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Experimental evaluation of R410A, R407C and R134a alternative refrigerants in residential heat pumps

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ABSTRACT

Alternative refrigerants with low-GWP are under investigation for residential heat pumps, air-conditioners and heat pump water heaters, since R410A, R407C and R134a have GWP of 2088, 1650 and 1430, respectively. In this study, five alternative refrigerants: R459A, R454B, R447A, HPR2A and R32 were investigated for the replacement of R410A in a 10 kW Air-to-Water (A/W) reversible heat pump. Two alternative refrigerants for R134a: R1234yf and R513A were tested in a split Heat Pump Water Heater (HPWH) having a water tank of 200 liters. R454C was evaluated as a possible alternative to R407C in a 3 kW Water-to-Air (W/A) reversible heat pump. A total of 8 alternative refrigerants with low-GWP were evaluated with not less than 114 performance tests. These experimental results will be useful for the HVAC community for facilitating the selection of the most promising candidates for drop-in replacement of R410A, R134a and R407C in residential 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, air-conditioners and heat pump water heaters, since R410A, R407C and R134a have GWP of 2088, 1650 and 1430, respectively. These investigations are numerical (Kedzierski *et al.*, 2015, Shen *et al.*, 2016) or experimental (Amrane and Wang, 2015, Wang and Amrane, 2016, Pardo *et al.*, 2016, Taira *et al.*, 2016).

The objective of this work is to assess and to compare the heat pump performance when drop-in tests are carried with:

- five alternative refrigerants to R410A in a 10 kW air-to-water reversible heat pump: R459A, R454B, R447A, HPR2A and R32, with GWP of 460, 466, 583, 600 and 675, respectively;
- one alternative to R407C in a 3 kW water-to-air reversible heat pump: R454C with a GWP of 148;
- two alternative refrigerants to R134a in a split Heat Pump Water Heater (HPWH) having a water tank of 200 liters: R1234yf and R513A with GWP of 4 and 631, respectively.

The choice of the alternative refrigerants is based on the result analysis of the AHRI Low-GWP AREP Program (Amrane, 2015, Amrane and Wang, 2015, Wang and Amrane, 2016).

The paper is divided in three parts:

- experimental evaluation of R410A alternative refrigerants in an air-to-water reversible heat pump;
- experimental evaluation of R407C alternative refrigerant in a water-to-air reversible heat pump;
- experimental evaluation of R134a alternative refrigerants in a split water heater heat pump.

For each part, the refrigerant properties are presented, then the experimental procedure is described, and finally the experimental results are reported and analyzed.

2. EXPERIMENTAL EVALUATION OF R410A ALTERNATIVE REFRIGERANTS IN AN AIR-TO-WATER REVERSIBLE HEAT PUMP

2.1 Properties of alternative refrigerants to R410A

Table 1 presents the main properties of the refrigerants studied to replace R410A. The data source is the software NIST REFPROP Version 9.1.

Table 1: Refrigerant properties

Refrigerant	Composition	GWP_{100}	Critical temperature (°C)	Normal boiling point (°C)	Glide (K)	Safety class
R410A	R32/R125 (50/50%w)	2088	70.2	-51.6	0.1	A1
R32	R32 (100%w)	675	78.0	-52.0	0	A2L
HPR2A	R32/R134a/R1234ze (76/6/18%w)	600	82.0	-50.7	4.1	A2L
R447A	R32/R1234ze(E)/R125 (68/28.5/3.5%w)	583	80.2	-47.6	5.1	A2L
R454B	R32/R1234yf (68.9/31.1%w)	466	78.1	-50.4	1.3	A2L
R459A	R32/R1234yf/R1234ze (68/26/6%w)	460	76.5	-49.5	1.9	A2L

Alternative refrigerants have a lower GWP than R410A, between -67% and -78%. With the exception of R32, which is a pure refrigerant, the other alternatives are mixtures and mainly composed of R32 (~70%w) and of a HFO (~30%w), R1234ze(E) or R1234yf. The safety class of alternative refrigerants is A2L, which means they have a low flammability and are non-toxic. All alternative mixtures have a glide.

2.2 Experimental investigation

Drop-in tests were carried out to assess the heat pump performance. The heating capacity of the tested air-to-water heat pump is close to 10 kW at H1 rating condition. It is a reversible, packaged and non-ducted appliance. The heat pump is equipped with a fixed capacity scroll compressor and a calibrated orifice as expansion device. The initial charge of R410A is 2.35 kg.

The test conditions in cooling mode and in heating mode are described in Table 2 and Table 3, respectively. For each refrigerant, a charge optimization was done at the C1 rating condition, then the rating and operating limit condition tests were performed, and finally, performance verification with R410A was carried out on C1 and H1 rating conditions to detect any anomaly after the use of the alternatives. The tests were carried out in one of CETIAT climatic rooms according to EN 14511 standard. During tests, measurements allowed the determination of thermal capacities, electric energy consumptions, efficiencies (EER or COP), as well as pressures and temperatures 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%.

Table 2: 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 rate.

