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HFO1234yf as a Drop-in Replacement for R134a in Domestic Refrigerators: A Life Cycle Climate Performance Analysis

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ABSTRACT

Based on recent surveys, about 17% of the overall energy consumption comes out from refrigeration. Nowadays the use of environmentally friendly refrigerants has become a "must" in order to mitigate the global warming. A Vapor Compression Plant (VCP) produces typically both a direct and an indirect contribution to global warming where the first one is related to the Global Warming Potential (GWP) of the fraction of refrigerant charge, released accidentally in the atmosphere or not recovered when the system is scrapped. The employment of an environmental metric, in order to facilitate the choice of low GWP refrigerants, has to be implemented in VCPs. LCCP is one of the most comprehensive parameters which takes into account all the relevant indirect emissions related to the whole process of VCP and refrigerant manufacturing and their transportation. In this paper the results of an experimental comparative analysis between R134a and HFO1234yf, implemented in a domestic refrigerator, are presented. It have been measured energy consumptions under sub-tropical conditions in accordance with the UNI-EN-ISO15502. In addition a LCCP analysis, to evaluate the environmental impact due to HFO1234yf used as a substitute of R134a, is reported.

Keywords: Vapor compression system, Drop-in, R134a, HFO1234yf, LCCP.

1. INTRODUCTION

Roughly 17% of the worldwide energy consumption originates from refrigeration. Most modern refrigeration units are based on vapor compression plants (VCP). Since the beginning of their commercial diffusion, the development of the latter has been strictly related to the characteristics of working fluids. The traditional refrigerant fluids, i.e. CFCs and HCFCs, have been banned by the Montreal Protocol [1] because of their contribution to the disruption of the stratospheric ozone layer (Ozone-Depleting substances ODs) [2-4]; CFCs have been banned since 1996. In most of the European countries the use of the HCFCs has become forbidden in new systems since 2000, leaving HFCs as the only fluorinated refrigerants permitted in the EU whom do not contain chlorine and hence have zero Ozone Depletion Potential (ODP). Human activities have increased the concentration of greenhouse gases in the atmosphere. This resulted in a substantial warming of earth surface and atmosphere that adversely affected the natural ecosystem [5]. Thus, in addition to zero ODP, the working fluids in refrigeration systems must also have low global warming potential (GWP). Emissions of HCFs currently contribute about 1 % of worldwide greenhouse gas emissions, but they are growing by 8-9 % per year and are likely to further growth in the future [6]. The Kyoto Protocol [7], pursuant to the United Nations Framework Convention on Climate Change (UNFCCC), sets binding targets for greenhouse gas emissions. National laws and regulations implementing the Kyoto Protocol differ from one another, but they typically call for a phase down of HFC consumption. More recent measures, already adopted or proposed at local level (regional, national, municipal), are even more stringent. Based on the EU Regulation N°517/2014 in domestic refrigerators and freezers, the use of HFCs, with 150 or more as GWP, has been banned from 1 January 2015. These restrictions are forcing the shift to a fourth generation of refrigerants with both ODP and GWP regulations [8].

One of the main field of energy consumption of refrigeration comes out from domestic refrigerators. R134a was the most widely used refrigerant in refrigerators for domestic application for its excellent thermodynamics and thermo-physical properties. Nevertheless, because of its 1430 as GWP, it will be phased-out soon, according to the Kyoto Protocol. Scientist and researchers are investigating [9-10] in development of environmentally friendly refrigerants for domestic refrigerators and freezers. Hydrocarbons (HCs) especially propane, butane, isobutane and isobutane blends are proposed [11] as environmental benign refrigerants. They show many advantages like zero ODP, negligible GWP, low critical pressures and high enthalpy difference during evaporation process but, on the other side, the main

disadvantages associated with their use lie in their high flammability and in not have a drop-in refrigerant nature because of its mismatching in volumetric cooling capacity and operating pressure. HCs are flammable and classified [12] in the range of low toxic, highly flammable refrigerants (A3). In spite of the high flammability these refrigerant fluids are used in new domestic refrigerators in Europe, but are forbidden in USA and Japan.

