R-407H as drop-in of R-404A. Experimental analysis in a low temperature direct expansion commercial refrigeration system

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ABSTRACT

This work analyses experimentally the possibility of using the reduced GWP refrigerant R-407H (HFC family, GWP=1378) as drop-in substitute of R-404A (HFC family, GWP=3945) in low temperature centralized direct expansion refrigeration system. The experimental plant and the test methodology are described. It covered top up or partial drop-in and energy consumption tests at -20ºC of product temperature and 25, 35 and 45ºC of condensing temperature using a small-scale supermarket under laboratory conditions. It has been measured that the use of R-407H instead of R-404A is favourable from the point of view of energy efficiency. Reductions in the energy consumption up to 7.7% (compressor) and 4.0% (whole system) have been measured. However, there is an increment in the compressor's discharge temperature up to 13.8K. In addition, the operation of the system with both refrigerants was correct.

KEYWORDS

R-404A; R-407H ; F-Gas, commercial refrigeration; energy analysis; drop-in

NOMENCLATURE

COP	coefficient of performance
E	energy consumption, kWh
GWP	Global warming potential, 100 years horizon
h	specific enthalpy, $kJ \cdot kg^{-1}$
h_{fg}	latent heat of phase-change, $kJ \cdot kg^{-1}$
HC	hydrocarbon refrigerant
HCFC	hydrochlorofluorocarbon refrigerant
HFC	hydrofluorocarbon refrigerant
HFO	hydrofluoroolefin refrigerant
HR	relative humidity, %
P	pressure, bar
P_C	power consumption, kW
$\dot{Q}_O$	cooling capacity, kW
T	temperature, ºC
t	time
VCC	volumetric cooling capacity, $kJ \cdot m^{-3}$
x_v	vapour title

GREEK SYMBOLS

v	specific volume, $m^3 \cdot kg^{-1}$

SUBSCRIPTS

air	air entering to the evaporator
dis	discharge
exp	expansion device
i	inlet
l	saturated liquid
O	evaporating level
o	outlet
prod	product
S	isentropic
K	condensing level
v	saturated vapour

1. Introduction

Commercial refrigeration sector includes hermetic stand-alone, condensing unit, and multipack refrigeration systems. According to UNEP (2011), this sector accounts for approximately 32% of the world HFC consumption or 40% of the HFC consumption in the refrigeration/AC sectors. Hermetic stand-alone systems, quantified in 32 million units plus 20.5 million vending machines, usually rely on R-22, R-134a, R-404A, R-507A or recently R-290. Condensing units, generally composed by one or two compressors, one condenser and one receiver assembled into a unit that serves one or more services, are quantified in 34 million units, generally using R-22, R-134a, R-404A, R-507A and R-407C. In addition, centralized refrigeration systems, consisting of a rack of multiple compressors contained in a machinery room providing service to multiple display cabinets, involve more than 500000 plants worldwide (sales area around 500 m^2). They generally use direct expansion systems with large refrigerant charges. The main refrigerants used in the centralized systems are R-22 and R-507A, especially in USA, and R-404A, R-507A and R-407A, in Europe. These systems are prone to high leakage rates, especially through the mechanical joints. Among them, centralized systems are the ones with largest direct contribution to the global warming, because of their large refrigerant charges and high annual leakage rates, quantified to be between 15 to 25% (Schwarz et al., 2011).

In October 2016, the 28th Meeting of the Parties to the Montreal Protocol adopted the Kigali Amendment on hydrofluorocarbons, including the HFCs on the Montreal Protocol (UNEP, 2016). This is an historic agreement who aims to reduce the use and production of HFC worldwide. The Kigali Amendment's objective is to reduce the emissions of HFC gases over 80 billion tonnes of carbon dioxide equivalent (CO_{2e}) by 2050. It establishes a phase-down schedule of HFC substances based on the overall CO_{2e} direct emissions, so it depends on the GWP value of the HFC substances. This amendment follows the same action line as the F-Gas Regulation of Europe (European Commission, 2014), who has limited the GWP value of the substances that could be used in different refrigeration applications according to different time lines. Regarding commercial refrigeration, the most important limitations are the limit of GWP of 2500 for stationary equipment from 2020 on and the limit of GWP of 150 for multipack centralised refrigeration systems with rated capacity of more than 40kW from 2022, except for the primary circuits of cascade systems, which GWP limit has been fixed in 1500.

The previous agreements and regulations condition the use of high-GWP refrigerants in commercial refrigeration systems. In fact, the use of the most widespread refrigerants in this sector, the R-404A and its equivalent R-507A (Llopis et al., 2010), with GWP of 3945 and 3987 respectively, will be limited. Following the trend of agreements and regulations, refrigerant manufactures have designed different drop-in mixtures of R-404A/R-507A with lower GWP values (Table 1) that could be used in different regions of the world with different horizon time lines.

The first group of R-404A drop-in substitutes, initially designed to be drop-in replacements of R-22, lowered the GWP value from 2500 to 3000. Those mixtures avoided the use of R-143a (GWP = 4805) in the composition and added hydrocarbons to be compatible with mineral lubricants. R-422A and R-417B (Fernández-Seara et al., 2010; Llopis et al., 2011), where two of the most generalized fluids.

The second group of R-404A drop-in substitutes with an A1 security classification, focused on the use of R-32 (GWP = 677) in the composition, reaching a GWP range between 1500 to 2500. R-407A (GWP = 1923) was tested by Yana Motta et al. (2014) using a 2.2 kW semihermetic condensing unit with an evaporator for a walk-in freezer using a thermostatic valve. For an indoor chamber temperature of -26ºC and external ambient temperature of 35ºC they measured similar capacity and 6% higher COP than R-404A. Also, Yana Motta et al. (2014) with the same facility and Bortolini et al. (2015) with an hermetic compressor and capillary tube, tested the R-407F (GWP = 1674). Yana Motta et al. (2014) measured similar capacity and increased COP than R-404A and Bortolini et al. (2015) measured 10% increase in capacity and similar COP regarding R-404A for indoor air temperatures from -25 to -15 ºC with external ambient temperature from 25 to 45ºC.

The third group, also with A1 security classification, has reached GWP values between 500 to 1500 by using in the composition R-32 and proportions of the unsaturated HFO fluids. Two of the main characteristics of this group are larger temperature glide in evaporating level and higher discharge temperatures than R-404A. The most recommended drop-in substitutes by the manufacturers are R-407H (GWP = 1378), R-449A (GWP = 1396) and R-448A (1260). R-448A was tested experimentally by Yanna-Mota et al. (2014) with the same plant and conditions described before. They measured similar cooling capacity than R-404A but increased COP from 3 to 11%. Recently, Mota-Babiloni et al. (2015) tested R-448A using an open-type compressor in a plant with shell-and-tube heat exchangers and a thermostatic valve, measuring reductions on cooling capacity from 1 to 15% but increments on the COP ranging from 6 to 21% regarding R-404A. However, the authors have not found scientific experimentation about the refrigerants R-407H and R-449A, except of the manufacturer's documentation and tests. R-407H has obtained a definite A1 classification in Ashrae Standard 34.

Finally, the last drop-in group of R-404A corresponds to refrigerant fluids with GWP below 500. To achieve so reduced GWP value, the mixture has been composed by R-32 (A2) and R-1234yf (A2L), thus the proposed mixtures obtain and Ashrae 34 security classification of A2L. Of this group, Sedliak J. (2013) and Shrestha and Abdelazid (2014) presented the evaluation of this refrigerant using calorimeter tests with hermetic compressors. Both of them measured increased capacity than R-404A and differences from -11.8 to 14.6% regarding the COP of the system. The COP increments of this refrigerant were placed at high evaporating and condensing levels. Also, about the mixture R-454B the authors have not found scientific documentation.