Table 3: 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 rate.

The operating limit conditions were fixed by the heat pump manufacturer: they correspond to the boundary conditions of operation of the heat pump with R410A. During the test, the discharge temperature was limited to 115°C to avoid any damage to the compressor.

2.3 Results of the experimental evaluation of R410A alternative refrigerants

2.3.1 Charge optimization

To perform the charge optimization, the initial alternative refrigerant charge was about 1,65 kg (corresponding to 70% of the initial R410A charge). At C1 rating condition (see Table 2), refrigerant was added (+50 g every 30 minutes) while four parameters were monitored: 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 optimal charges obtained are reported in Table 4.

Table 4: Charge optimization results (at C1 rating condition)

Refrigerant	R410A (base)	R32	R454B	R459A	HPR2A	R447A
Charge (kg)	2.35	1.52 *(-35.1%)*	2.00 *(-14.9%)*	1.96 *(-16.5%)*	1.80 *(-23.4%)*	1.86 *(-20.8%)*
Cooling capacity (kW)	8.01	8.63 *(+7.7%)*	8.25 *(+3.0%)*	7.93 *(-1.0%)*	7.75 *(-3.2%)*	7.44 *(-7.1%)*
EER (-)	2.71	2.83 *(+4.4%)*	2.97 *(+9.6%)*	2.90 *(+7.1%)*	2.90 *(+7.0%)*	2.83 *(+4.4%)*
Superheating (K)	9.40	8.10 *(-1.3 K)*	4.10 *(-5.3 K)*	4.30 *(-5.1 K)*	4.30 *(-5.1 K)*	4.10 *(-5.3 K)*
Subcooling (K)	6.10	1.20 *(-4.9 K)*	4.50 *(-1.5 K)*	5.60 *(-0.5 K)*	2.00 *(-4.1 K)*	3.70 *(-2.4 K)*

Alternative refrigerant charges are lower (-35% to -15%) than with R410A. These results are consistent with the literature (Amrane and Wang, 2015; De Bernardi, 2014; Leck *et al.*, 2014; Pardo *et al.*, 2016).

2.3.2 Cooling mode

Figure 1 presents the results obtained in cooling mode: ratios of performance (alternative/R410A) and discharge temperature. Table 5 and Table 6 provide values for the heat pump cooling capacity and EER, respectively.

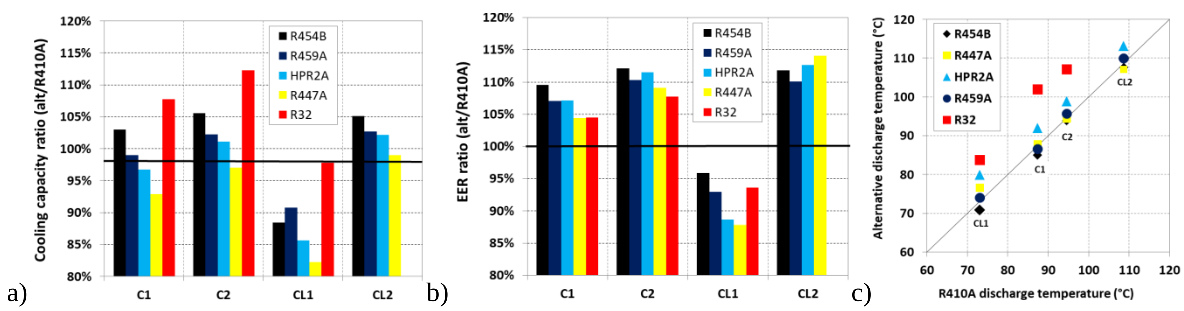

Figure 1: Heat pump performance in cooling mode: a) Capacity ratio; b) EER ratio; c) Discharge temperature

Table 5: Cooling capacity (green color highlights best performance)

Cooling capacity (kW) Ratio (alternative/base)	R410A (base)	R32	R454B	R459A	HPR2A	R447A
C1 (A35/W12-7)	8.01	**8.63 *(107.7%)***	8.25 *(103.0%)*	7.93 *(99.0%)*	7.75 *(96.7%)*	7.44 *(92.9%)*
C2 (A35/W23-18)	8.80	**9.88 *(112.3%)***	9.29 *(105.5%)*	9.00 *(102.3%)*	8.90 *(101.1%)*	8.54 *(97.0%)*
CL1 (A18/W*-5)	**9.30**	9.09 *(97.8%)*	8.22 *(88.4%)*	8.44 *(90.7%)*	7.97 *(85.7%)*	7.65 *(82.3%)*
CL2 (A42/W*-25)	8.87	Discharge T > 115°C	**9.32 *(105.1%)***	9.11 *(102.7%)*	9.06 *(102.1%)*	8.78 *(99.0%)*

Table 6: EER (green color highlights best performance)

