An experimental investigation of the energetic performances of HFO1234yf and its binary mixtures with HFC134a in a household refrigerator

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ABSTRACT

In this paper, a comparative experimental analysis between HFC134a, HFO1234yf and a refrigerant mixture of HFC134a/HFO1234yf (10/90% weight) implemented in a domestic refrigerator is introduced. Adding 10% of HFC134a to HFO1234yf, the mixture becomes nonflammable with GWP still less than 150.The experimental tests have been conducted under sub-tropical conditions in accordance with the UNI-EN-ISO15502 standard.Two kinds of tests have been shown: pull down and 1-day energy consumption. The results show that HFC134a/ HFO1234yf (10/90% weight) is the best drop-in refrigerant fluid for HFC134a in the domestic refrigerator used for the experimental tests. The refrigerant mixture has the closest behaviour to that of HFC134a in terms of temperatures and pressures. Furthermore, the cycle working with the optimal charge of the mixture shows an energy saving of 16 and 14% with respect to HFC134a and HFO1234yf, respectively.

Keywords

HFC134a
GWP
EU regulation no 517/2014
HFO1234yf
HFC134a/HFO1234yf mixture (10/90% weight)
Domestic refrigerator
Energy consumption

1. Introduction

The refrigerator/freezer is one of the most important and the greatest energy-consuming home appliances. Domestic refrigeration is almost exclusively based on vapour compression plants. One of the most employed refrigerants for domestic scope is HFC134a due to its excellent thermodynamic properties (Greco and Vanoli, 2006). HFC134a is an HFC fluid with zero ODP but with a 100 year GWP of 1301. Due to climate change concerns, many governments have taken action to regulate greenhouse gas emissions as a consequence of the Kyoto Protocol (Kyoto, 1997). National laws and regulations implementing the Kyoto Protocol differ from one another, but they typically call for a phase down of HFC consumption (Aprea et al, 2012, Aprea et al, 2013, Cabello et al, 2015, Cabello et al, 2017, Sarbu, 2014). More recent standards (either already taken or suggested) at local stage (regional, national, municipal) are even more rigorous. Based on the UE Regulation No. 517/2014 (EU n. 517/2014) in domestic refrigerators and freezers the use of HFCS with a GWP of 150 or more has been banned from 1 January 2015. In reaction to global warming regulations, a fourth generation of low GWP refrigerants has been developed following chlorofluorocarbons (CFCs), hydrochlorofluorocarbons

(HCFCs) (Aprea, Greco, 1998, Greco et al, 1997), and hydrofluorocarbons (HFCs). In this new generation of refrigerant fluids, there are hydrofluoroolefins (HFO) that are derivatives of olefins rather than alkanes (paraffins). Two popular HFO refrigerants are HFO1234yf and HFO1234ze. Both HFOs have a zero ozone depletion potential (ODP) with extremely low global warming potentials (GWP). Because of their lower GWP values, these refrigerants have a much shorter life cycle in the atmosphere. In this paper, attention is paid on HFO1234yf. DuPont and Honeywell jointly identified HFO1234yf as a possible alternative to HFC134a.

HFO1234yf has thermodynamic properties very similar to HFC134a but with a GWP of 4. It also has low acute toxicity. The only problem is that it is mildly flammable with a lower flammability limit (LFL) of 6.2 in air at 20–25 °C. Recently, one of the major automotive manufacturers refused to adopt HFO1234yf in the air conditioning plant, due to its flammability of 150 (Lee et al., 2013). To overcome this problem, it is possible to add pure HFC134a to HFO1234yf (with a composition of 10/90% weight) and the mixture becomes non-flammable with GWP still less than 150 (Lee et al., 2013). This mixture is also cheaper and more compatible than HFO1234yf.

Many papers have been published on HFO1234yf as a drop-in replacement of HFC134a in the open literature (see Janković et al, 2015, Lee, Jung, 2012, Mota-Babiloni et al, 2014, Righetti et al, 2015, Sethi et al, 2016, Wang, 2014, Yataganbaba et al, 2015, Zilio et al, 2011). However, only few papers are available on its mixture with HFC134a (see Chen et al, 2015, Kondo et al, 2013; Lee and Jung, 2012; Mota-Babiloni et al., 2014).