HFO refrigerants are actually unsaturated HFC refrigerants and widely recognized [13] as the next generation of refrigerants because of their environmental friendliness, cost-effectiveness, and greater energy efficiencies. HFOs are distinguished from HFCs by being derivatives of olefins rather than alkanes (paraffins). Furthermore HFO are miscible in Polyolester (POE)-type lubricating oils; the miscibility of HFOs with POE lubricants is comparable to that of R134a.

A popular HFO refrigerant is HFO1234yf [14]. Table 1 reports a comparison between the thermodynamic, environmental and security properties of this refrigerant fluid and R134a. HFO1234yf has zero ODP and extremely low values of GWP which ensure that such refrigerant has a much shorter life cycle in the atmosphere than R134a. This HFO refrigerant has an A2L safety classification, meaning it has low toxicity but is slightly flammable. HFO1234yf has been developed as a replacement for HFC-134a in automobile air conditioning and it also can be considered as a drop-in of R134a in existing vapor compression plants because of their similar thermodynamic behaviors. However, the main weaknesses of its employment could be found in its initial cost, higher than R134a.

Table 1. Properties of HFO1234yf in comparison with R134a

Refrigerant	Chemical composition	Mol. weight [g.mol-1]	T crit. [°C]	p critical [bar]
R134a	CH_2FCF_3	102	101.1	40.59
HFO1234yf	$CF_3CF{=}CH_2$	114	95.0	33.82
Refrigerant	Normal boiling point [°C]	Safety class	ODP	GWP [kg_{CO2}.kg-1]
R134a	-26.0	A1	0	1430
HFO1234yf	-29.0	A2L	0	4

A vapor compression plant produces typically both a direct and an indirect contribution to global warming where the first one is related to the GWP of the fraction of refrigerant charge released accidentally in the atmosphere or not recovered when the system is scrapped. The indirect contribution consists in the so-called energy-related contribution; it originates from CO_2 emissions in the atmosphere due to the energy production processes. However, the employment of refrigerants with low direct impact doesn't carries consequentially to a low indirect impact in the VCP. Consequentially the employment of an environmental metric in order to facilitate the choice of low GWP refrigerants has to be implemented in VCPs. The Life Cycle Climate Performance LCCP is one of the most comprehensive parameters which takes into account all the relevant indirect emissions related to the whole process of VCP and refrigerant manufacturing and transportation.

In this paper is presented an experimental study of HFO1234yf as drop-in refrigerant in a wide range of working conditions in a fully monitored domestic refrigerator. Furthermore, the results of an experimental comparative analysis between R134a and HFO1234yf are reported. It have been measured energy consumptions under sub-tropical conditions in accordance with the UNI-EN-ISO15502 [15].

2. THE LCCP CONCEPT

A number of methods for calculating the total incidence of global warming by a vapor compression plant, has been developed. The Total Equivalent Warming Impact (TEWI) index takes into account both contributions to global warming of the system. Through the TEWI concept, one can quantify the amount of CO_2 released in the atmosphere due to system losses (direct impact) and energy consumption (indirect impact) related to the combustion of fossil fuels for the electric energy production.

The TEWI index is calculated as [16]:

$$TEWI = CO_{2,dir} + CO_{2,indir} \tag{1}$$

$$CO_{2,dir} = RC\left[p_L + \left(\frac{1-REC}{V}\right)\right]V \cdot GWP \tag{2}$$

$$CO_{2,indir} = \alpha \cdot \frac{Q'_{ref}}{COP} \cdot H \cdot V \tag{3}$$

The direct global warming effect of refrigerant fluids, stemming from the absorption they produce of long-wave radiations, depends on their GWP and on the fraction of refrigerant charge released in the atmosphere. The last is mainly due to losses during the operational plant life time (p_L) and to the residual amounts which, according to the current state of technology, are not recyclable and thus are released to the atmosphere when taking the plant out of operation (1-REC). The main disadvantages of the TEWI approach is to not consider both the energy consumption and emissions, related to production and transportation of refrigerant or blowing agents.