EER (-) Ratio (alternative/base)	R410A (base)	R32	R454B	R459A	HPR2A	R447A
C1 (A35/W12-7)	2.71	2.83 *(104.5%)*	**2.97 *(109.6%)***	2.90 *(107.1%)*	2.90 *(107.2%)*	2.83 *(104.4%)*
C2 (A35/W23-18)	2.93	3.16 *(107.8%)*	**3.29 *(112.1%)***	3.24 *(110.3%)*	3.27 *(111.5%)*	3.20 *(109.1%)*
CL1 (A18/W*-5)	**3.78**	3.54 *(93.6%)*	3.62 *(95.9%)*	3.51 *(93.0%)*	3.35 *(88.7%)*	3.32 *(87.8%)*
CL2 (A42/W*-25)	2.53	Discharge T > 115°C	2.83 *(111.9%)*	2.79 *(110.1%)*	2.85 *(112.7%)*	**2.89 *(114.1%)***

With the exception of the CL1 limit condition, the alternative refrigerants show higher performance than R410A. The cooling capacities at C1, C2 and CL2 conditions are increased with R454B (+3% to +5.5%), equivalent or even higher with R459A (-1% to +2.7%), equivalent and lower with HPR2A (-3.3% to +2.1%) and lower with R447A (-7.1% to -1%). R32 leads to higher capacities (+7.7% to +12.3%) than R410A at C1 and C2 conditions.

All refrigerants show cooling capacities lower than those with R410A at CL1 limit condition, from -17.7% with R447A to -2.2% with R32. EER are better with alternative refrigerants at conditions C1, C2 and CL2 (+4.4% to + 14.1%). For CL1 limit condition, all refrigerants give lower EER (-12.2% to -4.1%) than R410A. With the exception of CL1, alternative refrigerants achieve equivalent or even better performance than R410A.

The discharge temperatures observed for alternative refrigerants (except R32) in cooling mode are close to those with R410A. R32 did not allow performing CL2 limit condition test because the discharge temperature was higher than 115°C. To reach a temperature below 115°C, the outlet water temperature was set to 14°C.

2.3.3 Heating mode

Figure 2 presents the results obtained in heating mode: ratios of performance (alternative/R410A) and discharge temperature. Table 7 and Table 8 give values of the heat pump heating capacity and COP, respectively.

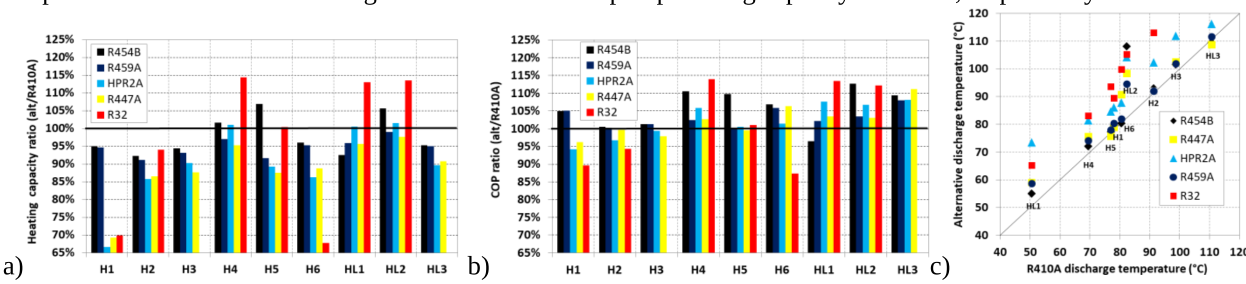

Figure 2: Heat pump performance in heating mode: a) Capacity ratio; b) COP ratio; c) Discharge temperature

Table 7: Heating capacity (green color highlights best performance)

Heating capacity (kW) (ratio alternative/base)	R410A (base)	R32	R454B	R459A	HPR2A	R447A
H1 (A7(6)/W30-35)	**10.10**	7.06 *(69.9%)*	9.60 *(95.0%)*	9.55 *(94.6%)*	6.73 *(66.6%)*	6.99 *(69.2%)*
H2 (A7(6)/W40-45)	**10.44**	9.81 *(94.0%)*	9.63 *(92.3%)*	9.51 *(91.1%)*	8.94 *(85.7%)*	9.03 *(86.5%)*
H3 (A7(6)/W47-55)	**9.95**	Discharge T > 115°C	9.38 *(94.3%)*	9.26 *(93.1%)*	8.98 *(90.2%)*	8.71 *(87.6%)*
H4 (A-7(-8)/W*-35)	4.33	**4.95 *(114.4%)***	4.40 *(101.7%)*	4.20 *(97.0%)*	4.37 *(101.1%)*	4.12 *(95.3%)*
H5 (A2(1)/W*-35)	6.21	6.23 *(100.4%)*	**6.63 *(106.8%)***	5.68 *(91.6%)*	5.54 *(89.3%)*	5.43 *(87.5%)*
H6 (A12(11)/W*-35)	**10.86**	7.36 *(67.7%)*	10.43 *(96.0%)*	10.34 *(95.2%)*	9.37 *(86.3%)*	9.64 *(88.7%)*
HL1 (A-15/W*-22)	3.50	**3.95 *(113.0%)***	3.23 *(92.5%)*	3.35 *(95.9%)*	3.52 *(100.6%)*	3.34 *(95.6%)*
HL2 (A-10/W*-42,5)	3.71	**4.21 *(113.6%)***	3.91 *(105.6%)*	3.67 *(99.1%)*	3.76 *(101.5%)*	3.62 *(97.6%)*
HL3 (A24(20)/W*-54,8)	**12.33**	Discharge T > 115°C	11.75 *(95.3%)*	11.71 *(95.0%)*	11.06 *(89.7%)*	11.18 *(90.7%)*