Table 1. R-404A/R-507A drop-in substitutes for low temperature applications

MIXTURE NAME	Composition (% by mass)	GWP (AR4)	GWP (AR5)	SECURITY CLASSIFI CATION	Energy tests
R-404A	HFC-125/ HFC-134a/ HFC-143a (44/4/52)	3922	3945	A1	(Llopis et al., 2010)
R-507A	HFC-125/ HFC-143a (50/50)	3985	3987	A1	(Llopis et al., 2010)
2500 < GWP < 3000					
R-422A	HFC-125/ HFC-134a/HC-600a (85.1/11.5/3.4)	3144	2847	A1	(Fernández-Seara et al., 2010)
R-417B	HFC-125/HFC-134a/HC-600 (79/18.25/2.75)	3027	2741	A1	(Llopis et al., 2011)
1500 < GWP < 2500					
R-407A	HFC-32/HFC-125/HFC-134a (20/40/40)	2107	1923	A1	(Yana Motta S. et al., 2014)
R-407F	HFC-32/HFC-125/HFC-134a (30/30/40)	1825	1674	A1	(Bortolini et al., 2015; Yana Motta S. et al., 2014)
500 < GWP < 1500					
R-407H	HFC-32/HFC-125/HFC-134a (32.5/15/52.5)	1495	1378	A1	-
R-449A	HFC-32/HFC-125/HFO-1234yf/HFC-134a (24.3/24.7/25.3/25.7)	1396	1282	A1	-
R-448A	HFC-32/HFC-125/HFC-134a/HFO-1234yf/HFO-1234ze(E) (26/26/20/21/7)	1372	1260	A1	(Mota-Babiloni et al., 2015; Yana Motta S. et al., 2014)
GWP<500					
R454A	HFC-32/HFO-1234yf (36/64)	244	244	A2L	(Sedliak, 2013)
R454B	HFC-32/HFO-1234yf (68.9/31.1)	465	467	A2L	-

The R-404A and R-507A substitution process for low temperature applications is of relevant importance now, because regulations are limiting their use or their refilling, and because there is an urgent need to reduce the amount of high-GWP substances used worldwide. As previously detailed, some reduced GWP mixtures allow obtaining similar even to higher cooling capacities with enhanced COP; however the experimentation with these new mixtures has not been completed up to now. Scientific reports regarding R-407H, R-449A and R-454B have not been found by the authors. Accordingly, this work aims to contribute to the R-404A substitution analysis by presenting the experimental evaluation of the R-407H as R-404A drop-in substitute in a low temperature application. In this case, the analysis is divided into three parts: first, a thermodynamic theoretical comparison about both refrigerants (Section 2), second, a top up test energy analysis performed with a small-scale supermarket at frozen product level (Section 4), and third a 24 hour energy analysis at different heat rejection levels (Section 5). The analysis has been based on energy parameters, no environmental analysis has been performed.

2. Thermodynamic properties and theoretical performance

R-407H corresponds to a non-azeotropic mixture of R-32/R-125/R-134a (32.5/15.0/52.2%, by mass) designed to be a drop-in substitute of both R-404A and R-507A, thus it can be used with POE lubricants. Table 2 reflects the main properties of both refrigerants. R-407H has a GWP value reduction of 65.8% regarding R-404A by avoiding the use of R-143a and introducing the moderate-GWP fluid R-32 (A2). R-407H has obtained an A1 Ashrae Standard 34 security classification. Figure 1 contrasts pressure-enthalpy diagrams of both fluids. As it can be observed, both refrigerants have practically coincident liquid saturation lines, but R-407H presents larger latent heat of phase-change than R-404A (increment of 37.3% at -30ºC). Also, R-407H density is about 10% higher than that of R-404A (Table 2). The difference between the vapour saturation lines and liquid density variation could have influence on R-404A expansion valves. If they are thermostatics, important differences could be obtained, nonetheless electronic expansion valves would be able to be reprogrammed for the new refrigerant. Also, R-407H has an important glide, especially at low evaporation levels (6.8K at T_O=-30ºC). Another important difference is the specific vapour volume. R-407H presents higher specific volume than R-404A (+76.3%,-30ºC at saturation), that will result in lower refrigerant mass flow rates in the plant. This last effect could have influence on the R-404A expansion valves, which could result larger for the operation with R-407H.

	R-404A		R-407H	
Composition (% wt)	44.0%	HFC-125	32.5%	HFC-32
	52.0%	HFC-143a	15.0%	HFC-125
	4.0%	HFC-134a	52.5%	HFC-134a
Molecular weight ($g·mol^{-1}$)	97.6		79.1	
Normal boiling point (ºC)	-46.3		-41.1	
Critical temperature (ºC)	72.1		86.5	
Critical pressure (bar)	37.3		48.6	
Glide at 30ºC[a] (K)	0.4		5.4	
Glide at -30ºC[a] (K)	0.7		6.8	
h_{fg} at T=30ºC[a] ($kJ·kg^{-1}·K^{-1}$)	134.4		197.5	
ρ saturated liquid at T=30ºC ($kg·m^{-3}$)	1020.2		1101.3	
h_{fg} at T=-30ºC[a] ($kJ·kg^{-1}·K^{-1}$)	190.0		260.8	
v at T=-30ºC ($m^3·kg^{-1}$)	0.0948		0.1671	
$GWP_{100\ years}$ (IPCC, 2014)	3945		1378	
ASHRAE safety group	A1		A1	

[a]Glide and h_{fg} evaluated at pressure corresponding to the phase change temperature with a vapour title of 50%

Table 2. Physical, environmental and safety characteristics of R-404A and R-407H (IPCC, 2013; Lemmon et al., 2013)

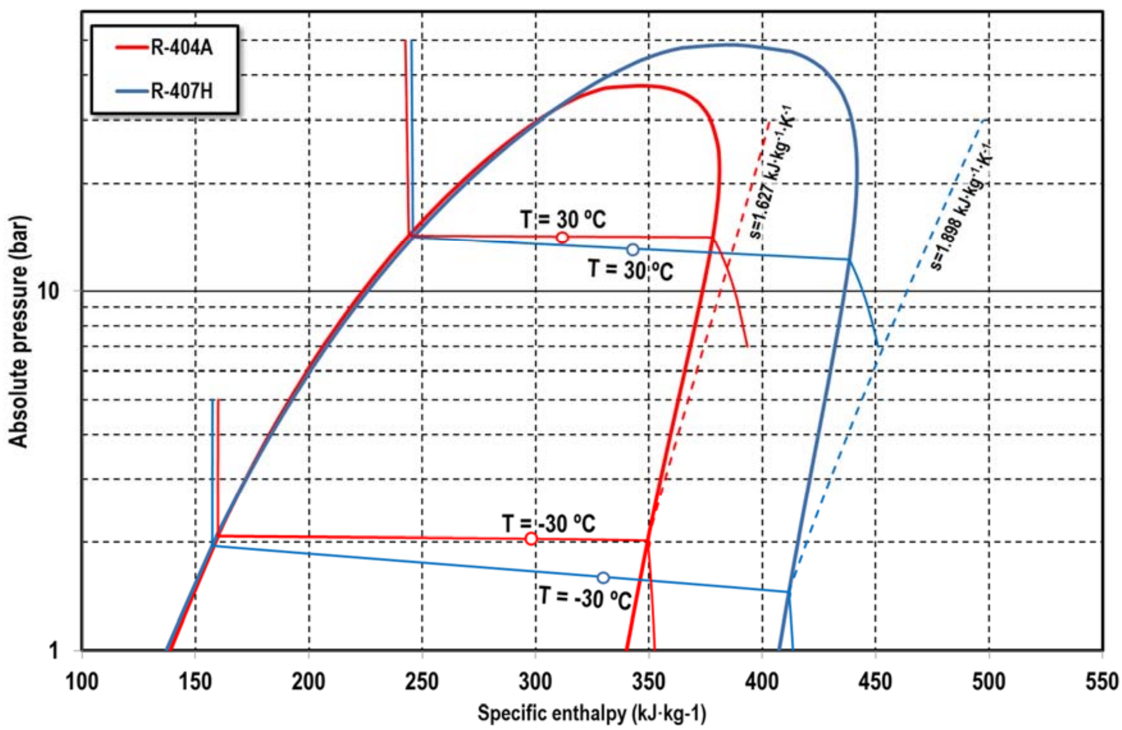

Figure 1. Pressure-enthalpy diagrams of R-404A and R-407H

Figure 2 summarizes the theoretical comparison of the main operating parameters of an ideal single-stage vapour compression system operating with R-404A and R-407H at an evaporating level of -35ºC for three condensing levels (25, 35 and 45ºC). For the parameters calculation, since R-407H presents a non-neglectful glide, the condensing pressure has been evaluated for a vapour title of 50%, as presented by Eq. (1) and the evaporating pressure using the average enthalpy value at the evaporator, Eq. (2). This criteria is recommended by Radermacher and Hwang (2005). For these pressures, the volumetric cooling capacity, Eq. (3), and the COP, Eq. (4), are evaluated assuming an ideal compression cycle. Also, Figure 2 presents the comparison of the isentropic discharge temperature and the inlet vapour title at the evaporating process. All the thermodynamic properties were evaluated using Refprop 9.1 (Lemmon et al., 2013).