The Life Cycle Climate Performance (LCCP) is a TEWI based methodology which provide a more accurate evaluation of the VCP impact on global warming, since it takes in account the energy consumption both for VCP operating both for the whole process of refrigerant production-transportation-employment.

The LCCP index is calculated as [17]:

$$LCCP = CO_{2,dir,t} + CO_{2,indir,t} \tag{4}$$

$$CO_{2,dir,t} = RC\left\{\left[p_L + \left(\frac{1-REC}{V}\right) + p_{acc}\right]V + N_{serv}P_{serv} + P_{prod}\right\}GWP$$
$$+RC\left\{\left[p_L + \left(\frac{1-REC}{V}\right) + p_{acc}\right]V + N_{serv}P_{serv} + P_{prod}\right\}GWP_{adp} \tag{5}$$

$$CO_{2,indir,t} = \alpha \cdot \frac{Q'_{ref}}{COP} \cdot H \cdot V + RC\left[p_L + \left(\frac{1-REC}{V}\right)\right]V \cdot co_{2,eq,ref} +$$
$$+\sum_{mat} m_{mat} \cdot co_{2,eq,mat} + \sum_{mat} E_{mat} \cdot m_{mat} \cdot co_{2,eq,mat} \tag{6}$$

The direct contribution includes the one above mentioned in (2) with, in addition, the refrigerant leakages due to: accidents, system servicing operation and refrigerant

production and transport. The last term of the direct contribution takes into account the reaction byproduct of the atmospheric breakdown of the refrigerant emissions by means of the GWP_{adp}. The indirect contribution embraces the so-called energy-related contribution which originates from CO_2 emissions in the atmosphere due to the energy consumption of the system, the energy required for refrigerant producing, system and components manufacturing and the energy contribution for end-of-life recycling/recovery of system and refrigerant.

In the evaluation of LCCP index for both refrigerants considered in this paper all the leak rates and the CO_2 emissions per material kilo, related to the indirect contribution, come from 16.05.2015 data proper of International Institute of Refrigeration (IIR). The CO_2 emission rate per kWh has been estimated by Ecometrica 2011 [18], whereas through the RAEE standard [19], based on 81kg as the refrigerator net mass, it has been estimated the amount of all materials composing the tested VCP. Both the GWP (Table 1) and the GWP_{adp} (GWP_{adp},CO_2=0; GWP_{adp},HFO=3.3) index values are provided by the Europ. Dir. 517/2014 [20].

3. EXPERIMENTAL APPARATUS

Experimental tests are carried out through an experimental apparatus composed by a vapor compression plant, an investigation apparatus and a virtual instrument for performances and criticality analysis. A block diagram of the VCP is represented in Figure 1.

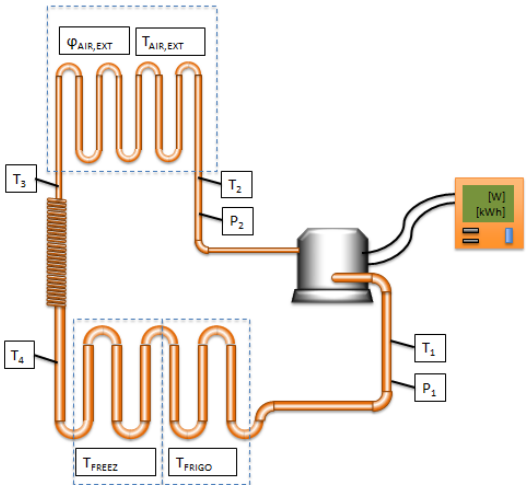

Figure 1. Block diagram of the VCP

The refrigerant system considered for experimental test is a double port Samsung domestic refrigerator. EU Directive 92/75/EC [18] established an energy consumption EU Energy Label scheme for refrigerators. The energy efficiency of the appliance is rated in terms of a set of energy efficiency classes initially from A to G on the label, A being the most energy efficient, G the least efficient. In an attempt to keep up with advances in energy efficiency, since 2010, A+, A++ and A+++ grades were introduced. The refrigerator under test above mentioned, belongs to the A+ class for energy efficiency.