Table 8: COP (green color highlights best performance)

COP (-) (ratio alternative/base)	R410A (base)	R32	R454B	R459A	HPR2A	R447A
H1 (A7(6)/W30-35)	3.88	3.47 *(89.6%)*	4.07 *(104.9%)*	**4.07 *(105.1%)***	3.65 *(94.2%)*	3.73 *(96.2%)*
H2 (A7(6)/W40-45)	3.30	3.11 *(94.3%)*	**3.31 *(100.5%)***	3.30 *(100.2%)*	3.19 *(96.8%)*	3.28 *(99.7%)*
H3 (A7(6)/W47-55)	2.67	Discharge T > 115°C	**2.70 *(101.3%)***	2.70 *(101.2%)*	2.65 *(99.3%)*	2.61 *(97.9%)*
H4 (A-7(-8)/W*-35)	2.11	**2.40 *(113.9%)***	2.33 *(110.5%)*	2.16 *(102.5%)*	2.23 *(105.8%)*	2.16 *(102.7%)*
H5 (A2(1)/W*-35)	3.03	3.06 *(101.1%)*	**3.32 *(109.8%)***	3.03 *(100.2%)*	3.04 *(100.5%)*	3.01 *(99.5%)*
H6 (A12(11)/W*-35)	4.10	3.58 *(87.3%)*	**4.38 *(106.8%)***	4.34 *(105.9%)*	4.16 *(101.4%)*	4.36 *(106.3%)*
HL1 (A-15/W*-22)	2.16	**2.45 *(113.5%)***	2.09 *(96.5%)*	2.21 *(102.1%)*	2.32 *(107.6%)*	2.24 *(103.5%)*
HL2 (A-10/W*-42,5)	1.58	1.77 *(112.2%)*	**1.78 *(112.7%)***	1.63 *(103.5%)*	1.68 *(106.7%)*	1.63 *(103.1%)*
HL3 (A24(20)/W*-54,8)	3.05	Discharge T > 115°C	3.33 *(109.4%)*	3.29 *(108.0%)*	3.30 *(108.1%)*	**3.39 *(111.2%)***

With the exception of H4, H5, HL1 and HL2 conditions, the alternative refrigerants lead to lower heating capacities than with R410A. COPs are equivalent or greater for all the conditions. The heating capacity at H1 rating condition (figure 2 a)) is significantly reduced with R447A, HPR2A and R32 because the heat pump has carried out defrosting cycles that did not occur during the tests with R454B, R459A and R410A.

R454B and R459A lead to heating capacities lower or equivalent than R410A, from -7.5% to +6.8% and from -8.9% to -1.1% respectively. Heating capacities with HPR2A are lower or equivalent to those with R410A (-33.4% to +1.3%). R447A shows lower heating capacities than R410A (-30.8% to -2.4%). R459A achieves equal or greater COPs than R410A (+0.2% to +8%).

All COPs with R454B are equivalent or greater than with R410A (+0.5% to +12.7%), with the exception of the HL1 limit condition where it is lower (-3.5%), HPR2A obtains COPs equal or greater than R410A (-0.7% to +8.9%) for H3 to HL2 conditions and lower for H1 and H2 conditions (-5.8% and -3.2%). R447A shows lower or equivalent COPs than R410A for the conditions between H1 and H3 (-3.8% to -0.3%) and higher or equivalent for the conditions H4 to HL2 (-0.5% to +11.2%). Capacities and COPs obtained with R32 for negative air temperatures are significantly greater than those with R410A, between +0.4% to +14.4% and +1.1% to +13.9%, respectively. For these conditions (H4, HL1, HL2), R32 show the best performances.

There is an important dispersal of the discharge temperatures, but with the exception of R32, the four alternatives get discharge temperatures close to those of R410A. They might be used in drop-in for all heating conditions tested in this study. R32 did not allow performing H3 rating condition and HL3 limit conditions, because the discharge temperature was higher than 115°C. To reach a discharge temperature below 115°C, the outlet water temperatures were set to 48°C for H3 and 43°C for HL3.

2.3.4 Performance verification

To make sure that the use of the alternative refrigerants did not damage the heat pump, tests with the initial R410A charge (2.35 kg) were performed after each series of tests with the alternative refrigerants. 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 gaps obtained are quite small (from -1% to +5%) and within the uncertainty of measurement. According to the results, we can conclude that there was no notable damage of the heat pump after the use of the refrigerant alternatives.