In our previous work (Aprea et al., 2016) the substitution of HFC134a with HFO1234yf in a domestic refrigerator has been studied using an experimental investigation. The results clearly show that HFO1234yf may be a drop-in replacement of HFC134a. The major disadvantages with the use of this fluid are: i) the greater electric power absorbed by the compressor (about +18%); ii) it is mildly flammable (ASHRAE Safety Classification A2L); and iii) it is a very expensive refrigerant (around 200€/kg). In the present paper, attention is devoted to the non-flammable mixture HFC134a/HFO1234yf (10/90% weight) with a GWP just lower than 150, according the EU Regulation mentioned above. The main interesting properties of HFO1234yf, HFC134a and HFC134a/HFO1234yf mixture (10/90% weight) are reported in Table 1.

Table 1. Properties of HFO1234yf, HFC134a, and HFC134a/HFO1234yf (10/90% weight).

Refrigerant	**Chemical composition**	**Molecular weight (g/mol)**	**Critical T (℃)**	**Critical p (bar)**	**Normal boiling point (℃)**	**Safety class**	**ODP**	**GWP**
HFC134a	CH_2FCF_3	102	101.1	40.59	−26.0	A1	0	1301
HFO1234yf	$CF_3CF{=}CH_2$	114	94.7	32.81	−29.5	A2L	0	4
HFC134a/HFO1234yf	$CH_2FCF_3/CF_3CF{=}CH_2$	112.8	95.3	34.51	−29.4 $\Delta T_g = 0.04$	N.A.	0	133.7

The thermodynamic properties of the fluids studied in the present paper are evaluated with the computer program RefProp 9.1. The mixture mentioned above has very similar properties to HFC134a and is a quasi-azeotropic mixture with a temperature glide lower than 0.1 K.

This paper reports the experimental tests with the energetic characterisation of a domestic refrigerator working with the HFC134a/HFO1234yf (10/90% weight) mixture in comparison with HFC134a and pure HFO1234yf.

2. Experiments

2.1. The experimental setup

In this work the tests are carried out in an experimental test facility which consists of a domestic refrigerator that belongs to the A+ class for energy efficiency, originally designed for a refrigerant charge of 100 g of HFC134a. A detailed description of the apparatus is reported in Aprea et al. (2016). The system has two separate compartments: a freezer (at the upper side) and a fresh food storage (at the lower side), with a total volume of 473 l. The main components of the circuit are a hermetic reciprocating compressor, a forced air cooled condenser, a capillary tube and an evaporator operating in forced convection. The evaporator is placed in the freezer and an air distribution system connects the refrigerator to the freezer. The control of the refrigerator's temperature takes place through a damper valve that regulates the amount of air delivered to the refrigerator compartment. The scheme is fitted with an adaptive defrost control system that lies in electric resistors arranged in proximity of the evaporator. A schematic of the whole plant and of all the sensors is shown in Fig. 1.