The experimental investigation consisted in: measurement of temperature, through the placement of 9 PT100 thermo-resistances (accuracy ± 0.1 K) in the circuit; indirect evaluation of high and low VCP pressures, considering the difficult in direct pressure detecting into the heat exchanger serpentines. In particular, through the REFPROP calculation software, pressure values have been easily obtained by temperature detections at the saturation curve of the refrigerant utilized into the refrigerator. To evaluate the environmental relative humidity the Protimeter System 996 Precision Humidity Measurement System has been placed in the room test. A network analyzer, named Energy Test, has also been considered for the evaluation of energy and power consumptions for both the tested refrigerants. For real time monitoring of pressure and temperature evolutions into the whole vapor compression cycle under test, a virtual instrument in Labview area, named Frigocheck 2.0, has been developed.

4. EXPERIMENTAL TESTS ANS RESULTS

In this work, energy performances of R134a are compared with HFO1234yf. Furthermore an LCCP analysis for both fluids under test have been conducted.

All the experimental tests have been conducted according to the UNI-EN-ISO15502. The standard requires 24-hour tests while the refrigerator is in an environment which presents 25°C as average temperature and a relative humidity confined in the 45÷75% range. To operate in accordance with the above standard, it is also necessary that during the 24-hour tests, the refrigerator experiences at least one defrost cycle. The experimental tests have been performed while the refrigerator was working at an average values of 5°C for T_{FRIGO} with a charge of 101g for R134a experiments and of 115g for HFO1234yf. The last value is the optimal charge.

All the tests have been evaluated while T_{FREEZ} and was set at average values of α°C and -26°C.

In the Figures 2-3 are shown the temperature trends at the evaporator during an operation time of 24h (1440 minutes) for both fluids. From the figures one can observe that the two fluids exhibits the same behaviors, but R1234yf shows always lower values of the evaporating temperature.

Figures 4-5 exhibits evolution of the temperature at inlet of compressor during an operation time of 24h for both fluids. Tests with HFO1234yf register a small decrease of such temperature, with respect to R134a, due the greater charge of the former refrigerant (115g) than the latter (101 g).

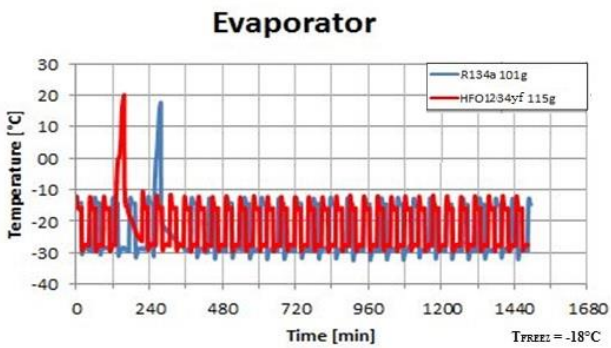

Figure 2. Temperature at the evaporator during 24-hour test for R134a and HFO1234yf, with T_{FREEZ} = -18°C

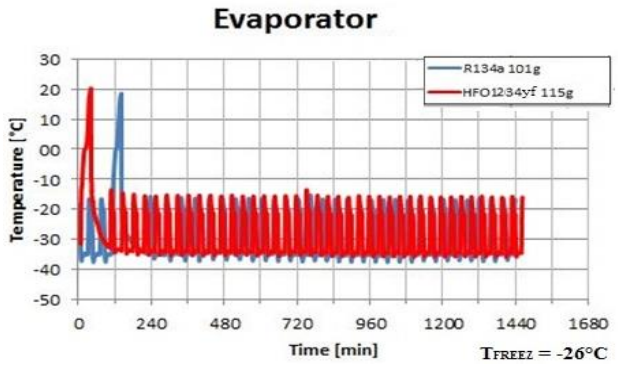

Figure 3. Temperature at the evaporator during 24-hour test for R134a and HFO1234yf, with T_{FREEZ} = -26°C