With the exception of R32, the alternative refrigerants might be considered as drop-in alternatives to R410A for both modes and all the conditions tested in this study. R454B and R459A showed the best performances. R32 could be used in drop-in, but the heat pump operating map should be decreased because of high discharge temperatures, especially when condensation occurs at high temperatures.

3. EXPERIMENTAL EVALUATION OF R407C ALTERNATIVE REFRIGERANT IN A WATER-TO-AIR REVERSIBLE HEAT PUMP

3.1 Properties of alternative refrigerant to R407C

Table 9 presents the main properties of the refrigerant studied to replace R407C. The data source is the software NIST REFPROP Version 9.1.

Table 9: Refrigerant properties

Refrigerant	Composition	GWP_{100}	Critical temperature (°C)	Normal boiling point (°C)	Glide (K)	Safety class
R407C	R32/R125/R134a (23/25/52%w)	1650	86.1	-40.1	7.0	A1
R454C	R1234yf/R32 (78.5/21.5%w)	148	82.4	-42.4	8.5	A2L

The GWP of R454C is significantly lower than that of R407C (-91%) and it is below the most compelling GWP limit (150) of the European F-Gas regulation. R454C has an A2L safety class, which means it has a low flammability and is non-toxic. R454C has a glide slightly higher than R407C.

3.2. Experimental investigation

Drop-in tests were carried out to assess the heat pump performance. The heating capacity of the tested water-to-air heat pump is close to 2.9 kW at H1 rating condition. It is a reversible, packaged and ducted appliance. The heat pump is equipped with a fixed capacity hermetic rotary compressor and a capillary tube as expansion device. The initial charge of R407C is 0.64 kg.

The test conditions in cooling mode and in heating mode are given in Table 10 and Table 11, respectively. For both refrigerants, a charge optimization was done at the CL2 limit condition, then the rating and operating limit condition tests were performed, and finally performance verification with R407C was carried out on the C1 rating condition to detect any anomaly. The tests were carried out in one of CETIAT climatic rooms, according to EN 14511 standard. During tests, measurements allowed the determination of thermal capacities, electric energy consumptions, efficiencies (EER or COP), as well as pressures and temperatures 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%.

Table 10: Rating (C) and operating limit conditions (CL) in cooling mode

	Inlet water temperature (°C)	Outlet water temperature (°C)	Water flow rate (l/h)	Air temperature (°C)	Air flow rate (m^3/h) (at 1013 mbar and 20°C)
C1	30	35	-	27(19)	475
C2	22	*	485	22(15)	450
CL1	41	*	250	37(27.7)	500
CL2	42	*	250	22(15)	500

Table 11: Rating (H) and operating limit conditions (HL) in heating mode

	Inlet water temperature (°C)	Outlet water temperature (°C)	Water flow rate (l/h)	Air temperature (°C)	Air flow rate (m^3/h) (at 1013 mbar and 20°C)
H1	20	17	-	20(15)	475
H2	12	*	250	12(7.2)	500
HL1	36	*	250	27(19.5)	450
HL2	36	*	485	27(19.5)	450

The operating limit conditions) were fixed by the heat pump manufacturer: they correspond to the boundary conditions of operation of the heat pump with R407C.

3.3 Results of the experimental evaluation of R407C alternative refrigerant

3.3.1 Charge optimization

To perform the charge optimization, the initial alternative refrigerant charge was about 0.416 kg (corresponding to 65% of the initial R407C charge). At CL2 limit condition (see Table 10), refrigerant was added (+25g every 30 minutes) while four parameters were monitored: EER, cooling capacity, superheating and subcooling. The objective was to determine the optimal charge for a superheating close to 2 K. The optimal charges obtained for both refrigerants are reported in Table 12.

Table 12: Charge optimization results (at CL2 limit condition)

Refrigerant	R407C (base)	R454C
Charge (kg)	0.64	0.64 *(0%)*
Cooling capacity (kW)	1.75	1.88 *(+7.1%)*
EER (-)	2.46	2.44 *(-0.6%)*
Superheating (K)	3.20	4.80 *(+1.6 K)*
Subcooling (K)	6.80	13.90 *(+7.1 K)*

R454C and R407C have the same optimal charge: 0.64 kg. R454B shows a greater cooling capacity and a lower EER than R407C. These results are consistent with the literature (Wang and Amrane, 2016).

3.3.2 Cooling mode

Figure 3 presents the results obtained in cooling mode: ratios of performance (alternative/R407C) and the discharge temperature. Table 13 provides values for the heat pump cooling capacity and EER.

