An experimental investigation on the substitution of R134A with HFO1234YF in the domestic refrigerators

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Abstract

The latest international regulations on the reduction of greenhouse gases are strongly redesigning the scenario of use of refrigerants, gradually eliminating the possibility of employing the HFCs. Among all sectors of refrigeration, one of the most affected by these restrictions is the domestic refrigeration. Although for it have been suggested some solutions, such as the construction of household refrigerator operating with the hydrocarbons, there remains the need to find a substitute for R134a. In particular, the substitution may involve both existing machines and already in operation, which can not be loaded with hydrocarbons, and new devices. With the aim of finding a simple implementation solution, in the present work, it is reported an experimental investigation carried out on a domestic refrigerator designed and built to operate with R134A and for which a drop-in with HFO1234YF has been realised. The experimentation has been addressed so as to highlight the behaviour of the system as a result of the drop-in, with a particular interest in the energy performance variation.

Keywords: R134A; HFO1234YF; drop-in; domestic refrigerator; energy saving; environmental impact

Nomenclature

E	electrical energy consumptions	[Wh]
GWP	global warming potential	
h	enthalpy	[kJ kg^{-1}]
HOC	heat of combustion	[mJ kg^{-1}]
LFL	lower flammability limit	[% vol]
P	electrical power absorbed	[W]
p	pressure of the refrigerant	[bar]
OEL	occupational exposure limit	[PPMv]
S_{cab}	external surface of the cabinet	[m^2]
U	Thermal trasmittance of the walls	[Wm^{-2}K^{-1}]
$V_{in,cab}$	internal volume of the cabinet	[m^3]
t	time	[s]
T	temperature	[°C]

Greek Symbols

δ	duty cycle	[%]

Subscripts

1y	along 1 year
air	of air
c	cabinet
cond	condensation, condenser
dis	discharge of the comrpessor
ev	evaporator
f	at freezer
H24	along 1-day
i	at inlet
o	at outlet
pd	during the pull-down test
r	at refrigerator
ref	of refrigerant
suc	suction of the compressor
sor	sorround
ON	phase of working of the compressor
OFF	phase of stop of the compressor

1. Introduction

The focus in reducing the global warming of our planet has led to consider the synthetic refrigerants with more uncertainty. Whilst in recent decades there has been considerable interest in rediscovering the use of natural fluids [1–6], in most real applications still dominate the synthetic fluids such as the hydro-fluoro-carbon (HFC).These fluids, greeted with a considerable enthusiasm at the end of the last century for their zero ODP, now are considered particularly damaging to the environment because of their GWP, which is equal to more than 1000 times that of carbon dioxide. In recent years, there have been some legislative procedures restricting the use of HFCs. In Europe, the phase-out of HFCs has already been scheduled and initiated on 1st of January, 2015[7], banning the use of fluids with a GWP greater than 150 for the household refrigerators. Similar measures have been adopted in Japan while they are being studied in Canada, the United States and Mexico, where it is expected the beginning of the phase-out of HFCs as of January 1 of 2019[8]. Therefore, an impending world needing to replace these refrigerants with others having low GWP exists. In some field, such as domestic refrigeration, it has already been proposed to replace R134a, reference fluid used from the 90s[9], with isobutane (R600a). However, although this solution has already been accepted by the European market, it involves some technical difficulties related to the high flammability of R600a. While the reduced amount of charge present in a domestic refrigerator for the European market is not of particular concern, the manufacturers of the household refrigerator had to redesign some areas of their production plant (i.e. warehouse storage of refrigerant, and charging stations), causing massive investments for the companies involved. Of no lesser importance is the adoption of specific components (i.e. the compressors) able to operate with HCs. Also, as evidenced by Bansal et al. [10] the use of R600a may have high barriers to the American market (US market) because of more stringent standards for fire prevention (UL Standard 250), as well as other markets might be reluctant to such a solution. An alternative solution has been put forward with the introduction into the market of the fourth generation refrigerants: the hydro-fluoro-olefins (HFO) characterised by GWP values less than 10, such as HFO1234ZE and HFO1234yf. To date such fluids have been widely investigated under different points of view:

1. Flammability and toxicity[11–14]
2. Heat transfer properties and Thermodynamic[15–23]
3. Energy performances [22,24–32]
4. Solubility with POE, PAG, and Mineral oil [33–36].

Based on the works just mentioned, it is clear that the majority of experimental investigations, aimed at evaluating the energy performances achievable with HFO, was produced using plants for air conditioning, mobile air-conditioning, and commercial refrigeration. According to [10,37], it is evident the absence of experimental investigation ended to validate the possibility of replacing R134a with HFOs in domestic refrigerators, and at the same time, it highlights the need to investigate in that direction. In this regard, this article presents the experimental analysis of HFO1234YF (Tab. 1 and Fig. 1) as a drop-in replacement for R134A in a frost-free domestic refrigerator.