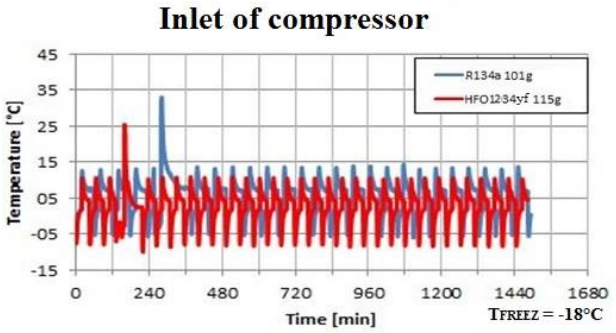

Figure 4. Temperature at inlet of compressor during 24-hour test for R134a and HFO1234yf, with T_{FREEZ} = -18°C

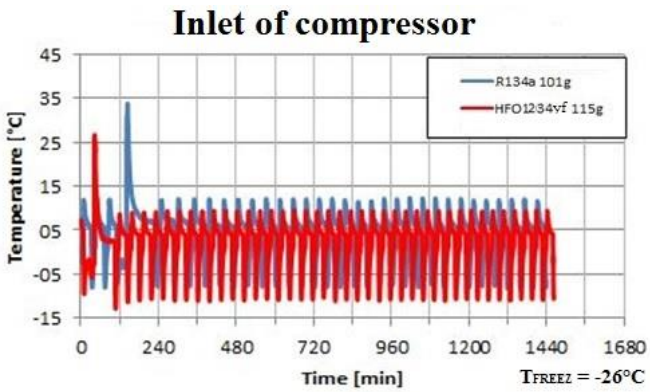

Figure 5. Temperature at inlet of compressor during 24-hour test for R134a and HFO1234yf, with T_{FREEZ} = -26°C

In Figure 6 are reported the air temperatures of the cold and the freezer cells, where one can observe that both the fluids have a good response at the T_{FREEZ} = -18°C setting; whereas in the cold cell, HFO1234yf swings around T_{FRIGO} = 4°C, rather than the required value of 5°C.

Figure 7 reports air temperature in cold and freezer cells when the refrigerator setting is: T_{FRIGO} = 5°C, T_{FREEZ} = -26°C. It is clearly appreciable that, although in the freezer cell both R134a and HFO1234yf swing with the same trend around a T_{FREEZ} close to -26°C, in the cold cell none of the two refrigerants meets the demand of maintaining T_{FRIGO} at 5°C, so the cell is colder than expected. Such anomalous behaviors of the air temperature into the cold cell of the refrigerator has to be attributed to damper effect. The damper is an independent thermostat which opens or closes the air conveyor, that allows an air blowing from the freezer to the cold cell, to adjust the temperature of the latter. Since that in the refrigerator under test the evaporator is located only into the freezer cell, the cold cell cooling is done by air vents. Therefore, when the refrigerator is working at T_{FREEZ}= -26°C, the air flux from freezer to cold cell cools more than needed and T_{FRIGO} falls below 5°C when the damper effect takes place.

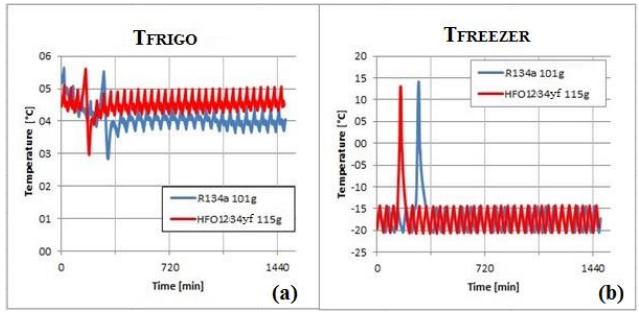

Figure 6. (a) Air temperature of the cold cell set at 5°C; (b) temperature of the freezer cell set at -18°C