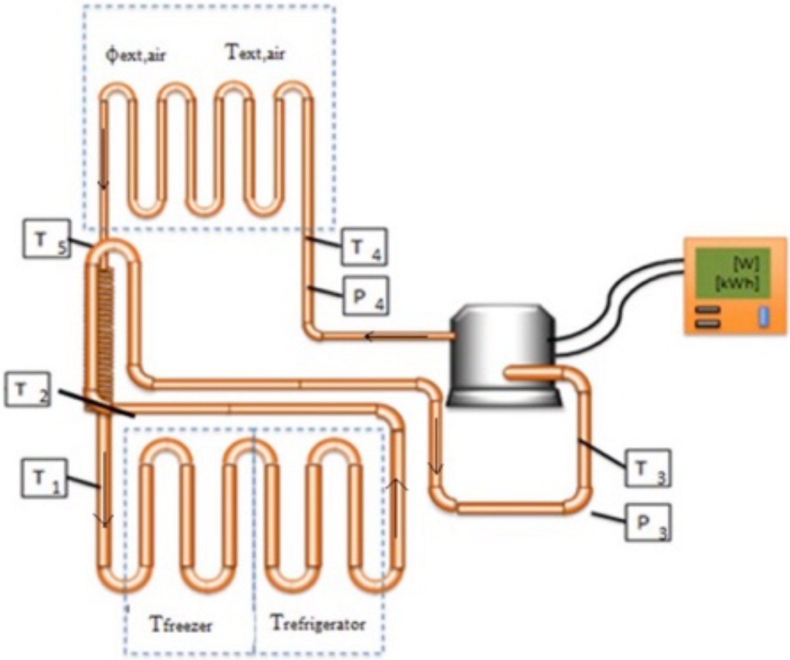

Fig. 1. A sketch of the experimental plant.

The circuit is instrumented with eight calibrated PT100 thermo-resistances with an accuracy of ±0.15 K placed inside the freezer, inside the refrigerator compartment, at the compressor inlet and outlet, at the condenser outlet, at the evaporator inlet and outlet, in the test room in proximity of the refrigerator cabinet. A thermo-hygrometer monitored the temperature and relative humidity of the air in the test room (accuracy ±0.15 K, ±1%).

Pressure measurements have been carried out using two piezoelectric absolute pressure gauges (accuracy ±0.2%) placed at the inlet and the outlet of the compressor. An energy meter measured both the electric energy and the electric power absorbed by the refrigerator during the tests (accuracy ±1%). To evaluate the refrigerant charge of the plant, an electronic balance was used with an accuracy of ±0.1g. According to Moffat (1988) the uncertainty on the mixture mass fraction is ±1%.

Each sensor was connected to a 32-bit A/D acquisition system attached to a personal computer. Frigocheck 2.0, a virtual instrument developed in Labview area, has been utilised for real-time monitoring of pressure and temperature evolutions in the whole domestic experimental apparatus.

2.2. Experimental procedure

With the measured, steady state values of pressure and temperature along the circuit, it is possible to evaluate the refrigerant enthalpy using the computer program RefProp 9.1 (Lemmon et al., 2010). For different operating conditions, in agreement with Moffat (1988), an accuracy within the range of ±1.10–1.95% was estimated for the enthalpy.

The experiments have been conducted according to the UNI-EN-ISO15502. During continuous running tests, ambient temperature was maintained at 25 °C with a relative humidity confined in the 45–75% range. The freezer and the refrigerator air temperatures have been settled at −18 and 55 °C, respectively.

Initially, the experimental apparatus was charged with 100 g of HFC134a for conducting baseline tests. Later on, HFC134a was recovered from the system. Then, the refrigerator was charged with the optimal charge of HFO1234yf (115 g) found in a previous study (Aprea et al., 2016) and different kinds of experimental tests have been carried out. Finally, the HFO1234yf was recovered, and the experimental plant was charged with different amounts (between 100 and 137.5 g) of refrigerant mass of the HFC134a/HFO1234yf mixture (10/90% weight).

Two kinds of experimental tests have been carried out: the pull-down and 1-day consumption tests. During the pull-down tests, the optimal charge of the refrigerant mixture has been identified.

3. Experimental results and discussion

Pull down time is the time required to reduce the air temperature inside the refrigerator from the ambient condition (25°C) to the desired freezer and cabinet air temperatures of −18 and 5 °C, respectively (according to UNI-EN-ISO15502). The freezer air temperature versus time during the pull-down tests is reported in Fig. 2.

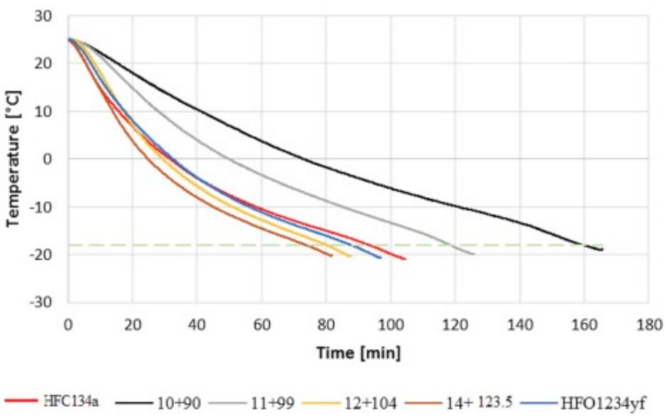

Fig. 2. Freezer air temperature as a function of temperature in pull down tests.