	HFO1234YF	R134A
Chemical formula or composition [%wt]	$CH_2=CFCF_3$	CH_2FCF_3
Molecular weight [g mol^{-1}]	114.04	102.03
Normal boiling point [°C]	-29.5	-26.1
Critical temperature [°C]	94.7	101.1
Latent heat at -30°C [kJ kg^{-1}]	180.51	219.5
Latent heat at +40°C [kJ kg^{-1}]	132.27	163.0
Specific volume at -30°C [m^3 kg^{-1}]	0.1708	0.2259
GWP$_{100\ years}$	4	1370
Safety Group (Ashrae stand 34-2010)	A2 (A2L)	A1
OEL [PPMv]	400	1000
LFL [% vol]	6.2	None
HOC [MJ kg^{-1}]	n.a.	4.2

Tab. 1. Physical, environmental and safety characteristics of the considered refrigerants [38]

2. Investigation

With the aim to analyse the feasibility of replacing R134a with HFO1234YF in a domestic refrigerator, it has been examined a recently constructed commercial device.

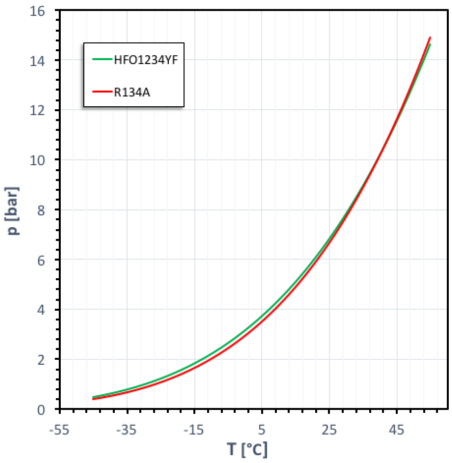

Fig. 1 Saturation pressure for R134A and HFO1234YF

As a starting point of the investigation, it has been carried out a characterization of the fridge as well as it was built regarding energy consumptions and pull-down time. Successively, the refrigerator has been subjected to the "*drop-in*" of R134a with HFO1234YF. Finally, it has proceeded to a new characterization of the apparatus in agreement with what will be described below. Fig. 1 shows the saturation pressures as a function of temperature for the two refrigerants under investigation.

2.1. Experimental facility

The plant used for the experimental investigation is a frost-free domestic refrigerator having a charge of R134A equal to 100 g, as defined by the manufacturer. The refrigerator cabinet is divided into two separate compartments: a three-star freezer (hereto referred to as freezer), and a fresh food storage (hereto referred to as refrigerator). In Tab. 2 are given the additional features of the two compartments. In particular, it shows the value of U obtained experimentally using a thermal conductivity meter.

	Dimension	Freezer compartment	Refrigerator compartment
$V_{in,cab}$	[m^3]	0.131	0.342
S_{cab}	[m^2]	2.20	3.30
U	[Wm^{-2}K^{-1}]	0.369 ±2.4%	0.369±2.4%
U^*S_{cab}	[WK^{-1}]	0.81	1.22
Position	[-]	Upper side	Lower side

Tab.2 Characteristics of the compartments.

For both compartments there is a single cooling circuit (Fig. 2) composed of a hermetic reciprocating compressor, a forced air cooled condenser, a capillary tube and an evaporator operating in forced convection. The evaporator is entirely inserted into the freezer compartment, while an air distribution system, comprising an air delivery duct and an air suction duct, connects the refrigerator to the freezer. In this way, in the freezer compartment, it is established a cold air circulation that allows reaching a low temperature (-18°C). Also, a portion of air coming from the freezer reaches the refrigerator compartment and allows for keeping the air temperature to an intermediate level (+5°C). A damper valve, moved using a thermostatic mechanical drive, controls the amount of air delivered to the refrigerator compartment. The user desired temperature levels be selected using two regulators: a digital type connected to the freezer, and a mechanical type plugged into the refrigerator compartment. The first directly controls the operation of the compressor, while the second acts on the mechanical damper adjustment. The capillary tube is wrapped for a good part of its length (>90%) around the suction pipe of the compressor. In this way, during the lamination, the refrigerant becomes cool thanks to the refrigerant leaving the evaporator. As a consequence, the enthalpy variation of the fluid at evaporator increases, while the refrigerant leaving the evaporator undergoes an additional overheating. However, thanks to the forced ventilation of the condenser placed near to the compressor, a greater superheating of the refrigerant along the suction line does not involve high compressor discharge temperatures to the benefit of its reliability. The employed refrigerator is equipped with an adaptive defrost system, realised using electric resistors arranged in the vicinity of the evaporator. An electronic control system activates a defrost procedure that consists in interrupting the power supply of the compressor and in turning on the electric resistances. In so doing, the frost melts while the air temperature in the freezer rises. During the defrost procedure, the frost melted is ducted to the exterior of the cabinet and collected in a water tray in which are embedded a few coils of the condenser. At the end of defrosting, the compressor is turned on, and the cooling process restarts under a new and severe unsteady state condition: this time the refrigeration duty has to overcome an additional thermal load connected to the raising of the temperature in the freezer occurred during the defrosting. However, the frost melted collected in the water tray facilitates the cooling of the refrigerant at the condenser, reducing in part the increase in energy consumption.