$$P_K = f(T_K, x_v = 0.5) \tag{1}$$

$$P_O = f\left(T_O, \frac{h_{l,PK} + h_{v,PO}}{2}\right) \tag{2}$$

$$VCC = \frac{h_{v,PO} - h_{l,PK}}{v_{v,PO}} \tag{3}$$

$$COP = \frac{h_{v,PO} - h_{l,PK}}{h_{dis,S}(P_K, s_{v,PO}) - h_{v,PO}} \tag{4}$$

R-407H offers similar VCC than R-404A at low evaporating levels, but at a given evaporating temperature the difference rises at high condensing levels, for example at a condensing level of 45ºC the VCC of R-407H is 10.2% higher than that of R-404A. However, the theoretical COP of R-407H is higher for all the condensing levels, showing increments from 8.6% at 25ºC to 21.7% at 45ºC. That indicates that the energy performance of R-407H would be better than that of R-404A. In addition, another important aspect to be considered in real plants is the vapour title at the evaporator inlet. As it can be observed in Figure 2, R-407H offers lower vapour titles for all the condensing levels. The reduction of the vapour titles of R-407H regarding R-404A ranges 12 to 16%. This reduction will enhances the overall heat transfer characteristics of the evaporator. Thus, an increment of the evaporating temperature in real applications can be expected. Nonetheless, R-407H has an important drawback derived from the use of R-32, resulting in an increase of the discharge temperature. The isentropic discharge temperatures of R-407H show increments from 22.6 to 26.6 K regarding the operation with R-404A. Therefore, an important increment of the discharge temperature could be expected in real applications.

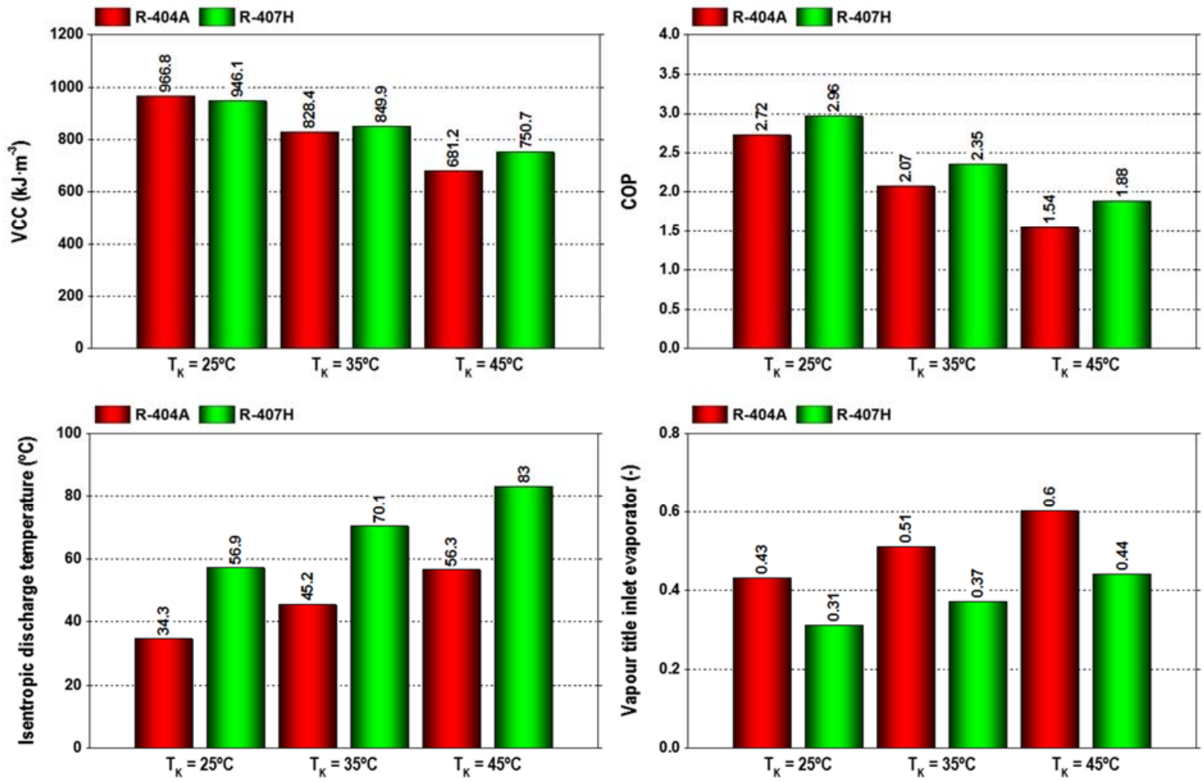

Figure 2. Thermodynamic VCC, COP, isentropic discharge temperature and vapour title at inlet of evaporator (T_O=-35ºC)

3. Test methodology and experimental set-up

This section describes the test methodology used to evaluate the refrigerant mixtures as well as the experimental set up and uncertainties of the measurement system.

3.1. Test methodology

The refrigerant mixtures have been evaluated using two types of tests. First, a top up (partial drop-in test) test has been performed to analyse the feasibility of R-407H partial recharge in a system when running with R-404A. This test has covered the operation of the plant at 35ºC of condensing temperature with pure R-404A, then with an addition of 10, 20 and 30% of R-407H and finally with pure R-407H. This test is analysed in section 4. Second, an energy consumption test of the plant during 24 hours of stable operation has been performed at three condensing levels (25, 35 and 45ºC). This test is described in section 5.

3.2. Experimental plant

The experimental plant used for the evaluation of the refrigerant mixtures is schematized in Figure 3. It corresponds to a single stage cycle driven by a semihermetic compressor, a condenser and liquid receiver that serves a commercial horizontal island cabinet for frozen product, which is placed inside a climatic chamber. The heat rejection of the system is performed using a water loop, as described by Sanz-Kock et al. (Sanz-Kock et al., 2014).

Semihermetic compressor, designed for R-404A operation, has a nominal power of 1.5kW and a displacement of 9.54 $m^3 \cdot h^{-1}$ at 1450 rpm, uses POE BSE32 lubricant and incorporates an additional cooling system at the compressor crankcase. Condenser is a brazed plate heat exchanger (B25-TH-20) with a heat transfer surface area of 1.12 m^2. The horizontal island cabinet, with dimensions of 1875 mm long, 1000 mm height and 1170 mm width is a commercial element. It incorporates a 1580 mm length finned-tube evaporator of one 3/8'' refrigerant circuit with total tube length of 50.56 m and an internal volume of $2.494 \cdot 10^{-3}$ m^3. It incorporates 0.3 mm aluminium fins (78 x 288 cm^2, 78 x 192 cm^2, 158 x 240 cm^2). The evaporating process is controlled by an electronic expansion valve using an NTC sensor and a pressure gauge at the exit of the evaporator. The driver of the expansion valve can be customized for any refrigerant fluid. The defrosting of the evaporator is made with 2000 W electrical resistors and an NTC sensor placed over the fin surface. The climatic chamber is class 3 (ISO 23953-2:2015, 2015). It maintains indoor temperature and relative humidity using PID regulators.

