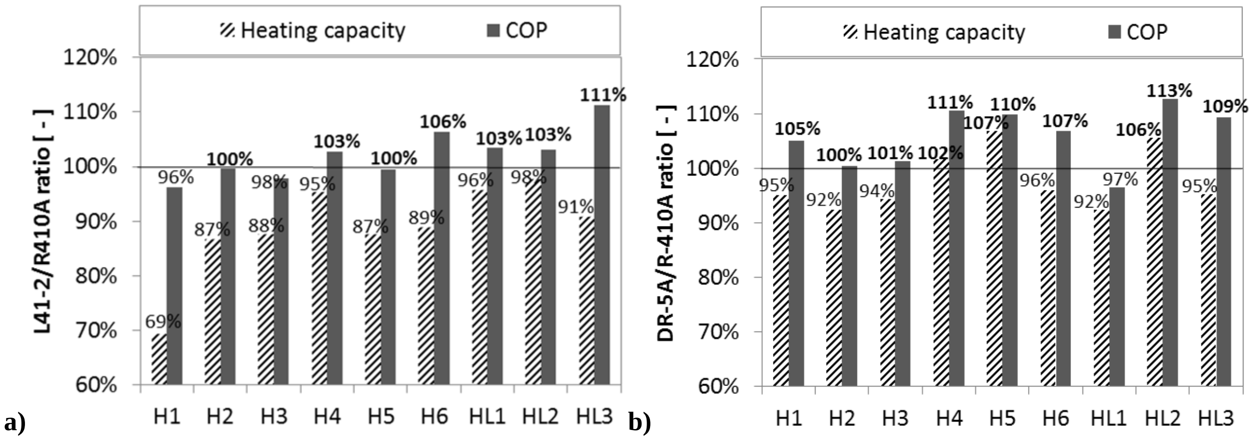

Figure 3: Heat pump performance using the alternative refrigerants in heating mode: a) L41-2; b) DR-5A

DR-5A allows an equivalent or greater COP to be reached than that with R-410A, between -3% and +13%. DR-5A heating capacities obtained are mainly lower than those with R-410A, from -8% to -3%, except for H4, H5 and HL2 conditions (from +2% to +7%). With L41-2, COP is also equivalent or greater than that with R-410A, from -4% to +11%. L41-2 heating capacities are lower than those with R-410A, from -31% to -2%. The heating capacity at H1 rating condition is significantly lower than that with R-410A because the heat pump has carried out defrosting cycles that did not occur during the tests with DR-5A and R-410A.

Figure 4 shows the discharge temperatures obtained by the refrigerants in heating mode.

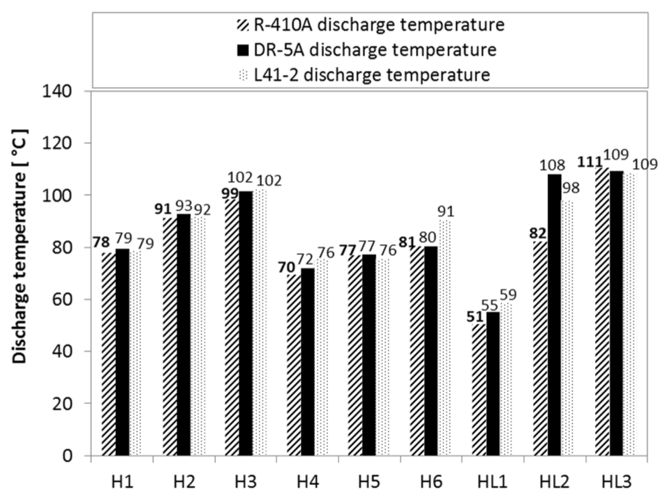

Figure 4: Discharge temperatures in heating mode

The discharge temperatures observed for the three refrigerants are quite close. Except for the L41-2 for H6 rating condition (+10°C) and for HL2 operating limit condition, where the discharge temperatures are +16°C and +26°C higher than that with R-410A, reaching 98 °C for L41-2 and 108°C for DR-5A. HL2 is a quite severe condition for cold climate and the alternatives might not be used in drop-in for it.

4.4. Heat pump performance verification

To make sure that the use of the alternative refrigerants did not damage the heat pump, tests with the initial R-410A charge (2.35 kg) were performed after each experimental series with the alternative refrigerants. It is important to note that this verification allowed determining the heat pump performance deviation but it does not give any answer concerning the long term use of the alternative refrigerants. The performance was checked on the C1 and H1 rating conditions. The results are reported in Table 8.

Table 8: Heat pump performance verifications

		Power input [kW] (*baseline gap %*)	**Cooling/ Heating capacity [kW] (*baseline gap %*)**	**EER/COP [-] (*baseline gap %*)**
C1	***Baseline R-410A***	***2.96***	***8.01***	***2.71***
	R-410A tests after using DR-5A	2.97 (*0%*)	7.94 (*-1%*)	2.67 (*-1%*)
	R-410A tests after using L41-2	3.02 (*+2%*)	8.31 (*+4%*)	2.76 (*+2%*)
H1	***Baseline R-410A***	***2.60***	***10.10***	***3.88***
	R-410A tests after using DR-5A	2.62 (*+1%*)	10.21 (*+1%*)	3.90 (*+1%*)
	R-410A tests after using L41-2	2.67 (*+2%*)	10.55 (*+5%*)	3.96 (*+2%*)

According to the results, we can conclude that there was no notable damage of the heat pump after the use of one or the other of the refrigerant alternatives as the performance gaps are quite small (from -1% to +5%) and within the uncertainty of measurement.

5. CONCLUSIONS

In this experimental study two refrigerants, DR-5A (R-454B) and L41-2 (R-447A), were tested in a 10 kW air-to-water heat pump in order to compare their performance, as drop-in low GWP alternatives to R-410A. R-410A replacement by L41-2 and DR-5A showed no particular problem and the performance obtained is, aside from some very few exceptions, almost equivalent (+/- 10%) to that with R-410A. Furthermore, in the operating limit conditions defined in the experimental plan, the heat pump worked normally with both alternative refrigerants. Thus, the heat pump operating map can be kept, excepted for the HL2 operating limit condition, because of the high discharge temperatures reached with both alternative refrigerants. In conclusion, this work has provided results for a better understanding and knowledge about R-410A replacement in heat pumps.

NOMENCLATURE

COP	Coefficient Of Performance	(-)
EER	Energy Efficiency Ratio	(-)
GWP	Global Warming Potential	(-)
ODP	Ozone Depletion Potential	(-)

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