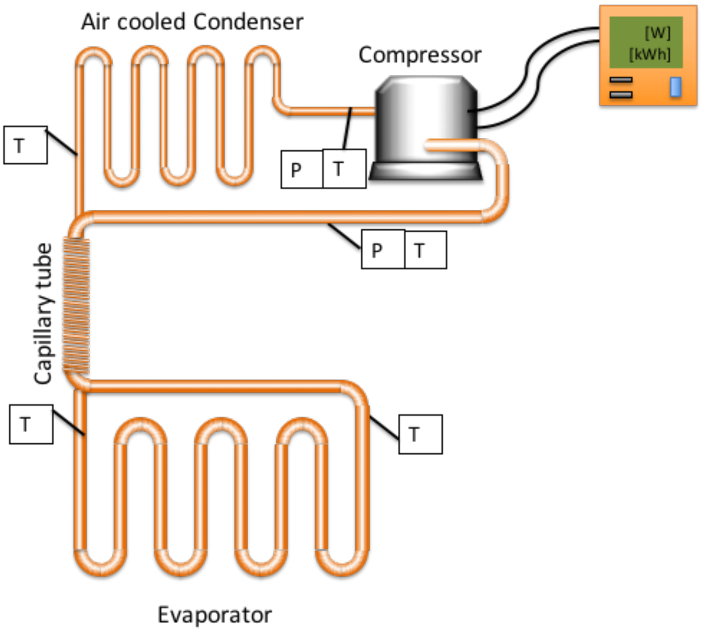

Fig. 2 Sketch of the refrigeration circuit

2.2. Sensors and instrumentations

A set of sensors and instrumentation has resulted in the characterization of the refrigerator before and after the drop-in. The use of the PT100 at entry and exit of each component of the system has allowed for monitoring the temperature of the refrigerant in the key points of the plant. The thermo-resistances were located outside the pipe, with a layer of heat transfer compound (aluminium oxide plus silicon) placed between the sensor and the pipe to provide proper thermal contact. The entire pipe was covered with 25 mm thick flexible insulation. The system of temperature measurement was checked against a sensor positioned in a pocket in a similarly insulated pipe. For various test conditions, the difference between the two measurements always resulted in less than 0.3 °C. To monitor the air temperature within the compartments, in each of them a thermo-resistance was placed in proximity of the thermometer, which the manufacturer placed to control the working of the refrigerator. The temperature measurement obtained by this configuration was compared with that achieved by placing a PT100 at different points. For various test conditions, the difference between the two measurements was less than 1.0 °C.

By neglecting the pressure drops through the heat exchangers, the evaporating pressure and the condensing pressure were measured using a couple of piezoelectric sensors, each of them placed respectively at the suction and the discharge of the compressor. An energy metre allowed to measure both the electric energy and the electric power absorbed by the refrigerator during the tests. A thermo-hygrometer allowed for monitoring the temperature and relative humidity of the air surrounding the cabinet. To measure the different refrigerant charges an electronic balance able to appreciate variations in mass of 0.1 g was used. Each sensor was connected to a 32-bit A/D acquisition system attached to a personal computer that allows a sample rate up to 10 kHz. A virtual instrument called FrigoCheck and realised in LabView, allowed for monitoring and recording each measurement during the tests. Additionally, by resorting to pressure and temperature measurements made in steady state conditions and by using the RefProp 9.1 software [38], for both refrigerants has been possible to calculate the enthalpy value. For different operating conditions and both examined fluids, in agreement with Moffat [39], it was estimated for the enthalpy an accuracy contained in the range: 1.10-1.95%. Tab. 3 contains further information on the sensors and the instruments used.

Transducers	Range	Uncertainty
PT100 4 wires	-100 ÷ 500 °C	± 0.15°C
Humidity sensor	-100 ÷ 70 °C / 0 ÷ 100%	± 0.15°C / ± 1.0%
Piezoelectric absolute pressure gauge	1 ÷ 10 bar; 1 ÷ 30 bar	± 0.2% ± 0.5% F.S
Energy meter	0 ÷ 1 MWh	± 1 %
Balance	0÷100 kg	± 0.1 g

Tab. 3 Characteristics of the sensors and instrumentations employed.