To identify the optimal charge of the HFO/HFC mixture, the amount of refrigerant mass has been varied between 100 and 137.5 g, whereas the charges of HCF134a and HFO1234yf have been fixed at 100 g and 115 g, respectively. It can be observed that with HFC134a the desired freezer air temperature was reached in 93′12″, while with HFO1234yf in 87′36″. Therefore, with HFO the pull-down time was reduced (−6%). An increase in the pull-down time by +71 and +27% was observed using the refrigerant mixture with charges of 100 and 110 g, respectively. This is due to an insufficient refrigerant quantity, whereas at 116 and 137.5 g the times are 80′ and 73′36″, leading to a significant reduction as compared to both HFC134a and HFO1234yf.

The electrical energy consumption (Epd) during the pull-down test for HFC134a, HFO1234yf and HFC134a/HFO1234yf mixture (with the different refrigerant charges) is reported in Fig. 3. According to this figure, the minimum energy consumption during the pull-down tests can be achieved with the refrigerant mixture at the refrigerant charges of 116 and 137.5 g. In particular, the mixture with these refrigerant charges leads to a reduction of Epd of about 10% as compared to HFC134a.

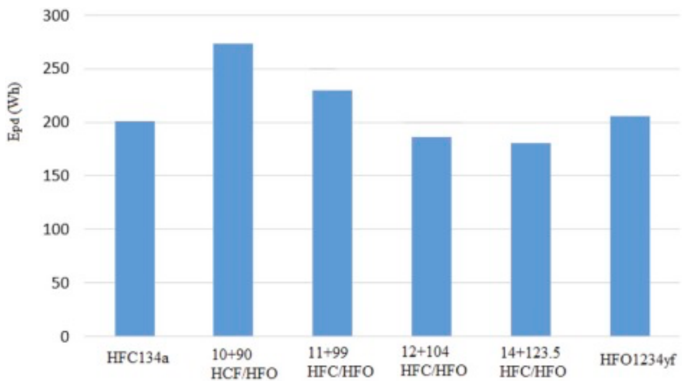

Fig. 3. Electric energy consumption during the pull-down tests.

The condensing pressure as a function of time in pull down tests is reported in Fig. 4. The higher peak values of the condensing pressure are those pertaining to the refrigerant mixture with a mass of 137.5 g (15.8 bar) and to pure HFO1234yf (15.6 bar), whereas the mixture with a charge of 116 g shows a lower pressure value (14.9 bar).

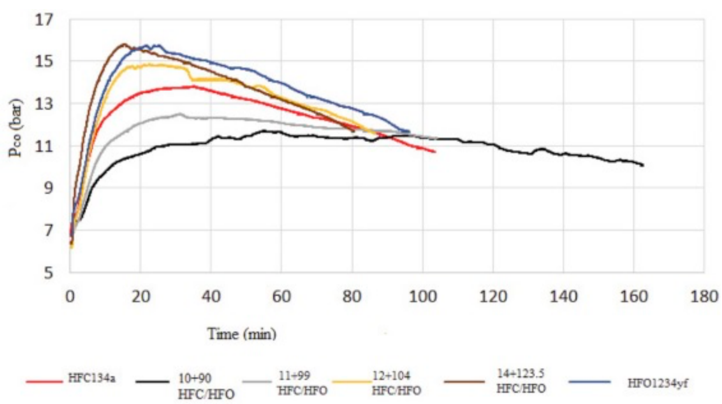

Fig. 4. Condensing pressure as a function of time in pull down tests.

In 1-day consumption tests the energy consumptions in a 24 h test for each refrigerant fluid have been carried out to characterise the actual operating conditions of the domestic refrigerator. To operate in accordance with the UNI-EN-ISO15502, it is also necessary that these test the refrigerator experiences at least one defrost cycle.