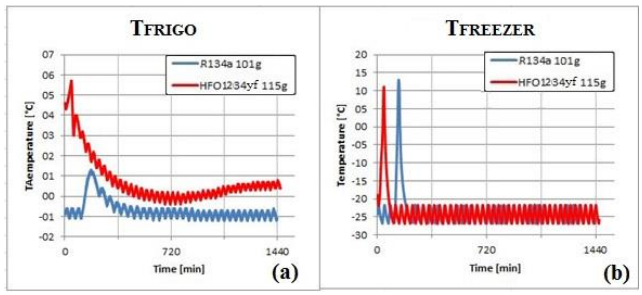

Figure 7. (a) Air temperature of the cold cell in 24 hours; (b) temperature of the freezer cell averaged at -26°C

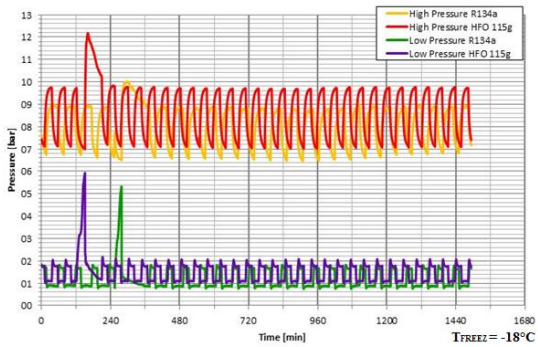

Figure 8. High and low pressures during 24-hour test for R134a and HFO1234yf, with T_{FREEZ} = -18°C

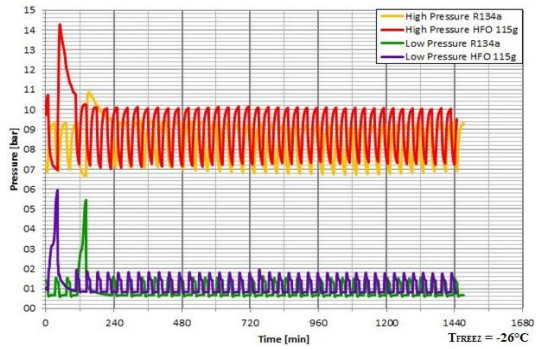

Figure 9. High and low pressures during 24-hour test for R134a and HFO1234yf, with T_{FREEZ} = -26°C

In the Figures 8 and 9 are plotted the high and low pressure trends of the tested vapor compression cycle for the refrigerator working with R134a and with HFO1234yf while T_{FREEZ} is set at -18°C and -26°C, respectively. One can observe that the high HFO1234yf pressure is approximately 10% greater than R134a, whereas the low ones are quite the same for both the T_{FREEZ} settings. Moreover HFO1324yf presents a roughly 20% larger peaks of high pressure, in correspondence of defrost cycle either in -18°C than in -26°C tests. Indeed, with HFO1234yf, the whole circuit is subject to greater pressure, resulting in increases of losses and mechanical stress for compressor.

Figures 10 and 11 show the refrigerator's average refrigerant power during an operation time of 24h for both the tested fluids and the freezer cell temperature settings. From the figures ON-OFF cycles of the compressor are regular and clearly visible, whereas the highest peaks are characteristics of the defrost cycle.

Average power of the refrigerator working with HFO1234yf are 17% greater than with R134a for both -18°C and -26°C. Such behavior is due to the similar values of temperature at the evaporator, shown by the two tested fluids, but with a greater subcooling for HFO1234yf that leads to a greater value of the latent heat of evaporation.

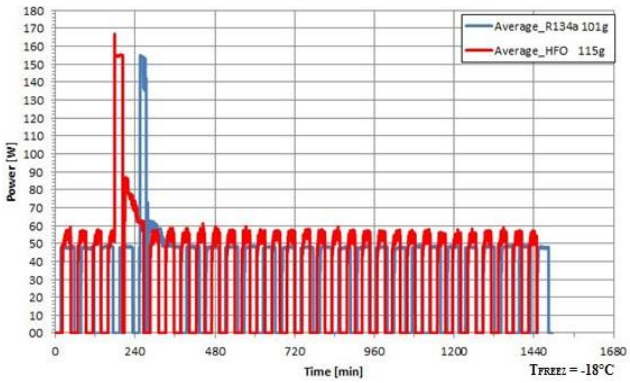

Figure 10. 24-hours average power for R134a and HFO1234yf, with T_{FREEZ} = -18°C