2.3. Experimental procedure

All tests have been developed following UNI-ISO 15502: 2005 concerning conditions for subtropical regions. The refrigerator is housed in a climate chamber capable of maintaining the air temperature at + 25 ° C ± 0.5 ° C and the relative humidity in the range 45-75%. The freezer set-point has been set to -18 °C. The refrigerator thermostat has been adjusted so as to maintain the temperature at + 5 °C. In agreement with what has been shown by Bansal [40] and Hermes [41] it was decided not to take the test pack within of refrigeration compartments, leaving, therefore, the typical inertial phenomena of the thermal load due to the foods and not to the thermodynamic characteristics of the refrigerants. The investigation was divided into two phases:

1. Operating system characterization with R134A as built, to identify the conditions of reference to compare with those obtained following the drop-in;
2. Characterization of the system operating with HFO1234YF.

For each step, two kinds of tests were carried out:

- Pull down: the plant started under the condition of thermal and hygrometric equilibrium between the air surrounding the cabinet and the air inner to the compartments, and all quantities reported in 2.2 were recorded. When the first shutdown of the compressor occurred, the elapsed time to achieve a temperature of -18°C in the freezer compartment was stored.
- 1-day consumption: starting under steady state condition, for which the compressor times to cycle ON and OFF kept happening with a maximum deviation of 5% each other, all quantities reported in 2.2 were recorded for 24 consecutive hours. Following the instructions reported in the UNI-ISO 15502:2005, if at least one defrost procedure happened, the test was considered valid. Also, it was evaluated the average duty cycle using the following equation:

$$\delta = AVERAGE\left(\frac{t_{ON}}{t_{ON}+t_{OFF}}\right) \qquad (1)$$

where t_{ON} and t_{OFF} are respectively the time when the compressor has been working (ON phase) and when the compressor has been kept off (OFF phase).

Not being known a priori the optimal charge of HFO1234YF it was imperative a survey to its detection. To this end, starting with a charge of HFO1234YF equal to 85 g, it has been realised a series of pull-down tests obtained adding 5 g of the refrigerant at a time.

3. Results and discussions

3.1. Pull down tests

Fig. 3 shows the profiles of air temperature inside the freezer ($T_{air,f}$) recorded during the pull-down tests for R134A and different charges of HFO1234YF. By using R134A, the refrigerator has employed 5'650 s to reach a $T_{air,f}$ equal to -18 °C. As a consequence of the drop-in with the HFO1234YF, the plant has changed the pull-down time. In particular, for a mass equal to 105g a delay of 408 s (+7.0 %) has been recorded, while adopting 110g the pull-down time has been reduced by 410 s (- 7.3 %)

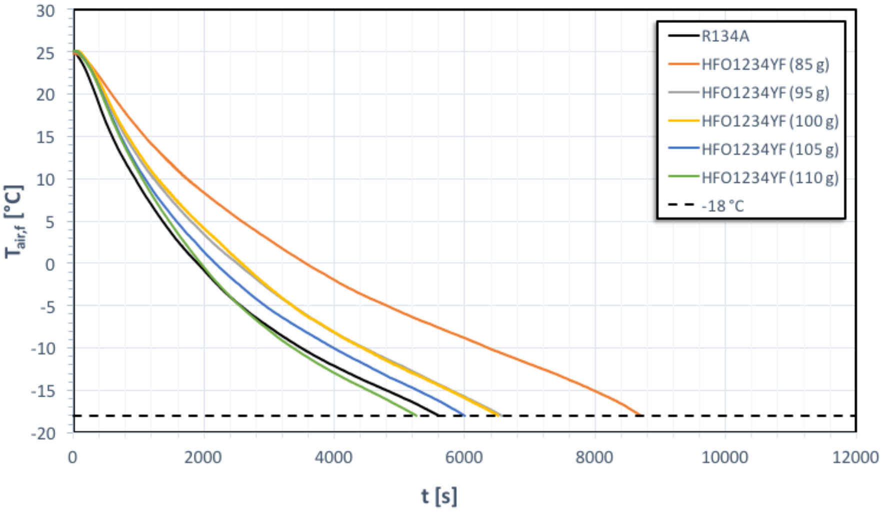

Fig. 3 Temperature profiles of the air inside the freezer compartment

The increase of HFO1234YF mass has led to a variation of electrical energy consumptions due to the pull-down test (E_{pd}). It has been noted (Fig.3 and Fig.4) by increasing the charge of HFO1234ZE the reduction of the pull-down time has not been accompanied by a considerable reduction of the electrical energy consumption compared to R134A. In particular, an HFO1234YF mass equal to 110g has led to a 2% reduction of E_{pd}, which is nearest to the accuracy of the energy meter used (Tab. 3).