Fig. 5 reports the yearly (E1y) electric energy consumption for all the refrigerant fluids. EH24 is recorded over a 24-hour test and E1y is the projection of annual consumptions, calculated as follows:

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

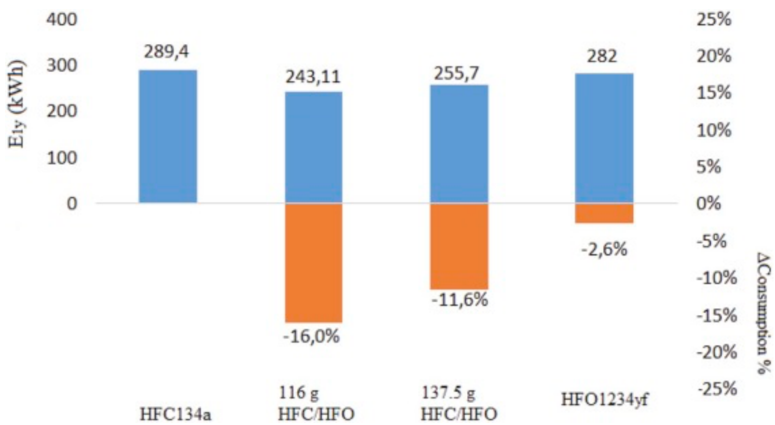

Fig. 5. Yearly electric energy consumption and energy saving for the refrigerant fluids in a 24-hour test.

The percentage variation between each refrigerant fluid and HFC134a is also reported at the bottom of the figure.

The figure clearly shows that after 24 hours of working with the refrigerant mixture with charges of 116 and 137.5 g, the plant has recorded energy savings equal to 16 and 11.6% with respect to HFC134a, respectively. The charge of 116 g is better than 137.5 g because it achieves: i) a lower condensing pressure (−6%) and ii) a lower energy consumption (−5%). Furthermore, the lower charge (−16%) ensures cost saving because HFO1234yf is a very expensive refrigerant. Therefore, the mass of 116 g can be considered the optimal charge of HFO1234yf/HFC134a (90/10% in weight) and it best reproduces the behaviour of the refrigerator when it operates with HFC134a. Indeed, with this refrigerant charge the mixture overperforms pure HFO achieving lower: i) condensing pressure; ii) pull down time; and iii) electric energy consumption in pull time tests and in 24-hour tests.

Table 2 summarises the experimental results obtained for the refrigerant fluids in 1-day tests. This table reports the refrigerant charge, the daily and yearly electric consumption, the electric power consumption during the ON time, the average ON and OFF time (the time when the compressor has been working and when has been kept off), and the average duty cycle δ. The last parameter was evaluated using the following equation:

$$\delta = AVERAGE\left(\frac{t_{ON}}{t_{ON}+t_{OFF}}\right) \tag{2}$$

Table 2. Comparison between the refrigerant fluids during the 1-day tests.

Refrigerant	**Charge (g)**	**E_{H24} (kWh day^{-1})**	**E_Y (kWh y^{-1})**	**Electric power (W)**	**t_{ON}(min)**	**t_{OFF}(min)**	**δ**
HFC134a	101	0.79	289.4	48.0	35.63	19.83	0.64
HFO1234yf	115	0.77	282.0	54.2	24.67	20.90	0.54

Refrigerant	Charge (g)	E_{H24} (kWh day^{-1})	E_Y (kWh y^{-1})	Electric power (W)	t_{ON}(min)	t_{OFF}(min)	δ
HFC134a/HFO1234yf (10/90% weight)	116	0.66	243.11	51.8	20.63	20.70	0.50

In this table, we can observe that using 116 g of HFC/HFO mixture yields a better parameter in comparison with HFC134a and pure HFO1234yf. The electric power during ON time is slightly higher for the mixture with respect to HFC134a but the ON time is significantly lower (−42%).