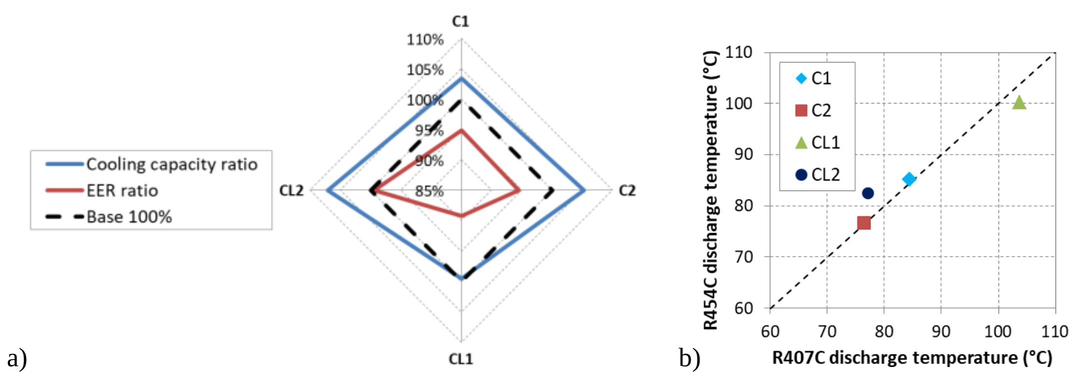

Figure 3: Heat pump performance in cooling mode: a) Capacity ratio and EER ratio; b) Discharge temperature

Table 13: Cooling capacity (green color highlights best performance)

	Cooling capacity (kW) (ratio alternative/base)		EER (-) (ratio alternative/base)	
	R407C (base)	**R454B**	**R407C (base)**	**R454B**
C1 (W30-35/A27(19))	2.13	**2.20 *(103.4%)***	**3.75**	3.55 *(94.8%)*
C2 (W22-*/A22(15))	1.96	**2.07 *(105.2%)***	**4.09**	3.87 *(94.5%)*
CL1 (W41-*/A37(27.7))	**2.74**	2.72 *(99.5%)*	**3.39**	3.03 *(89.3%)*
CL2 (W42-*/A22(15))	1.75	**1.88 *(107.1%)***	**2.46**	2.44 *(99.4%)*

Heating capacities with R454B are equivalent or greater (-0.5% to +7.1%) and COPs lower or equivalent (-5% to -0.6%) than those with R407C. The discharge temperatures observed with both refrigerants are close.

3.3.2 Heating mode
Figure 4 presents the results obtained in heating mode: ratios of performance (alternative/R407C) and discharge temperature. Table 14 provides values for heat pump heating capacity and COP.

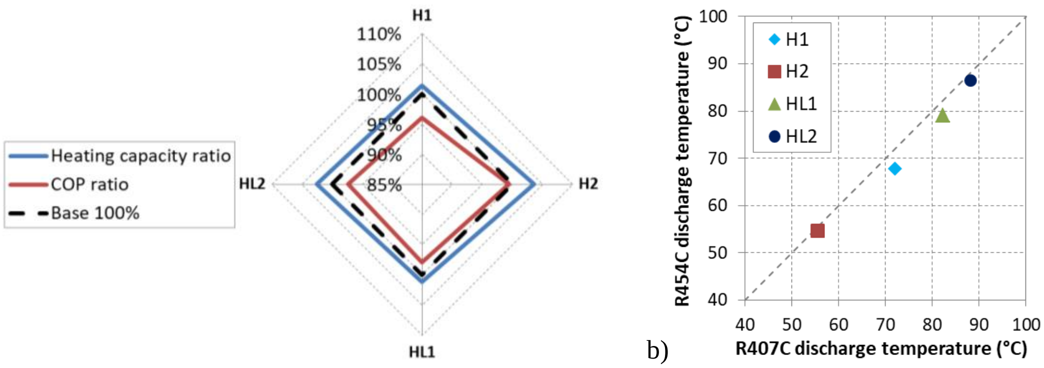

Figure 4: Heat pump performance in heating mode: a) Capacity ratio and COP ratio; b) Discharge temperature

Table 14: Heating capacity (green color highlights best performance)

	Heating capacity (kW) (ratio alternative/base)		COP (-) (ratio alternative/base)	
	R407C (base)	**R454B**	**R407C (base)**	**R454B**
H1 (W20-17/A20(15))	2.91	**2.95 *(101.4%)***	**4.52**	4.34 *(96.0%)*
H2 (W12-*/A12(7.2))	2.32	**2.41 *(103.6%)***	**4.41**	4.38 *(99.4%)*
HL1 (W36-*/A27(19.5))	3.23	**3.27 *(101.2%)***	**3.95**	3.87 *(97.9%)*
HL2 (W36-*/A27(19.5))	3.46	**3.55 *(102.6%)***	**4.08**	3.97 *(97.3%)*

Heating capacities with R454B are greater (+1.2% to +3.6%) and COPs lower or equivalent (-4.0% to -0.6%) than those with R407C. The discharge temperatures observed with both refrigerants are close.

3.3.4 Performance verification
To make sure that the use of R454C did not damage the heat pump, tests with the initial R407C charge (0.64 kg) were performed. The performance was checked at C1 rating condition. The performance gaps obtained for the cooling capacity and the EER are quite small, +2.5% and +2.7 %, respectively, and within the uncertainty of measurement. According to the results, we can conclude that there was no notable damage of the heat pump after the use of R454C.