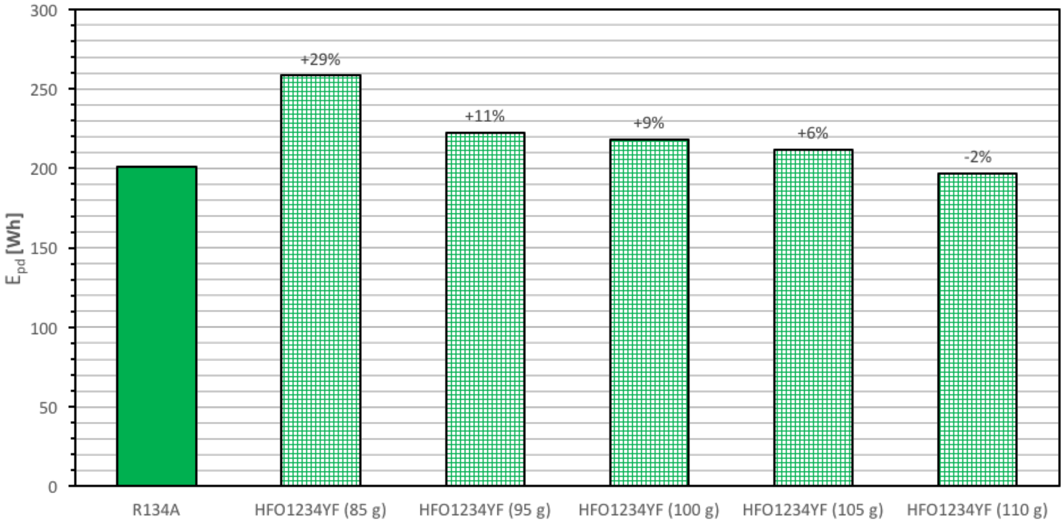

Fig. 4 Electric energy consumption during the pull-down tests

When the overall mass of HFO1234YF is equal to 110g, the compressor has absorbed a higher electric power (P_{el}) than that absorbed adopting a mass equal to 105g (Fig.5). At the same time, the greater mass of HFO1234YF has led to a maximum peak of condensation pressure: 16.1 bar against 12.5 bar. The highest pressure peak value suggests that a further add of refrigerant mass might have been exceeding. Consequently, because the refrigerant charge equal to 110g has resulted both in an energy and in a pull-down time saving, it has been taken as the optimal mass.

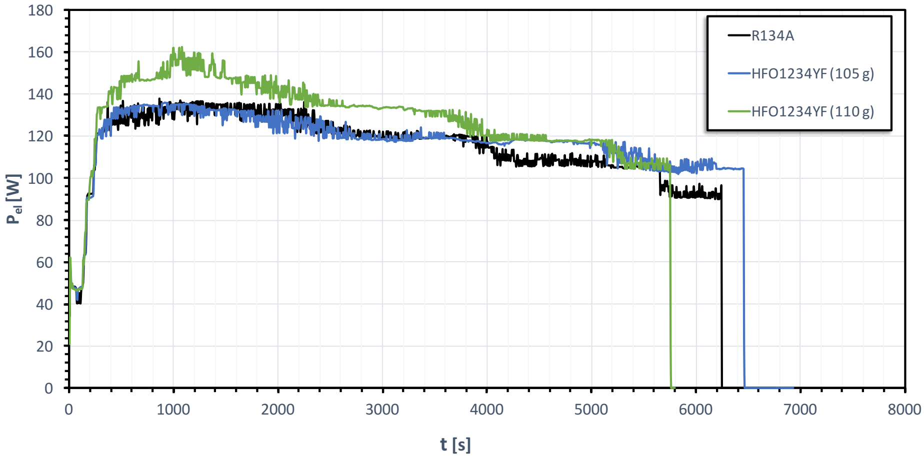

Fig. 5 Electric power absorbed during the pull-down tests

3.2. 1-day tests

Identified the optimal charge for the HFO1234YF, it proceeded with the second phase of the experimentation. In Fig.6 for both refrigerants are reported a test sample long 10'000 s. The profiles there reported show the change of the air temperature inside the freezer ($T_{f,c}$), inside the refrigerator ($T_{r,c}$), and surrounding the cabinet (T_{sor}). It is possible to note the respect of the test conditions given in 2.3, together with the relative humidity variation contained in the range 45-68% (following UNI-ISO 15502: 2005).