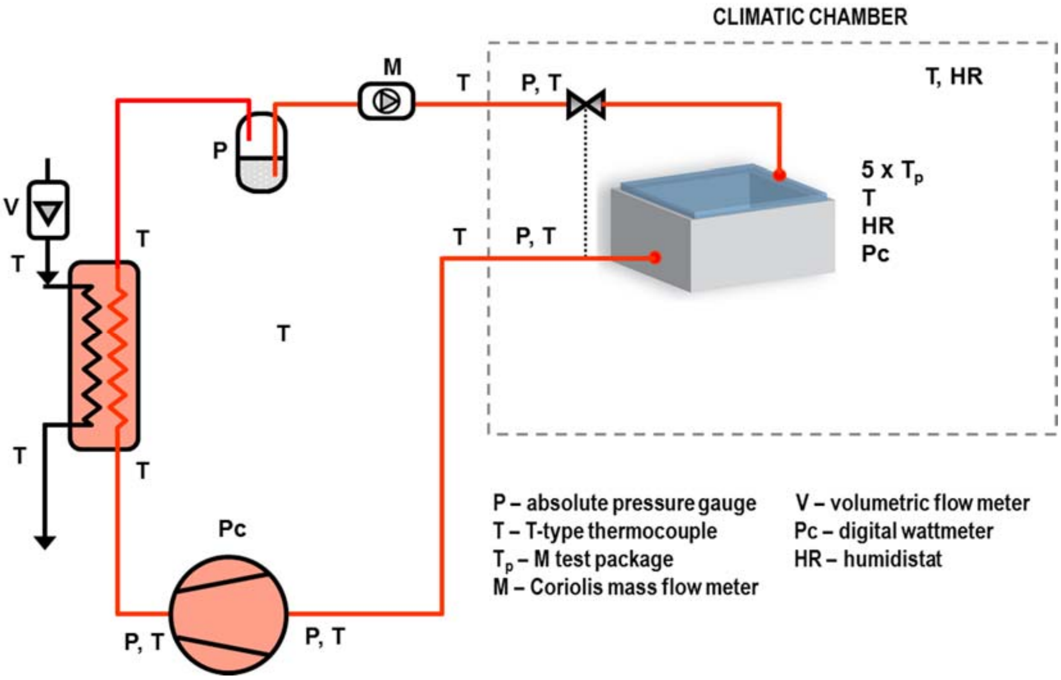

Figure 3. Scheme of the experimental plant and location of measurement devices

3.3. Measurement system and uncertainties

The plant is fully instrumented to be able to measure the main energy parameters of operation. The measurement devices and their uncertainty are detailed in Table 3. The refrigeration cycle incorporates 8 T-type thermocouples, 3 pressure gauges, 1 Coriolis mass flow meter, a volumetric flow meter and a digital wattmeter. The island cabinet uses 2 T-type thermocouples, 2 pressure gauges, 1 digital wattmeter, a combined humidity-temperature sensor and 5 M-test packages according to ISO 15502 for measuring the product temperature. The climatic chamber uses a combined humidity-temperature sensor and another T-type thermocouple is used for measuring the environment temperature. All sensors are gathered using two cRIO-9074 data acquisition systems (Sánchez et al., 2017).

	Temperature	Pressure	Mass flow rate	Volumetric flow rate	Power consumption	Relative humidity	Test package
Refrigeration cycle	8	3	1	1	1	-	-
Island cabinet	3	2	-	-	1	1	5
Climatic chamber	1	-	-	-	-	1	-
Others	1	-	-	-	-	-	-
Uncertainty (of reading)	± 0.5 K	± 0.3 %	± 0.1 %	± 0.33 %	± 0.5 %	± 2 %	± 0.5 K

Table 3. Number of sensor elements and uncertainties

4. Top up tests

The first experimental test corresponds to a top-up test or partial drop-in test, where proportions of R-407H were added to a running system with R-404A. The plant was charged with R-404A and steadied using electrical resistors inside the island cabinet (compressor always on operation), with the plant operating at a condensing temperature of 35ºC with the compressor at 1450 rpm. The defrosting period of the island cabinet was set to one each eight hours. The average product temperature in the test has been of -20ºC. Then, a leakage of 10% of the refrigerant charge of the plant was performed in the compressor discharge line and then it was refilled with 10% of removed charge with pure R-407H. Then the plant was evaluated again. This process was repeated three times in order to check the performance of the plant working with R-404A, 90-R-404A/10-R-407H, 80-R-404A/20-R-407H, 70-R-404A/30-R-407H and finally with pure R-407H. Table 4 details the composition of each refrigerant mixture tested in the top up tests as well as the main operating parameters. It can be observed that when the proportion of R-407H increases, the glide and the latent heat of phase change increase, especially at the evaporation level. In addition, there is an important increment of the specific volume of saturated vapour at the evaporation level.

Mixture	R-125 (%wt.)	R-134a (%wt.)	R-143a (%wt.)	R-32 (%wt.)	GWP (100y)	Glide (T=35ºC)	h_{fg} (T=35) (kJ·kg^{-1})	Glide (T=-35ºC)	h_{fg} (T=-35) (kJ·kg^{-1})	v (T=-35ºC) (m3·kg^{-1})
R-404A	44.00	4.00	52.00	0.00	3945	0.4	127.8	0.7	193.5	0.114
90-R-404A,10-R-407H	41.15	8.70	46.80	3.35	3700	1.1	133.5	1.9	200.7	0.118
80-R-404A,20-R-407H	38.30	13.40	41.60	6.70	3432	1.8	139.4	2.9	207.8	0.122
70-R-404A,30-R-407H	35.45	18.10	36.40	10.05	3176	2.4	145.4	3.7	214.9	0.127
R-407H	15.50	51.00	0.00	33.50	1378	5.2	190.8	6.8	265.9	0.176

Table 4. Refrigerant composition variation during partial drop-in tests and main parameters

To compare the energy performance of the plant, in steady-state conditions, with the different refrigerant mixtures (Table 4), a time of 2 hours has been considered. The test section starts one hour before the average product temperature (5 packages) reaches -20 ºC and one hour after. All the measurement samples (1440), one each 5 seconds, have been averaged to evaluate the performance of the system. Each value corresponds to the average value of three test according to the previous description. Cooling capacity is computed using Eq. (5) as product of the refrigerant mass flow rate and the enthalpy difference in the evaporator, where the expansion process has been considered isenthalpic. The COP, Eq. (6), is the quotient of the cooling capacity and the compressor power consumption. The uncertainty of the measurements was evaluated using Mofat's method (1985), resulting in an average uncertainty of 0.92% for the COP. This uncertainty value does not include the possible error introduced by Refprop mixing rules. The uncertainties of the rest of parameters correspond to the uncertainty of the measurement devices. Table 5 includes the experimental and computed parameters for the top-up analysis. It needs to be mentioned that enthalpies and phase-change temperatures were computed using the default mixing rules of Refprop 9.1, that are not customized for the evaluation of the refrigerant mixtures detailed in Table 4. To check the validity of the calculations a heat transfer comparison at the condenser of the plant was considered. The heat transfer of the refrigerant at the condenser, Eq. (7), was contrasted to the heat absorbed by the water at the condenser, Eq. (8). The discrepancy between those heat transfer rates offered a maximum deviation of 3.0% (Table 5)

$$\dot{Q}_O = \dot{m} \cdot \left(h_{O,o} - h_{exp,i}\right) \tag{5}$$

$$COP = \frac{\dot{Q}_O}{P_C} \tag{6}$$

$$\dot{Q}_K = \dot{m} \cdot \left(h_{K,i} - h_{K,o}\right) \tag{7}$$

$$\dot{Q}_{K,w} = \dot{V}_w \cdot \rho_w \cdot c_{p,w} \cdot \left(T_{w,o} - T_{w,i}\right) \tag{8}$$

Mixture	T_O (ºC)	T_{dis} (ºC)	$\dot{m}$ ($kg \cdot s^{-1}$)	P_C (W)	COP (-)	Q_K (W)	$Q_{K,w}$ (W)	$(Q_K - Q_{K,w}) / Q_K$ (%)
R-404A	-39.9	94.4	0.0072	947	0.89	1212	1185	2.2
90-R-404A,10-R-407H	-39.5	97.9	0.0069	954	0.89	1217	1210	0.5
80-R-404A,20-R-407H	-38.7	98.9	0.0070	969	0.92	1260	1239	1.7
70-R-404A,30-R-407H	-38.9	100.7	0.0066	950	0.94	1239	1222	1.4
R-407H	-36.5	109.2	0.0049	888	1.01	1131	1096	3.0

Table 5. Average experimental values of top-up evaluation and data validation at condenser

Figure 4 summarizes the difference of the main operating parameters with the different refrigerant mixtures regards the operation with pure R-404A, expressed as percentage variation or temperature difference regards R-404A. It can be observed that the average COP of the system increases as high quantity of R-407H is added to the system. For a 30% of R-407H by mass the increment in COP reaches 4.92% regarding pure R-404A value. Also, compressor's discharge temperature increases with higher quantity of R-407H, reaching an increment of 6.3K with a 30% proportion of R-407H. In addition, another important observed effect is that the average evaporating temperature (evaluated with the pressure measurement at the exit of the island cabinet and the average value of enthalpy in the evaporator) increases when R-407H is added to the system. For a proportion of 30%, the increment of evaporating temperature is of 1.05K. One reason for this last increment is that when R-407H is added to the system the vapour title at the inlet of the evaporator is reduced.

As summary, it can be affirmed that the partial refilling with R-407H of a system running with R-404A will increase its COP but it will also increase the compressor's discharge temperature. In addition, the plant will operate correctly with the different refrigerant mixtures.