The high and low-pressure trends of the tested vapour compression cycle for the refrigerator working with HFC134a, HFO1234yf, and HFC/HFO mixture (at 116 g refrigerant charge), respectively are plotted in Fig. 6, Fig. 7, Fig. 8. One can observe that the high HFO1234yf pressure is approximately 10% greater than HFC134a, whereas that of the mixture is almost the same. Moreover, HFO1324yf presents a roughly 20% larger peaks of high pressure in correspondence of defrost cycle, whereas that for the mixture is only 5%. Therefore, with HFO1234yf the whole circuit is subject to greater pressure, resulting in increases of losses and mechanical stress for compressor with respect to the refrigerant mixture. The evaporating pressures of all the refrigerant fluids are quite the same.

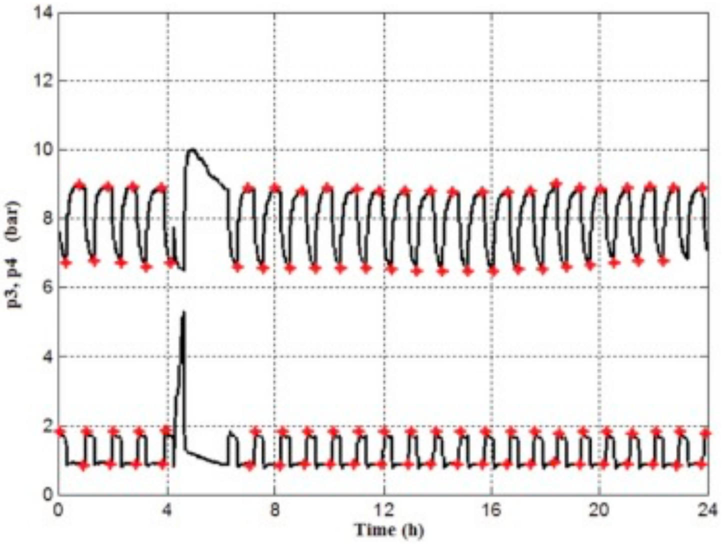

Fig. 6. Pressures of HFC134a during 1-day tests.

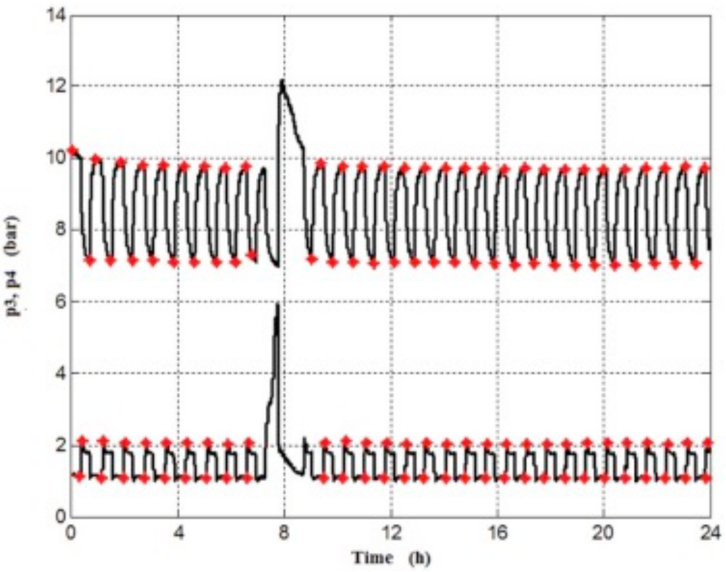

Fig. 7. Pressures of HFO1234yf during 1-day tests.