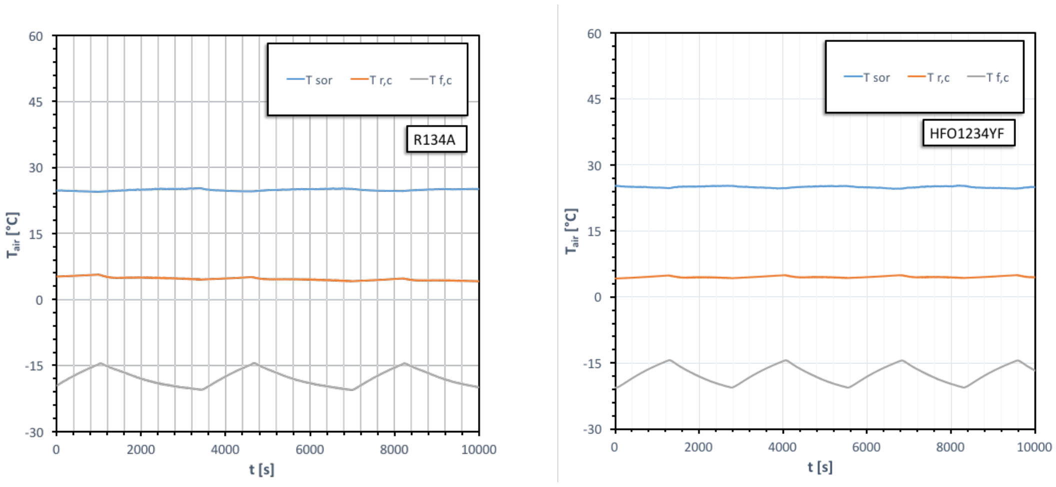

Fig. 6 Air temperature profiles during a sample of the 1-day test.

In particular, due to the act of the thermostat that regulates the working of the refrigerator, the $T_{f,c}$ has changed between -21 °C and -15 °C, with a mean value equal to -18 °C, while the $T_{r,c}$ has undergone smallest variations around the value + 5 °C. Such behaviour is justified by the greater thermal power dispersed through the walls of the freezer compartment than that dispersed through the walls of the refrigerator compartment. In fact, even if the U^*S_{cab} of the freezer compartment is less than that of the refrigerator compartment (Tab. 2), the freezer has been affected by higher thermal dispersion because of the higher difference between T_{sor} and $T_{f,c}$.

For the same test sample, Fig. 7 shows the refrigerant temperature profiles obtained at the key points of the plant, in addition to the representation of ON and OFF cycles of the compressor. By considering the Eq. 1, as a first result of the analysis, one can note that HFO1234YF has allowed for a reducing of the duty cycle: 50.6% against 66.0%. Accordingly, since the loading conditions for both refrigerants have been the same, it can be supposed that HFO1234YF developed a greater cooling capacity.

Looking at the ON phases and focusing on steady-state condition (approximately after 10 minutes), in the low-pressure zone of the plant one can observe slight deviations for the temperatures recorded for both refrigerants; in any case, the differences are contained within a narrow range equal to 1.5 °C. Contrary, HFO1234YF has caused an increase in the temperature levels in the high-pressure zone of the plant. In particular, the condensation temperature of HFO1234YF has been 3°C greater than that of R134A. Regarding the working pressures, the drop-in has led to a slight increase in evaporation pressure (1.11 bar against 0.91 bar) and higher condensation pressure (9.73 bar against 8.88 bar). However, when HFO1234YF is used, a compression ratio (p_{dis}/p_{suc}) equal to 8.8 occurred, which was 12% less than that of R134A. A lower compression ratio suggests that compressor operating with HFO1234YF was subjected to a higher volumetric efficiency. Looking at the thermodynamic properties of both refrigerants [38] and considering the corresponding thermodynamic state at the suction of the compressor, it is worthy to evidence the higher density reached by HFO1234YF: 5.2 kg m^{-3} against 3.8 kg m^{-3}. The better volumetric efficiency and the higher density at the suction of compressor suggest HFO1234YF has led to a mass flow rate greater than that obtained with R134A. To better understand the consequence of the mass flow rate increasing, one has to wonder what happened at evaporator regarding enthalpy. Looking at Fig. 8, as a result of the drop-in, one can note a significant reduction of the enthalpy variation at the evaporator (-20.1%), but, at the same time, the superheat degree has experimented a reduction (2.6°C) as well. The decrease of the duty cycle, the increasing of the mass flow rate, and the superheat degree demonstrate that drop-in with HFO1234YF has allowed for augmenting the cooling capacity of the fridge.