We finally can conclude that the R454C might be considered as drop-in alternatives to R407C without significant capacity reduction.

4. EXPERIMENTAL EVALUATION OF R134a ALTERNATIVE REFRIGERANT IN A SPLIT HEAT PUMP WATER HEATER

4.1 Properties of alternative refrigerants to R134a

Table 15 presents the main properties of the refrigerants studied to replace R134a. The data source is the software NIST REFPROP Version 9.1.

Table 15: Refrigerant properties

Refrigerant	Composition	GWP_{100}	Critical temperature (°C)	Normal boiling point (°C)	Glide (K)	Safety class
R134a	R134a (100%w)	1430	101.1	-26.1	0	A1
R513A	R1234yf/R134a (56/44%w)	631	96.5	-29.2	0	A1
R1234yf	R1234yf (100%w)	4	94.7	-29.4	0	A2L

The GWP of R513A is lower than that with R134a. R513A has an A1 safety class, which means it is non-flammable and non-toxic. The GWP of R1234yf is significantly lower than that with R134a and it is below the most compelling GWP limit (150) of the European F-Gas regulation. R1234yf has an A2L safety class, which means it has a low flammability and is non-toxic. Both alternative mixtures have no glide.

4.2. Experimental investigation

Drop-in test were carried out to assess the heat pump water heater (HPWH) performance. The HPWH in test is a split system having a water tank of 200 l. It is equipped with a fixed capacity hermetic rotary compressor and an electronic expansion device. The initial charge of R134a is 1.6 kg.

The tests consisted in a heating up of the water in the tank. When the desired temperature was reached (measured at the top of the tank by a Pt100 sensor), a hot water tapping of 10 liters/min was performed to determine the energy content until the tapped water reached the initial water temperature. During all tests, measurements allowed the determination of electric power inputs, refrigerant pressures and temperatures, water tank temperature and energy of the hot water tapping. For each refrigerant, a charge optimization was done, and then heating up of the tank was performed for three outdoor air temperatures. Finally performance verification with R134a was carried out to detect any anomaly. Refrigerants are compared based on the heating up time, the COP (water energy content/ electric energy consumption) and the maximal discharge temperature. The tests were carried out in one of CETIAT climatic rooms. 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%. The test conditions in charge optimization and in performance evaluation are described in Table 16 and Table 17, respectively.

Table 16: Test conditions for charge optimization

PHASE 1: Heating up				PHASE 2: Water tapping		
Outdoor air dry bulb (wet bulb) temperatures (°C)	Ambient air dry bulb temperature around the tank (°C)	Initial water tank temperature (°C)	Heating up of the tank	Water tapping flow rate (l/min)	Inlet water temperature (°C)	Stopping temperature of water tapping (°C)
7(6)	20	15	From 15°C to 45°C	10	14	15

Table 17: Test conditions for performance evaluation

PHASE 1: Heating up				PHASE 2: Water tapping		
Outdoor air dry bulb (wet bulb) temperatures (°C)	Ambient air dry bulb temperature around the tank (°C)	Initial water tank temperature (°C)	Heating up of the tank	Water tapping flow rate (l/min)	Inlet water temperature (°C)	Stopping temperature of water tapping (°C)
2(1) 7(6) 35	20	10	From 10°C to 60°C	10	10	10

4.3 Results of the experimental evaluation of R134a alternative refrigerants

4.3.1 Charge optimization

To perform the charge optimization, the initial alternative refrigerant charge was about 1.12 kg (corresponding to 70% of the initial R134a charge). Charge optimization was carried out at the conditions presented in Table 16. When refrigerant charge was added (+80 g), a new heating up of the tank was done to determine the electricity consumption, the energy content in the water tank and pressures and temperatures of the refrigerant circuit. The objective was to identify the performance curve inflexion point to determine the optimal charge. The optimal charges obtained are reported in Table 18.

Table 18: Charge optimization results (Heating up from 15°C to 45°C)

Refrigerant	**R134a (base)**	**R513A**	**R1234yf**
Charge (kg)	1.60	1.60 *(0%)*	1.68 (+5%)
Heating up time (hh:mm:ss)	03:35:31	03:29:13 *(- 6 min 13 s)*	03:36:19 *(+ 48s)*
COP (-)	3.79	3.79 *(0%)*	3.79 *(0%)*

R513A and R1234yf show optimal charge close to R134a and equivalent performances to R134a.

4.3.2 Heating up performance evaluation

Figure 5 presents the results obtained during the heating up of the water tank for three outdoor air temperatures. Table 19 provides the values for various parameters.