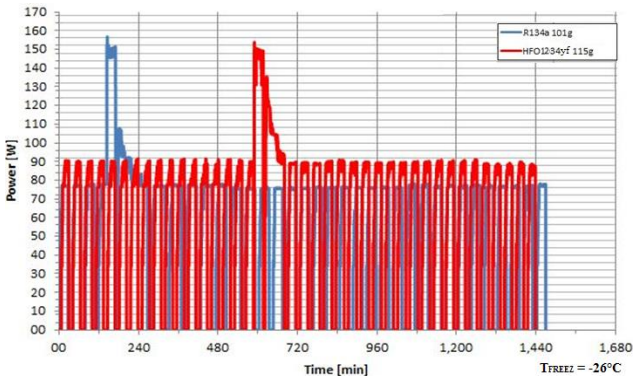

Figure 11. 24-hours average power for R134a and HFO1234yf, with T_{FREEZ} = -26°C

In order to evaluate the performances of the regenerator in both cases, the COP has been evaluated as:

$$COP = \frac{\dot{Q}_{ref}}{\hat{W}} \tag{7}$$

Supposing to work with the same mass flow rate for 24-hour and therefore the same density, is possible to consider that for both fluid Q_{ref} is the same, since that the test are done at equal thermal load, supposing the same defrosting period length.

It is also useful to introduce a performance index calculated as:

$$\varepsilon = \frac{COP_{HFO}}{COP_{R134a}} = \frac{\frac{1}{\hat{W}_{HFO}}}{\frac{1}{\hat{W}_{R134a}}} \tag{8}$$

Table 2 exhibits daily and annual energy consumptions for the tests performed, the index of performance and the percentage of energy saving in working with HFO1234yf, rather than R134a. When T_{FREEZ} is set to -18°C, a power reduction of around 2.60% is registered if the refrigerator is working with 115g of HFO1234yf, rather than 101g of R134a. On the other side if T_{FREEZ}=-26°C, cooling with HFO1234yf would provide the power consumption is 0.4% greater than R134a. The higher energy consumption, for HFO1234yf tests, detected when T_{FREEZ}=-26°C, could be probably attributed to the higher condensing pressures which could be symptom of a worst convective heat exchange at the condenser.

Table 2. Power consumption and energy saving for the test performed

Test	24-h cons. [Wh]	Annual cons. [kWh]	Average Power On [W]	ε [-]	En. Sav. [%]
R134a T_{FREEZ}=-18°C	792.8	289.4	47.4	1.000	0
HFO1234yf T_{FREEZ}=-18°C	772.5	281.9	52.4	1.026	+2.6
R134a T_{FREEZ}=-26°C	1294.5	472.5	70.5	1.000	0
HFO1234yf T_{FREEZ}=-26°C	1299.9	474.5	80.9	0.996	-0.4

In the evaluation of LCCP direct contribution 101g of R134a and 115g of HFO1234yf as refrigerant masses, together with their GWP indexes, have been considered.

Table 3. Reference values for calculating LCCP direct contribution

Parameter	R134a	HFO1234yf
m [kg]	0.101	0.115
GWP [kg_{CO2}.kg-1]	1430	4
GWP_{adp} [kg_{CO2}.kg-1]	1.6	3.3
p_L [%.yr-1]	2.5	2.5
p_{acc} [%.yr-1]	10	10
REC [%]	85	85
V [yr]	15	15
N_{serv} [-]	1	1
P_{serv} [%]	5	5
P_{prod} [%]	0	0

In Table 3 are reported the reference values for the evaluation of the direct contribution of both fluids according to equation (5).

On the other side, to estimate the indirect contribution, all the leak rates and the CO_2 emissions per material kilo and per kWh come from scientific literature data. In particular it has been considered α=0.435 kg_{CO2}.kWhyr-1. By means of the RAEE standard [19], based on 81kg as the refrigerator net mass, it has been estimated the amount of all materials from which it is made. Table 4 reports all the materials composing the refrigerator.