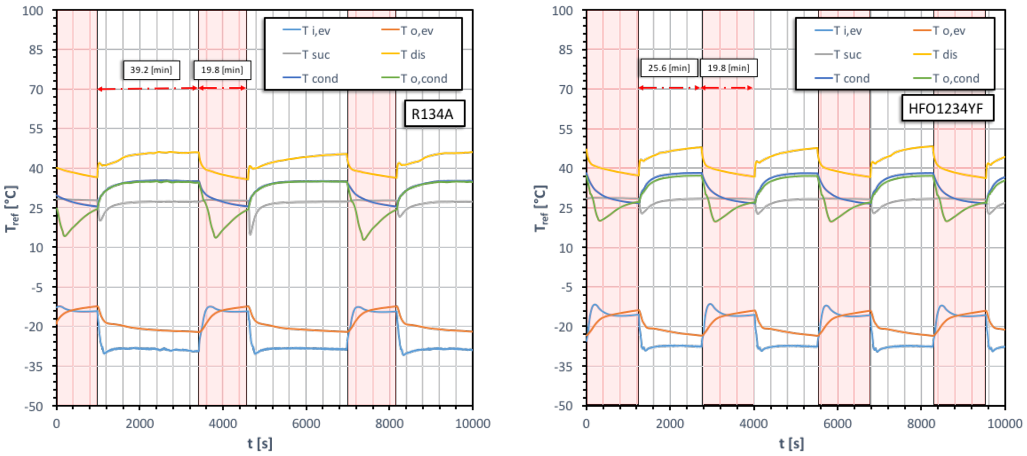

Fig. 7 Refrigerant temperature profiles at different points of the plant during a sample of a 1-day test; the red bands represent the OFF phase.

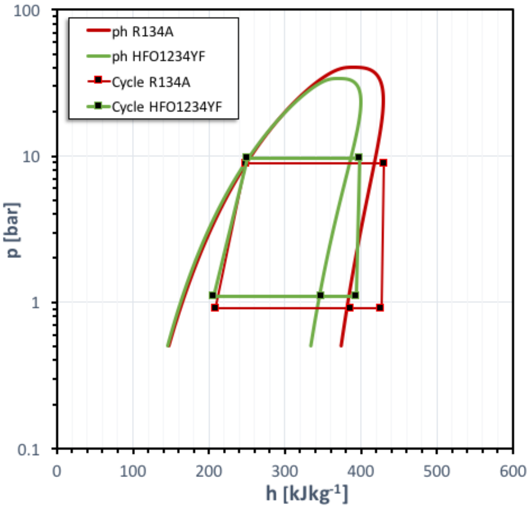

Fig. 8 Representation in the p-h plan of the thermodynamic cycle during the steady state conditions

By observing the compression phase plotted in Fig. 8, it is evident the influence of the air ventilation employed for the condenser (as described in 3.1). For both refrigerants, the difference of the enthalpy between the inlet and the outlet of the compressor has been slight. In particular, HFO1234YF has led to a greater specific compression work (5.01 kJ kg^{-1}K^{-1} against 3.35 kJ kg^{-1}K^{-1}), which, together a higher discharge temperature, suggests a worst isentropic efficiency of the compressor. This phenomenon and the higher mass flow rate justify the higher electric power absorbed (Fig.9) by the compressor after the drop-in: 60.2 W against 50.8 W. In a similar way, one can validate what previous has been reported in Fig. 5 as well.

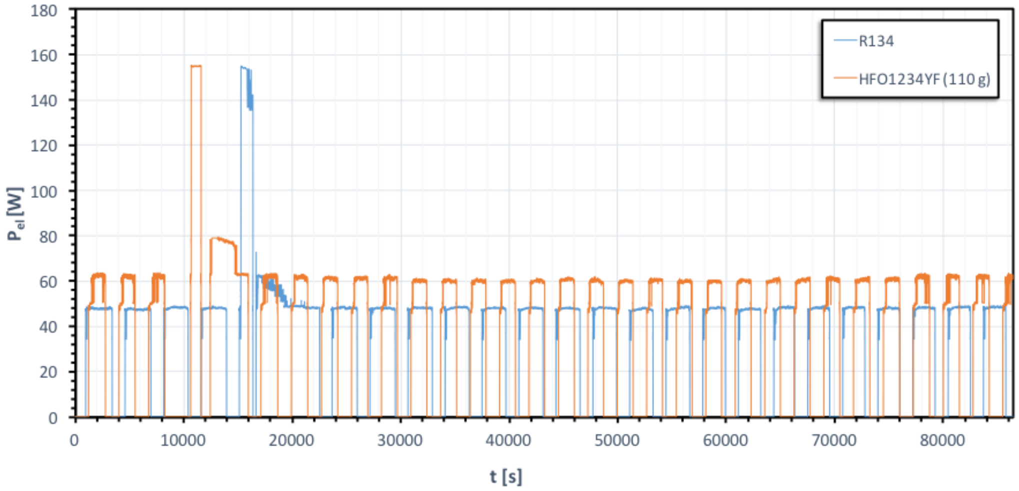

Fig. 9 Electric power absorbed during the 1-day tests and highlighting of defrosting phase as required by the test conditions given in 2.3.