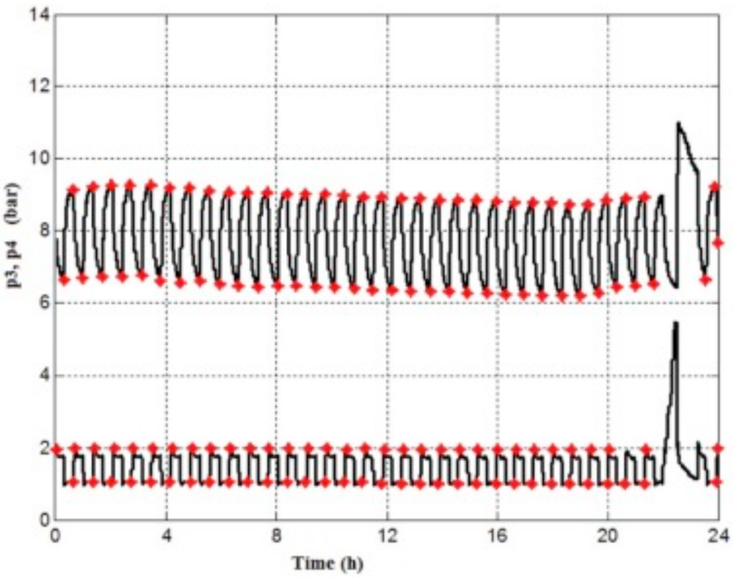

Fig. 8. Pressures of HFC134a/HFO1234yf (10/90% weight) with a charge of 116 g during 1-day tests

The temperature trends in the key points of the plant during an operation time of 24 h for all the refrigerant fluids are shown in Fig. 9, Fig. 10, Fig. 11. It is also possible to read from the figures the superheating (i.e. T3 − T1) because the pressure drops in the evaporator are negligible.

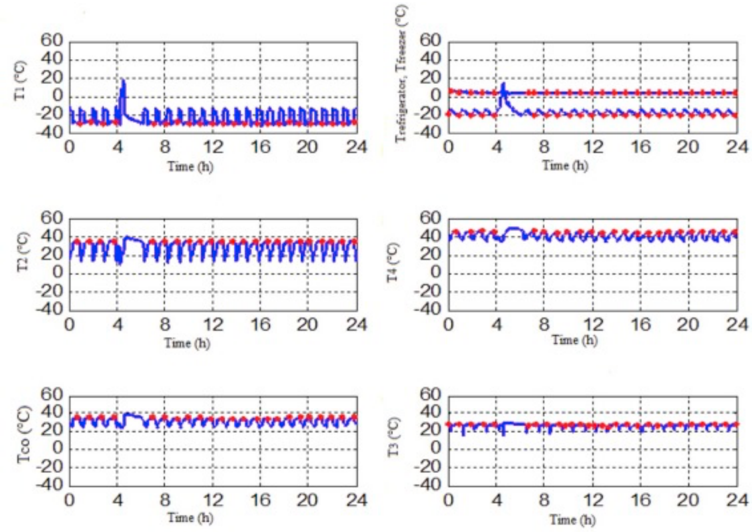

Fig. 9. Temperatures of HFC134a during 1-day tests

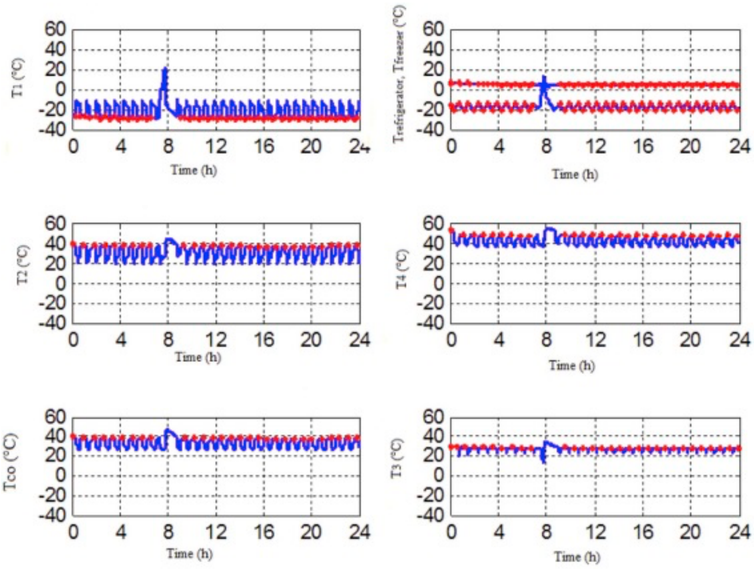

Fig. 10. Temperatures of HFO1234yf during 1-day tests.