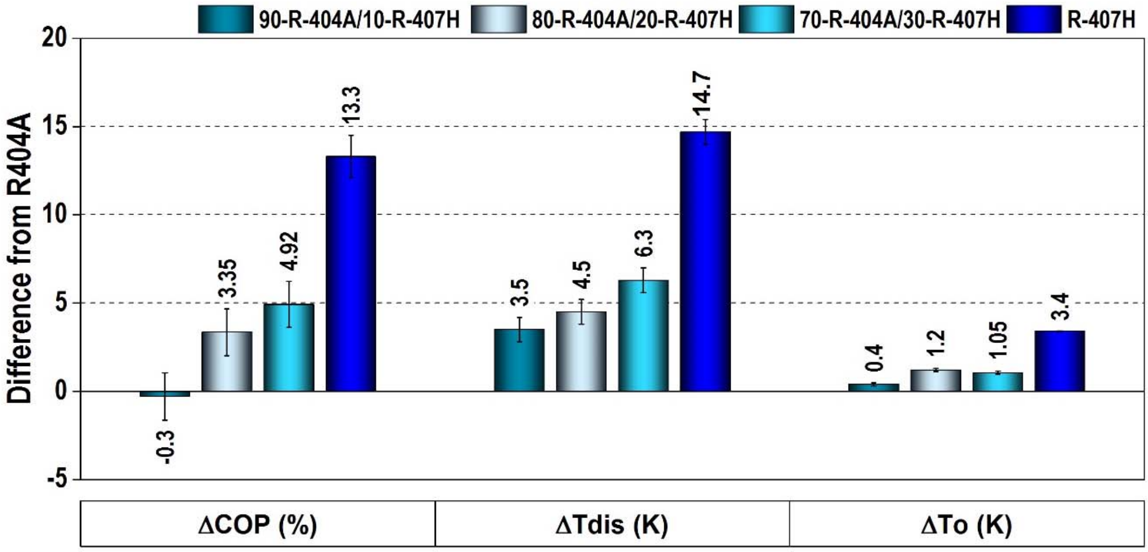

Figure 4. Main parameters differences of the refrigerant mixtures regarding R-404A

5. Energy consumption tests

The second type of analysis has been energy consumption tests of the system over a period of 24 hours of stable operation, where the product temperature was maintained at an average value of -20ºC and the condensing temperature was kept at 25, 35 and 45ºC. This type of test is identical to that presented by Sánchez et al. (2017), where the exact details of the experimental evaluation can be consulted.

5.1. Test summary and test conditions

As summary, the plant running with R-404A and its drop-in R-407H was operated with the compressor at 1600 rpm using ON/OFF control strategy (low-cut temperature of -50.0ºC, cut-in temperature of -24.8ºC). The superheat set point in the evaporator of the island cabinet was set to 14K. It is controlled by an electronic expansion valve where the pressure-temperature curves of each refrigerant were customized. The cabinet's controller regulated the operation of the expansion valve. The defrosting period was set to one each eight hours, ending when the temperature probe in the evaporator reached 5ºC. The product temperature (arithmetic mean of temperature of the five M-test packages) was maintained at -20ºC. The island cabinet was placed inside the climatic chamber, where 25ºC of dry bulb temperature and 55% of relative humidity were retained. The external conditions were established using a loop working with water running at a constant volumetric flow rate of 1 $m^3 \cdot h^{-1}$ and different outlet temperatures. The condensing temperature (average value during compressor operation using pressure measurement at the exit of the compressor and 50% of vapour title) was varied from 25, 35 to 45ºC.

Table 6 summarizes the test conditions during the 24 hour tests at each condensing level. The deviations during the test represent the difference between the maximum and minimum value of the variable during the test. Figure 5 shows the evolutions of the main operating temperatures during the R-404A test at a condensing level of 45ºC, and Figure 6 the pressure-enthalpy diagram of the cycle with both refrigerants at 45ºC of condensing temperature test one hour before starting the defrosting period.

Table 6. Reference parameters of the evaluation of the three refrigeration systems during 24 hour test

	R-404A			R-407H		
Parameter	T_K = 25ºC	T_K = 35ºC	T_K = 45ºC	T_K = 25ºC	T_K = 35ºC	T_K = 45ºC
Average condensing temperature (ºC)	26.1	35.5	43.8	26.6	35.5	43.6
Deviation during test (K)	0.7	0.7	0.7	0.7	0.7	0.7
Average product temperature (ºC)	-19.9	-20.0	-20.1	-20.4	-20.3	-20.2
Deviation during test (K)	0.5	0.5	0.7	0.5	0.5	0.6
Average climatic chamber temperature (ºC)	25.1	25.1	25.1	25.1	25.1	25.1
Deviation during test (K)	0.8	0.8	0.7	0.8	0.8	0.8
Average climatic chamber RH (%)	57.1	57.1	57.4	56.3	56.3	57.3
Deviation during test (%)	5.5	5.5	5.5	5.4	5.6	5.3

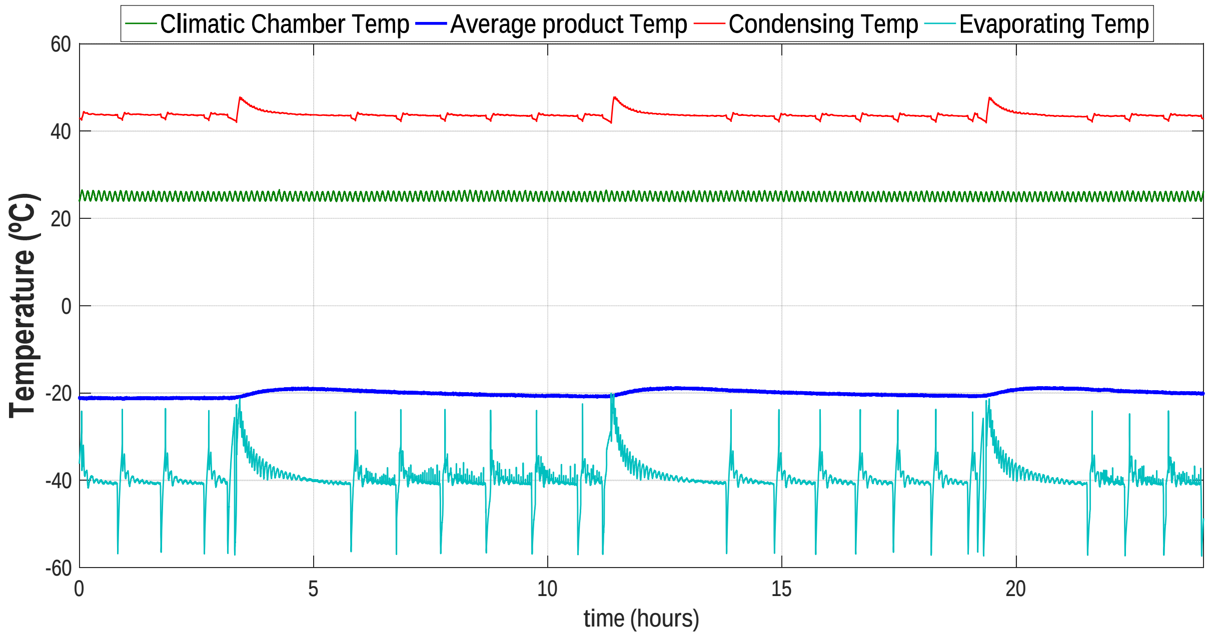

Figure 5. Climatic chamber, product, condensing and evaporating temperatures. R-404A test at T_K=45ºC