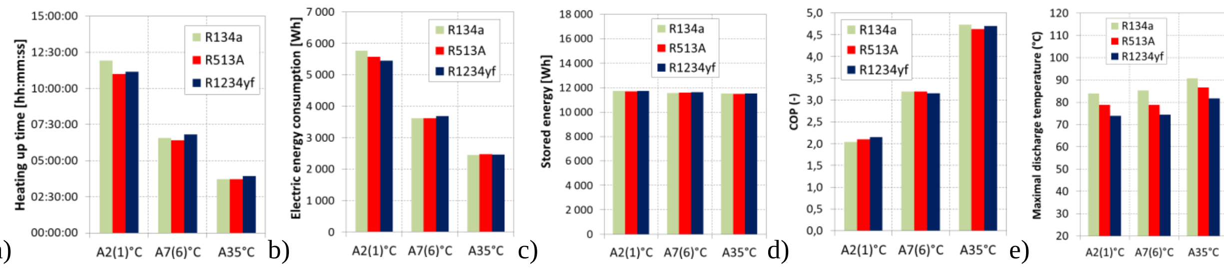

Figure 5: Heating up performance evaluation: a) Heating up time; b) Electric energy consumption; c) Water energy content; d) COP; e) Maximal discharge temperature

Table 19: Heating up performance evaluation (green color highlights best performance)

Dry air temperature (wet bulb) (°C)	**2(1)**			**7(6)**			**35**		
Refrigerant	**R134a (base)**	**R513A**	**R1234yf**	**R134a (base)**	**R513A**	**R1234yf**	**R134a (base)**	**R513A**	**R1234yf**
Heating up time (hh:mm:ss)	11:55:03	**10:59:30 *(-56min)***	11:08:24 *(-47min)*	06:35:03	**06:23:59 *(-11min)***	06:49:34 *(+14min)*	**03:42:55**	03:42:58 *(=)*	03:55:24 *(+12min)*
Electric energy consumption (Wh)	5 760	5 568 *(-3.4%)*	**5 446 *(-5.5%)***	3 618	3 622 *(+0.1%)*	3 685 *(+1.8%)*	2 441	2 478 *(+1.5%)*	2453 *(+0.5%)*
Stored energy (Wh)	11 718	11 704 *(-0.1%)*	11 732 *(+0.1%)*	11 563	11 577 *(+0.1%)*	11 623 *(+0.5%)*	11 538	11 484 *(-0.5%)*	11525 *(-0.1%)*
COP (-)	2,0	2,1 *(+3.3%)*	**2,2 *(+5.9%)***	**3,2**	**3,2 *(=)***	3,2 *(-1.3%)*	**4,7**	4,6 *(-2.0%)*	4,7 *(-0.6%)*
Maximal discharge temperature (°C)	83,9	78,9 *(-5.0 K)*	73,9 *(-10.0 K)*	85,3	78,9 *(-6.5 K)*	74,4 *(-10.9 K)*	90,8	86,7 *(-4.2 K)*	81,7 *(-9.1 K)*

R513A and R1234yf show equivalent performances (heating up time, COP, electric energy consumption) to those of R134a. The discharge temperatures reached with alternatives are lower than with R134a (-10K for R1234yf and -5 K for R513A). At 2(1)°C with both alternatives, the heating up times are lower than with R134a.

4.3.3 Performance verification

To make sure that the use of alternative refrigerants did not damage the HPWH, a heating up with the initial R134a charge (1.6 kg) was performed. The performance gaps obtained for heating up time and electric energy consumption are quite small, +7 min 21 s and +1.5%, respectively, and within the uncertainty of measurement. We can conclude that there was no notable damage of the heat pump after the use both alternative refrigerants. According to these results, R513A and R1234yf might be considered as drop-in alternatives to R134a without performance impact.

5. CONCLUSIONS

In this experimental study, a total of 8 low-GWP alternative refrigerants were evaluated with not less than 114 performance tests. The principal results of the study are summarized below.

R459A, R454B, R447A, HPR2A and R32 were investigated for the drop-in replacement of R410A in a 10 kW air-to-water reversible heat pump. R410A replacement by HFC/HFO mixtures showed no particular problem and the performance obtained is, aside from some very few exceptions, almost equivalent (+/- 10%) to that with R410A. Furthermore, in operating limit conditions, the heat pump worked normally with alternative refrigerants HFC/HFO mixtures. R32 could be used in drop-in, but the operating map of the heat pump would be decreased because of the high discharge temperatures reached. R454B and R459A showed the best performances.

R454C was evaluated as a possible alternative to R407C in a 3 kW water-to-air reversible heat pump. R454C obtained equivalent or greater capacities (-0.5% to +7.1%) and lower or equivalent COP (-5% to -0.6%) than R407C. It might be considered as a drop-in alternative to R407C.

R1234yf and R513A were tested for the replacement of R134a in a split heat pump water heater having a water tank of 200 liters. They showed equivalent performances to R134a. The discharge temperatures reached with alternatives are lower than those with R134a, of -10 K for R1234yf and -5 K for R513A. R513A and R1234yf might be considered as drop-in alternatives to R134a without significant performance impact.

These experimental results will be useful to the HVAC community for selecting the most promising refrigerant candidates for drop-in replacement of R410A, R134a and R407C. Beyond drop-in, improving the thermal performances of the heat pumps would require component optimization. For example, it would be necessary to re-size and to replace the expansion valve, especially when a calibrated orifice or a capillary tube is used, or to optimize the design of the heat exchanger(s).

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