However, the higher electric power absorbed after the drop-in has not led to an increase of the energy consumptions. In fact, a better energy performance due to HFO1234YF can be seen in Fig. 10, where are reported the electric energy consumptions recorded over a 24-hours test and the projections of annual consumptions, calculated as follows:

$$E_{1y} = E_{H24} \times 365\ days \tag{2}$$

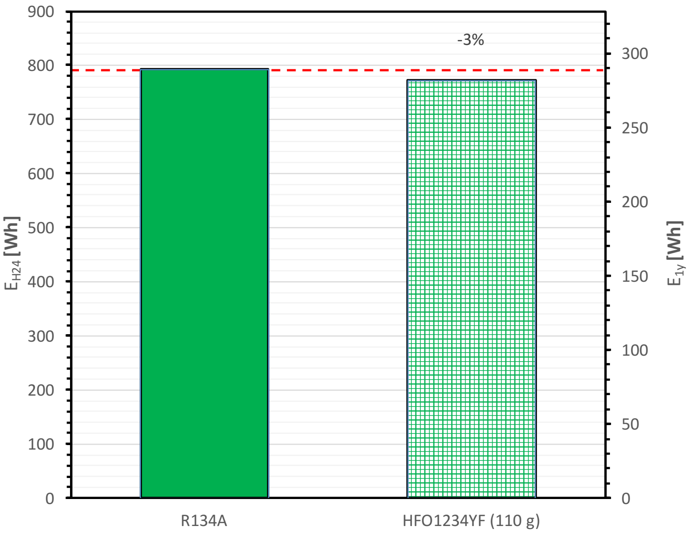

Fig. 10 Daily and yearly energy consumptions for both refrigerants.

After 24 hours of working with HFO1234YF, the plant has recorded an energy saving equal to 3%. Although this result is connected to the particular conditions adopted in this experimentation, it is likely that the energy saving recorded can also be expected in the presence of openings and closings of the door as happens in reality, because the dynamic behaviour of the plant has been the same for both refrigerants. It is worthy to note that such energy saving has to be attributed not only to the fluid but also to the optimization of the charge made in the present study. In fact, it is right to mention that under different circumstances, other researchers [18,28,29] showed that HFO1234YF can lead to an increase in energy consumptions when compared to R134a. On the contrary, as suggested by Bansal [40], HFO1234YF can offer up to 5% energy saving with simple cycle modifications. However, even if the energy saving, achievable as a result of a drop-in with HFO1234YF, was negligible, it should be noted that such a refrigerant allowed for preserving the operating conditions of the plant analysed, except the limitation due to a lower saturation pressure. Considered, therefore, the reduced GWP value of HFO1234YF, it can be said that such refrigerant may be one of the potential candidates to replace R134A in domestic refrigerators, both for plants already in operation and for new devices. Furthermore, the adoption of HFO1234YF would be at zero cost for the manufacturers of the household refrigerators. In fact, such as it has been shown here, it is not necessary to make any changes to the cooling circuit of a plant designed to operate with R134A, but it highlights only the need to achieve an optimization for the HFO1234YF charge.

4. Conclusions

In this paper an experimental comparison between R134A and HFO1234YF has been presented, when they are used as refrigerants for a domestic refrigerator. In particular, the analysis was carried out by operating the drop-in of R134A with HFO1234YF in a commercial plant of the type frost free and provided with a freezer and a refrigerator compartment. The analysis, conducted under temperature and humidity controlled, has been realised using two kinds of tests: pull down for the identification of the optimal charge of HFO1234YF and 1-day for the detection of the electric energy consumption. Regarding the test conditions and to the plant analysed, it can be concluded that:

- The drop-in of R134a with HFO1234YF maintains the functionality of the plant regarding the temperature reached in the refrigerating compartments.
- The charge of HFO1234YF which preserves the behaviour of the plant regarding the temperature pull-down time has resulted greater than 10% of that of R134a.
- HFO1234YF has allowed for reducing of a 7.3 % the pull-down time and of a 23% the duty cycle.
- HFO1234YF has led to a higher condensation pressure but to a higher mass flow rate thanks to a better volumetric efficiency and a greater density at the suction of the compressor.
- HFO1234YF has allowed for an increasing of the cooling capacity.
- A worst isentropic efficiency of the compressor has been observed when HFO1234YF is used. Although, after 24 hours of working a 3% energy saving has been obtained.

- HFO1234YF can be used in plants already in operation (drop-in) and as a refrigerant for new devices.

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