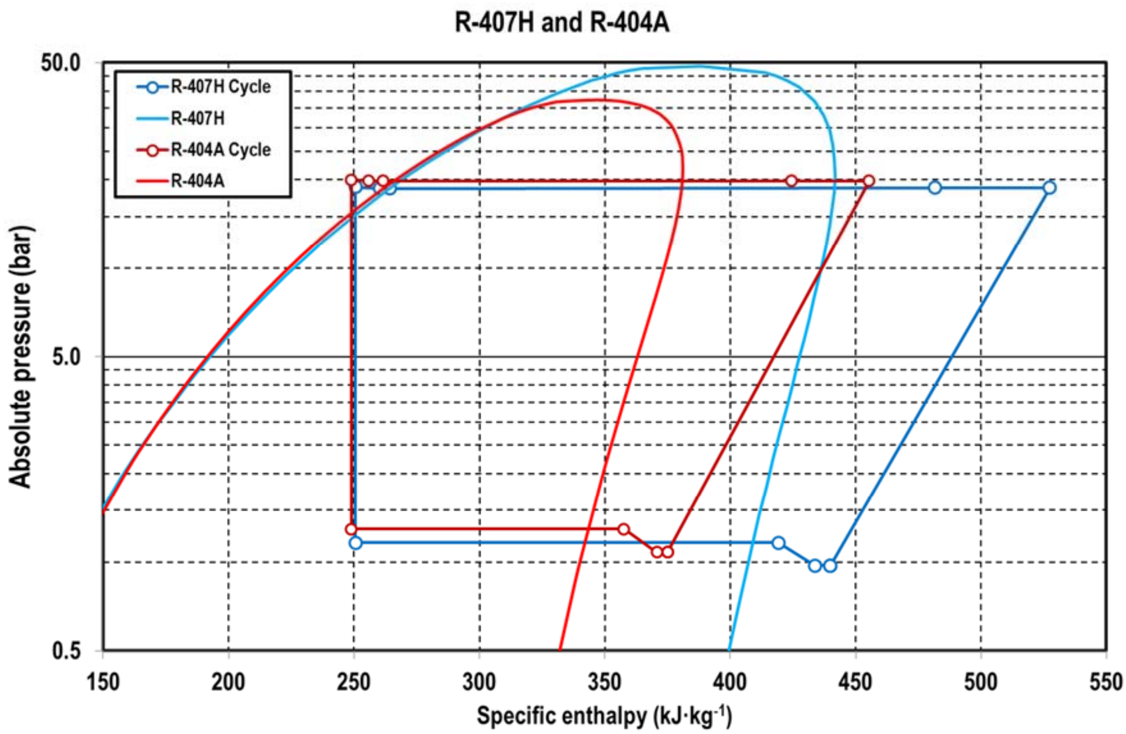

Figure 6. Pressure-enthalpy diagrams of R-407H and R-404A. T_K=45ºC. (one hour before starting the defrosting period)

Following, the temperature indicators in the 24 hour tests are detailed in subsection 5.2 and the operation time and energy indicators in subsection 5.3.

5.2. Temperature indicators

The average value of the evaporating temperature during the 24 hours, calculated using pressure at the exit of the island cabinet and the average enthalpy value in the evaporator (inlet and saturated vapour), of the tests is detailed in Figure 7. It can be observed that the evaporating level increases when higher the condensing temperature is for both refrigerants and that the average evaporating level of R-407H is higher than that of R-404A, which indicates that the overall heat transfer characteristics of the evaporator are enhanced. The increment on the evaporating level when using R-407H regarding R-404A is of 3.4K at 25ºC, 3.0K at 35ºC and 1.8K at 45ºC. The main reason could be the reduction of the vapour title at the inlet of the evaporator, but also modifications of the boiling heat transfer could occur, although they have not been analysed in this work. This increase in the evaporating level is translated to the temperature differences that drive the cooling process inside the island cabinet. Figure 8 shows the temperature difference between the air in the island cabinet in the return duct to the evaporator and the average product temperature regarding the evaporating level. As it can be seen, the use of R-407H instead of R-404A is able to reduce those temperature differences. Accordingly, the evaporating process with R-407H is more favourable than that measured with R-404A. However, as analysed in section 2, the component R-32 in R-407H mixture, increases the compressor discharge temperature. Figure 9 presents the average compressor's discharge temperature only when the compressor is in operation for both refrigerants. Measured increments of the discharge temperature for R-407H are of 13.1K at 25ºC, 12.4K at 35ºC and 13.8K at 45ºC. These increments are lower than that resulting from the theoretical analysis. They could be influenced by the external cooling system of the compressor (fan over the compressor crankcase) and by the pattern operation of the system. Nonetheless, measured increments on the discharge temperature are inside the operating range of the lubricant oil. For R-407H, at a condensing level of 45ºC the maximum measured punctual discharge temperature has been of 121.8ºC, whereas for R-404A in the same conditions of 105.6ºC.

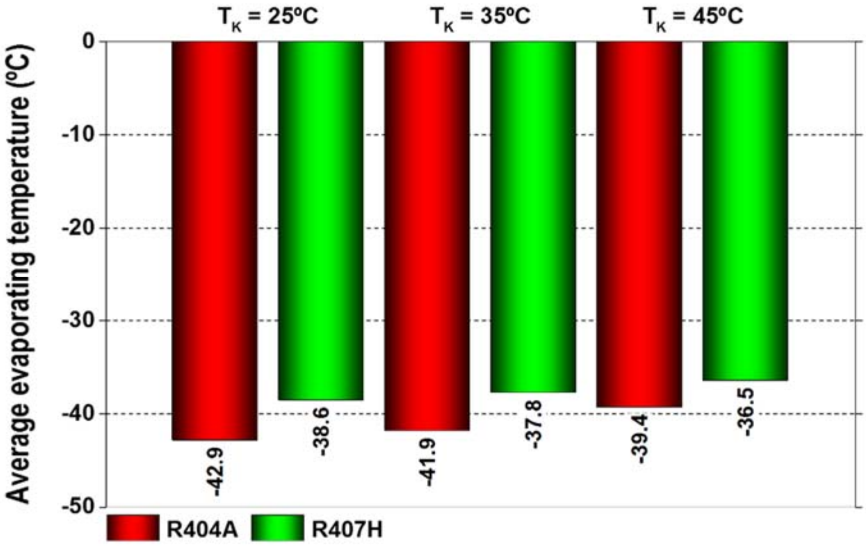

Figure 7. Average evaporating temperature in the island cabinet during 24h test

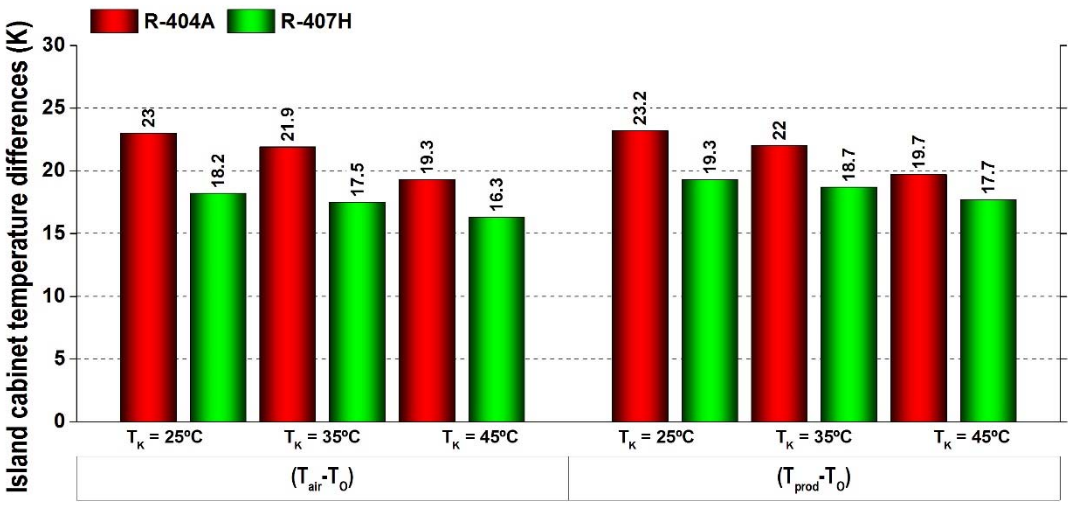

Figure 8. Average temperature differences between the evaporating temperature and air inside the island cabinet and product temperatures

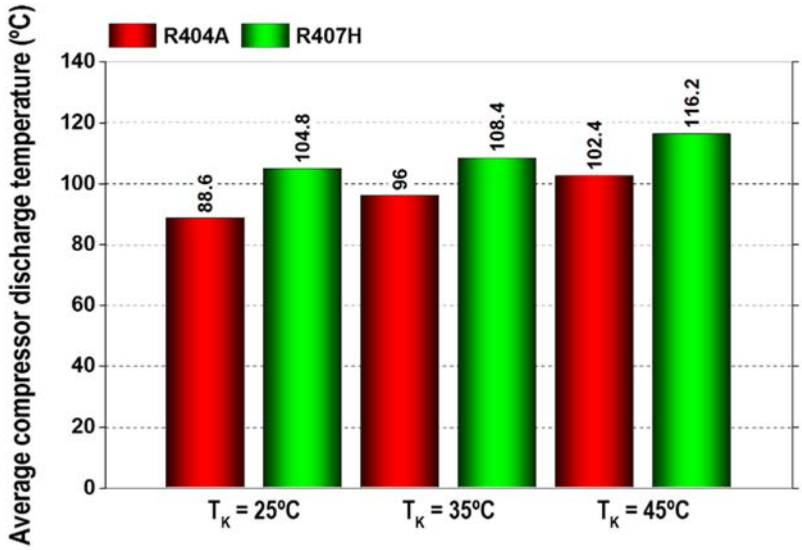

Figure 9. Average compressor's discharge temperature (Compressor ON)

5.3. Energy indicators

Energy consumption is a relation between the operating time and the average power consumption of the elements, being both needed to be compatible between both refrigerants to undertake a drop-in process. Figure 10 details the fraction of time of compressor's operation during the 24 hour test and the average value of the three defrosting periods included in the test section. The time percentage the compressor in operation with R-407H is similar to that with R-404A. Maximum measured deviation has been of -1.1% at 35ºC. Regarding the length of the defrosting period, it has been measured that R-407H presents longer defrosting periods (from -0.1 to 1.7 minutes). The difference of the defrosting time could be related with the amount of refrigerant inside the evaporator and it would have influence on the amount of cooling load introduced in the island cabinet during the defrosting period. Following, Figure 11 presents the average power consumption of the compressor, only when the compressor is in operation, and of the island cabinet during the 24 hours including three defrosting periods. It has been observed that when running with R-407H there is a reduction in the power consumption of the compressor, in average of 7.3%, regarding R-404A operation. In the island cabinet, however, there is an increment in average of 2.3% due to longer defrosting periods. Nonetheless, the compatibility of the R-404A compressor with R-407H is good.