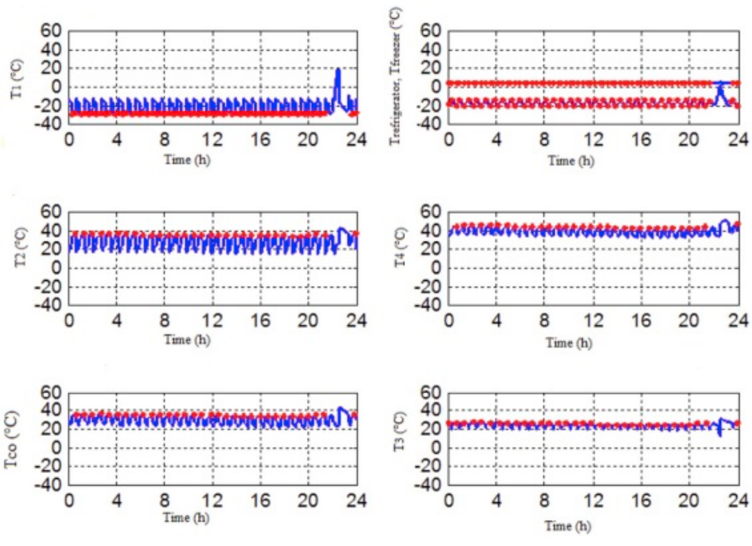

Fig. 11. Temperatures of HFC134a/HFO1234yf (10/90% weight) with a charge of 116 g during 1-day tests.

From the figures, one can observe that HFC134a and HFC/HFO mixture exhibits the same behaviours. The difference between the temperature of the mixture and that of HFC134a at the evaporator, condenser and capillary inlet follows within +0.3 K. The refrigerant mixture registers a small decrease of evaporator superheating, with respect to HFC134a, due the greater charge of the former refrigerant (116 g) than the latter (101 g). The temperature of pure HFO is always higher than that of both HFC134a and the refrigerant mixture. Therefore the refrigerant mixture best reproduces the HFC134a behaviour and then can be an optimal drop-in substitute in existing plants.

4. Conclusions

In this paper, a comparative experimental analysis between HFC134a, HFO1234yf and a refrigerant mixture of HFC134a/HFO1234yf (10/90% weight) implemented in a domestic refrigerator is introduced. Adding 10% of HFC134a to HFO1234yf, the mixture becomes non-flammable with GWP still less than 150.

The experimental analysis has been carried out in a commercial refrigerator designed for working with HFC134a. It consists of a commercial frost free device with a freezer and a refrigerator compartment. The experimental tests have been conducted under sub-tropical conditions in accordance with the UNI-EN-ISO15502 standard. Two kinds of tests have been shown: pull down and 1-day energy consumption.

From the experimental evidence the following conclusions can be drawn:

- The refrigerant mixture HFC134a/HFO1234yf (10/90%w) can be considered as a drop-in substitute of HFC134a in an existing plant.

- The optimal charge of the refrigerant mixture was 116 g, 16% greater than that of HFC134a.

- The pull-down time of the plant working with the refrigerant mixture was reduced with respect to both HFC134a (−14%) and pure HFO (−9%).

- The use of the mixture leads to a reduction in the electrical energy consumption during the pull-down tests of about 7.5 and 10% as compared to HFC134a and HFO1234yf, respectively.

- After 24 hours of working the mixture leads to an energy saving equal to 16 and 14% with respect to HFC134a and HFO1234yf, respectively.

- The average duty cycle obtained with the mixture in 1-day tests is 22 and 7.4% lower than that of HFC134a and pure HFO, respectively.

- Temperatures and pressures measured in key points of the plant are very similar for the refrigerant mixture and HFC134a, whereas the pressures and temperatures of pure HFO are always higher. Therefore the refrigerant mixture best reproduces the HFC134a behaviour.

On the basis of all the above-mentioned considerations, we can say that HFC134a/HFO1234yf (10/90% weight) is the best drop-in refrigerant fluid for HFC134a in existing plants. More advantages of the refrigerant mixture with respect to pure HFO1234yf are that the mixture becomes non-flammable and less expensive.

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