Table 4. Materials composing the refrigerator

Material	$CO_{2,eq\ mat}$ [$kgCO_{2,eqmat}$.kg-1]	Mass of material [kg]	Mass of material /total mass [%]
Aluminium	12.60	5.2	6.5
Copper	3.00	2.2	2.7
Plastic	2.80	8.1	10.0
Polyurethane	4.02	12.5	15.4
Steel	1.80	53.0	65.4

Table 5 provides the LCCP index values, together with the single CO_2 direct and indirect contributions, for both refrigerants and with references to the 24-hours tests with T_{FREEZ} values of: -18°C and -26°C.

Table 5. The LCCP indexes

Test	LCCP [kg_{CO2}]	$CO_{2,dir,t}$ [kg_{CO2}]	$CO_{2,indir,t}$ [kg_{CO2}]
R134a T_{FREEZ}=-18°C	2407.2	306.0	2101.2
HFO1234yf T_{FREEZ}=-18°C	2069.1	15.9	2053.3
R134a T_{FREEZ}=-26°C	3603.3	306.0	3297.3
HFO1234yf T_{FREEZ}=-26°C	3326.3	15.9	3310.5

For both TFREEZ considered, the relative calculated LCCP for HFO1234yf is always lower than R134a. In particular, thanks to the drop-in of HFO1234yf in place of R134a, a reduction in CO_2 emissions of 14% (test with T_{FREEZ} = -18°C) and 7% (test with T_{FREEZ} = -26°C) is registered. This is mainly due to the total direct contribution on global warming of HFO1234 since that it is about 20 times lower than R134a. Furthermore, at the same T_{FREEZ} one can observe that total indirect contribution on global warming, for R134a and HFO1234yf, are approximately the same.

7. CONCLUSIONS

In this paper the results of an experimental comparative analysis between R134a and HFO1234yf, implemented in a domestic refrigerator, are presented. It have been measured energy consumptions under sub-tropical conditions in accordance with the UNI-EN-ISO15502. In addition, a LCCP analysis, to evaluate the environmental impact from a global point of view, due to HFO1234yf used as a substitute of R134a, is reported. R134a has a relevant direct global warming effect stemming from its absorption power of long-wave radiations, which depends on its GWP and on the fraction of refrigerant charge released in the atmosphere. A possible substitute of R134a can be HFO1234yf, unsaturated HFO refrigerant with a very low global warming potential.

By means of experimental tests conducted on an A+ class domestic refrigerator working first with R134a and then with HFO1234yf, we can conclude that the latter is a valid substitute of R134a. Indeed, HFO1234yf total direct impact on global warming is very low, since it presents a very small GWP with respect to R134a, more than one thousand higher. Regards to the indirect impact, for R134a and HFO1234yf, is approximately the same.

Therefore the relative calculated LCCP for HFO1234yf is always lower than R134a.

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NOMENCLATURE

co_2	CO_2 emission coefficient per kilo, kg_{CO2}.kg-1
CO_2	CO_2 contribution to global warming, kg_{CO2}
COP	coefficient of performance
E	percent of energy for recycling, %
GWP	global warming potential, kg_{CO2}.kg-1
LCCP	life cycle climate performance, kg_{CO2}
H	annual operating hours, h.yr-1
m	mass, kg
N	dimensionless total number
p	percent annual refrigerant leak rate, %.yr-1
P	percent leak rate, %
Q'	power, kW
RC	refrigerant charge, kg_{CO2}
REC	refrigerant recycling rate, %
T	temperature, °C
TEWI	total equivalent warming impact, kg_{CO2}
V	plant useful life, yr
$\hat{W}$	electricity demand, kW

Greek symbols

α	CO_2 emission from power conversion, kg_{CO2}.kWhyr-1
ε	dimensionless performance index

Subscripts

acc	accidental
adp	atmospheric degradation product of the refrigerant
dir	direct
eq	equivalent
FREEZ	freezer cell
FRIGO	cold cell
HFO	HFO1234yf
indir	indirect
L	regular
mat	material
prod	refrigerant production and transport
R	refrigerant recycling
ref	refrigerant
serv	system servicing
t	total