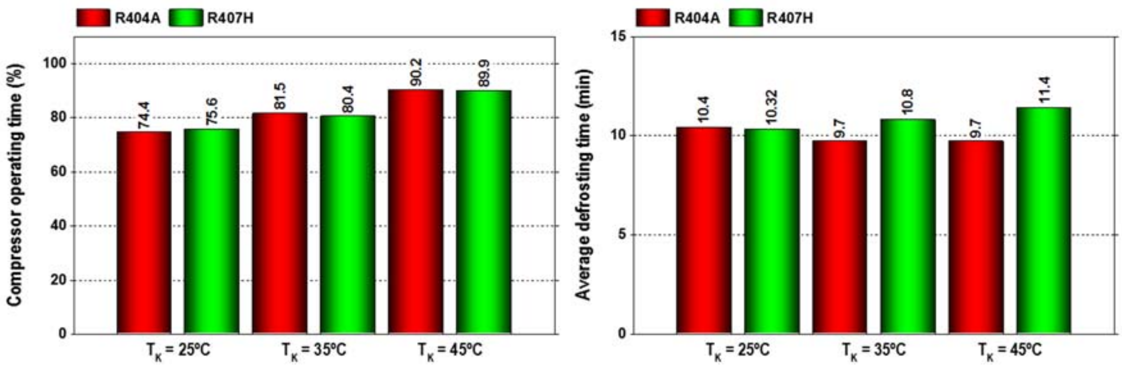

Figure 10 Compressor's operating time and average defrosting period during 24 hour test

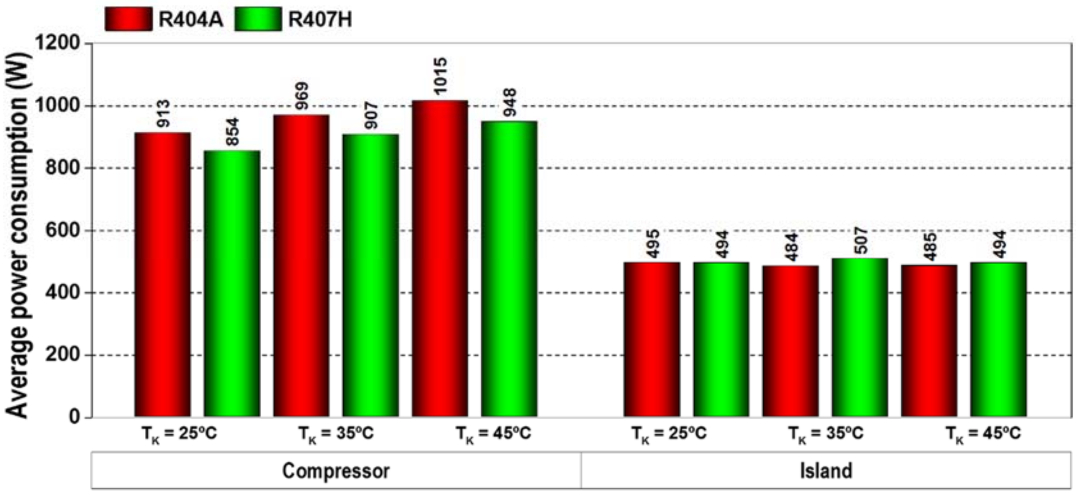

Figure 11. Average compressor's and island cabinet's power consumptions during 24 hour test

Finally, to compare the system with both refrigerants from the point of view of energy consumption, the energy consumption (kWh) of each element has been calculated from the power consumption measurements and operating time according to Eq. (9) using a trapezoid integration method. In Eq. (9), 'i' represents each energy consumer, 'P_C' its power consumption and 'j' each sampled data. The expression is evaluated during the 24-hour test.

$$\boldsymbol{E_i = \frac{1}{36 \cdot 10^5} \cdot \int_0^{24h} P_{C,i}(t) \cdot dt = \sum_{j=1}^{24h} \left[\frac{P_{C,i}(j) + P_{C,i}(j-1)}{2} \right] \cdot [t(j) - t(j-1)]} \quad (9)$$

The results are detailed in Figure 12 for the compressor, island cabinet and their sum. Regarding the compressor energy consumption an important reduction of its energy consumption, derived from the reduction of power consumption, has been measured. The measured reductions of the compressor's energy consumption when using R-407H are of 7.4% at 25ºC, 7.7% at 35ºC and 7.0% at 45ºC. The island cabinet presents slight differences of energy consumption when R-407H is used, always showing an increment. It is of 0.9% at 25ºC, 4.6% at 35ºC and 1.7% at 45ºC. Finally, the overall energy consumption of the system also show a reduction when R-407H is used instead of R-404A. The total energy consumption reduction when working with R-407H is of 3.9% at 25ºC, 3.0% at 35ºC and 4.0% at 45ºC.

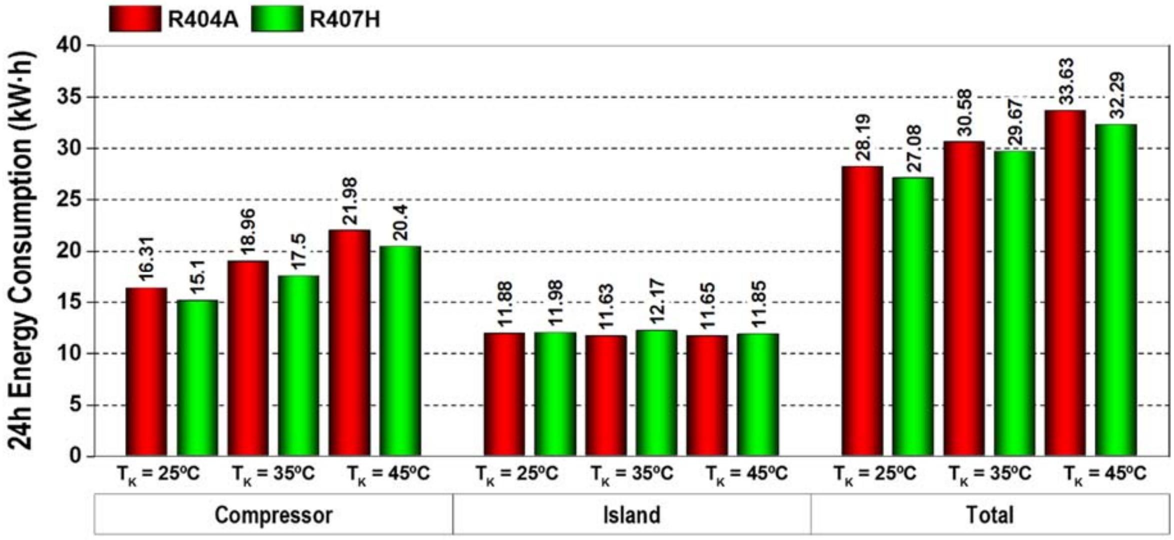

Figure 12. Energy consumption of compressor, island cabinet and the system during 24 hour test

6. Conclusions

This work describes the experimental set up and test methodology to evaluate the refrigerant R-407H as drop-in substitute of R-404A in a low temperature direct expansion vapour compression system of commercial use. The system with both refrigerants has been tested in laboratory conditions at a product temperature of frozen product of -20ºC, at three condensing temperatures 25, 35 and 45ºC, thus covering the common conditions of a supermarket. The experimental evaluation has covered top up or partial drop-in tests and energy consumption tests.

From the top up test, it has been concluded that partial refilling of R-404A existing systems with R-407H is feasible. The analysed plant operated correctly and showed increments of the COP for increased proportions of R-407H (up to 4.92% with a 30% of R-407H by mass at 35ºC). In addition, the refilling with R-407H caused an increase of the compressor's discharge temperature (of 6.3K with a 30% of R-407H by mass at 35ºC) and an increment of the evaporation temperature (of 1.05K with a 30% of R-407H by mass at 35ºC).

From the energy consumption test, it has been concluded that:

- The performance of the evaporator of the island cabinet with R-407H instead of R-404A was enhanced, because the evaporated level increased 3.4K at 25ºC, 3.0K at 35ºC and 1.8K at 45ºC. This increment was also translated to the temperature differences in the cabinet.
- Average compressor's discharge temperature for R-407H increased less than expected from a theoretical ideal cycle. The average measurements increments regarding the R-404A operation were of 13.1K at 25ºC, 12.4K at 35ºC and 13.8K at 45ºC. Punctual compressor discharge temperatures were inside the allowed range of the lubricant oil.
- Power consumption of the compressor when using R-407H was reduced in an average value of 7.3% regarding the R-404A operation. However, defrosting time was slightly longer with R-407H.
- Energy consumption of the compressor when using R-407H instead of R-404A was reduced in 7.4% at 25ºC, 7.7% at 35ºC and 7.0% at 45ºC. These reductions, translated to the overall consumption of the whole systems, resulted in cuts of 3.9% at 25ºC, 3.0% at 35ºC and 4.0% at 45ºC.

Accordingly, it can be concluded from this experimentation that the use of the reduced GWP refrigerant R-407H (GWP=1378) as drop-in replacement of R-404A (GWP=3945) is recommendable from the point of view of direct and indirect emissions for centralized low temperature direct expansion systems, since it will reduce both the direct and indirect contributions to the greenhouse effect.

7. Acknowledgements

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TABLES

Table 1. R-404A/R-507A drop-in substitutes for low temperature applications

MIXTURE NAME	Composition (% by mass)	GWP (AR4)	GWP (AR5)	SECURITY CLASSIFICATIO N	Energy tests
R-404A	HFC-125/ HFC-134a/ HFC-143a (44/4/52)	3922	3945	A1	(Llopis et al., 2010)
R-507A	HFC-125/ HFC-143a (50/50)	3985	3987	A1	(Llopis et al., 2010)
2500 < GWP < 3000					
R-422A	HFC-125/ HFC-134a/HC-600a (85.1/11.5/3.4)	3144	2847	A1	(Fernández-Seara et al., 2010)
R-417B	HFC-125/HFC-134a/HC-600 (79/18.25/2.75)	3027	2741	A1	(Llopis et al., 2011)
1500 < GWP < 2500					
R-407A	HFC-32/HFC-125/HFC-134a (20/40/40)	2107	1923	A1	(Yana Motta S. et al., 2014)
R-407F	HFC-32/HFC-125/HFC-134a (30/30/40)	1825	1674	A1	(Bortolini et al., 2015; Yana Motta S. et al., 2014)
500 < GWP < 1500					
R-407H	HFC-32/HFC-125/HFC-134a (32.5/15/52.5)	1495	1378	A1	-
R-449A	HFC-32/HFC-125/HFO-1234yf/HFC-134a (24.3/24.7/25.3/25.7)	1396	1282	A1	-
R-448A	HFC-32/HFC-125/HFC-134a/HFO-1234yf/HFO-1234ze(E) (26/26/20/21/7)	1372	1260	A1	(Mota-Babiloni et al., 2015; Yana Motta S. et al., 2014)
GWP<500					
R454A	HFC-32/HFO-1234yf (36/64)	244	244	A2L	(Sedliak, 2013)
R454B	HFC-32/HFO-1234yf (68.9/31.1)	465	467	A2L	-

Table 2. Physical, environmental and safety characteristics of R-404A and R-407H (IPCC, 2013; Lemmon et al., 2013)

	R-404A		R-407H	
Composition (% wt)	44.0%	HFC-125	32.5%	HFC-32
	52.0%	HFC-143a	15.0%	HFC-125
	4.0%	HFC-134a	52.5%	HFC-134a
Molecular weight ($g\cdot mol^{-1}$)	97.6		79.1	
Normal boiling point (ºC)	-46.3		-41.1	
Critical temperature (ºC)	72.1		86.5	
Critical pressure (bar)	37.3		48.6	
Glide at 30ºC[a] (K)	0.4		5.4	
Glide at -30ºC[a] (K)	0.7		6.8	
h_{fg} at T=30ºC[a] ($kJ\cdot kg^{-1}\cdot K^{-1}$)	134.4		197.5	
ρ saturated liquid at T=30ºC ($kg\cdot m^{-3}$)	1020.2		1101.3	
h_{fg} at T=-30ºC[a] ($kJ\cdot kg^{-1}\cdot K^{-1}$)	190.0		260.8	
v at T=-30ºC ($m^3\cdot kg^{-1}$)	0.0948		0.1671	
$GWP_{100\ years}$ (IPCC, 2014)	3945		1378	
ASHRAE safety group	A1		A1	

[a]Glide and h_{fg} evaluated at pressure corresponding to the phase change temperature with a vapour title of 50%

Table 3. Number of sensor elements and uncertainties

	Temperature	Pressure	Mass flow rate	Volumetric flow rate	Power consumption	Relative humidity	Test package
Refrigeration cycle	8	3	1	1	1	-	-
Island cabinet	3	2	-	-	1	1	5
Climatic chamber	1	-	-	-	-	1	-
Others	1	-	-	-	-	-	-
Uncertainty (of reading)	± 0.5 K	± 0.3 %	± 0.1 %	± 0.33 %	± 0.5 %	± 2 %	± 0.5 K

Table 4. Refrigerant composition variation during partial drop-in tests and main parameters

Mixture	R-125 (%wt.)	R-134a (%wt.)	R-143a (%wt.)	R-32 (%wt.)	GWP (100y)	Glide (T=35ºC)	h_{fg} (T=35) ($kJ \cdot kg^{-1}$)	Glide (T=-35ºC)	h_{fg} (T=-35) ($kJ \cdot kg^{-1}$)	v (T=-35ºC) ($m3 \cdot kg^{-1}$)
R-404A	44.00	4.00	52.00	0.00	3945	0.4	127.8	0.7	193.5	0.114
90-R-404A,10-R-407H	41.15	8.70	46.80	3.35	3700	1.1	133.5	1.9	200.7	0.118
80-R-404A,20-R-407H	38.30	13.40	41.60	6.70	3432	1.8	139.4	2.9	207.8	0.122
70-R-404A,30-R-407H	35.45	18.10	36.40	10.05	3176	2.4	145.4	3.7	214.9	0.127
R-407H	15.50	51.00	0.00	33.50	1378	5.2	190.8	6.8	265.9	0.176

Table 5. Average experimental values of top-up evaluation and data validation at condenser

Mixture	T_O (ºC)	T_{dis} (ºC)	$\dot{m}$ ($kg \cdot s^{-1}$)	P_C (W)	COP (-)	Q_K (W)	$Q_{K,w}$ (W)	$(Q_K - Q_{K,w}) / Q_K$ (%)
R-404A	-39.9	94.4	0.0072	947	0.89	1212	1185	2.2
90-R-404A,10-R-407H	-39.5	97.9	0.0069	954	0.89	1217	1210	0.5
80-R-404A,20-R-407H	-38.7	98.9	0.0070	969	0.92	1260	1239	1.7
70-R-404A,30-R-407H	-38.9	100.7	0.0066	950	0.94	1239	1222	1.4
R-407H	-36.5	109.2	0.0049	888	1.01	1131	1096	3.0

Table 6. Reference parameters of the evaluation of the three refrigeration systems during 24 hour test

Parameter	R-404A			R-407H		
	T_K = 25ºC	T_K = 35ºC	T_K = 45ºC	T_K = 25ºC	T_K = 35ºC	T_K = 45ºC
Average condensing temperature (ºC)	26.1	35.5	43.8	26.6	35.5	43.6
Deviation during test (K)	0.7	0.7	0.7	0.7	0.7	0.7
Average product temperature (ºC)	-19.9	-20.0	-20.1	-20.4	-20.3	-20.2
Deviation during test (K)	0.5	0.5	0.7	0.5	0.5	0.6
Average climatic chamber temperature (ºC)	25.1	25.1	25.1	25.1	25.1	25.1
Deviation during test (K)	0.8	0.8	0.7	0.8	0.8	0.8
Average climatic chamber RH (%)	57.1	57.1	57.4	56.3	56.3	57.3
Deviation during test (%)	5.5	5.5	5.5	5.4	5.6	5.3