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HFO1234ze as drop-in replacement for R134a in domestic refrigerators: an environmental impact analysis

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Abstract

In this paper are reported the results of an experimental comparative analysis between R134a and HFO1234ze, when they are employed as refrigerants in a domestic refrigerator. Under sub-tropical conditions, it have been measured the energy consumptions in accordance with the UNI-EN-ISO15502. For each experiment it have been estimated both the TEWI and the Life Cycle Climate Performance indexes to assess the environmental impact due to HFO1234ze when used in place of R134a.

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Keywords: Vapor compression system, Drop-in, Refrigerants, R134a, HFO1234ze, LCCP;

1. Introduction

In a world where about 17% of the overall energy consumption originates from refrigeration and where R134a is still the most employed refrigerant for domestic scopes, a substantial conversion toward the use of environmentally friendly refrigerants has become a "must". As a matter of fact, most modern refrigeration units are still based on vapor compression plants (VCP) in which the characteristics of the working refrigerant have often carried to critical points: the traditional refrigerant fluids, i.e. CFCs and HCFCs, linked to the beginning of their commercial diffusion, have been banned by the Montreal Protocol [1] because of their significant Ozone Depletion Potential (ODP) [2-4]. Therefore from the first United Nations Framework Convention on Climate Change (1987), it have been delineated

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the guidelines to be followed by all over the world nation, in order to mitigate the greenhouse gases emissions. 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). Therefore, over time, the focus has been progressively shifted on zero ODP refrigerants but most of the refrigerants nowadays employed, like R134a, shows a relevant direct impact in global warming, whom has been quantified through a parameter called GWP (Global Warming Potential).

Nomenclature

$co_{2,eq,mat}$	equivalent material CO_2 emission coefficient per kilo [$kg_{CO2}.kg^{-1}$]
$co_{2,eq,ref}$	equivalent refrigerant CO_2 emission coefficient per kilo [$kg_{CO2}.kg^{-1}$]
$CO_{2,dir}$	direct CO_2 contribution to global warming [kg_{CO2}]
$CO_{2,dir,t}$	total direct CO_2 contribution to global warming [kg_{CO2}]
$CO_{2,indir}$	indirect CO_2 contribution to global warming [kg_{CO2}]
$CO_{2,indir,t}$	total indirect CO_2 contribution to global warming [kg_{CO2}]
COP	coefficient of performance [-]
E_{mat}	percent of energy for material recycling, %
GWP	global warming potential [$kg_{CO2}.kg^{-1}$]
GWP_{adp}	global warming potential due to atmospheric degradation product of the refrigerant [$kg_{CO2}.kg^{-1}$]
H	annual operating hours [$h.yr^{-1}$]
LCCP	life cycle climate performance [kg_{CO2}]
m_{mat}	mass of material [kg]
N_{serv}	total number of system servicing [-]
ODP	ozone depletion potential [-]
p_{acc}	percent annual refrigerant accidental leak rate [$\%.yr^{-1}$]
p_L	percent annual refrigerant regular leak rate [$\%.yr^{-1}$]
P_{prod}	percent leak rate due to refrigerant production and transport [%]
P_{serv}	percent leak rate due to system servicing [%]
Q'_{ref}	refrigerant power [kW]
RC	refrigerant charge [kg_{CO2}]
REC	refrigerant recycling rate [%]
TEWI	total equivalent warming impact [kg_{CO2}]
T_{CELL}	temperature of the cold cell, [°C]
T_{FREEZ}	temperature of the freezer cell, [°C]
V	plant useful life [yr]
α	CO_2 emissions from power conversion [$kg_{CO2}.kWhyr^{-1}$]

Human activities have increased the energy consumption in buildings [5,6], because of the growing HVAC employment, environmental pollution [7] and 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. Therefore nowadays the use of environmentally friendly refrigerants has become a “must” in order to mitigate the global warming. The Kyoto Protocol [8], pursuant to the United Nations Framework Convention on Climate Change (UNFCCC), fixed mandatory targets for greenhouse gas emissions calling the all over the world countries for a phase down of HFC consumption. As a matter of fact, more recent measures, already adopted or proposed at local level (regional, national, municipal), are even more stringent. Based on the UE Regulation N°517/2014 in domestic refrigerators and freezers, employing HFCS, with 150 or more as GWP, has been forbidden from 1 January 2015. These restrictions are forcing the shift to a fourth generation of refrigerants with both ODP and GWP regulations [9].

Domestic refrigerators cause the main contribution in energy consumption related to the field of refrigeration. Because of its thermodynamics and thermo-physical properties, the most utilized refrigerant for domestic applications has been R134a until the Kyoto protocol established its phasing out due to its too high GWP (1430).

Therefore all over the world scientist and researchers are studying and investigating [10,11] the development of new refrigerant, with zero ODP and GWP as low as possible, whom should exhibits an environmental friendly behavior. Hydrocarbons (HCs) especially propane, butane, isobutane and isobutane blends are recommended [12] 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, main disadvantages associated with their use are related to 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 [13] 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 [14,15] 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 R134a. The HFO refrigerant considered in this paper is HFO1234ze. Table 1 reports the thermodynamic, environmental and security properties of such refrigerant, compared to R134a.

Table 1. Properties of HFO1234ze in comparison with R134a.

Refrigerant	Chemical composition	Molecular weight (*g/mol*)	Critical T (°*C*)	Critical p (*bar*)	Normal boiling point (°*C*)	Safety Class	ODP	GWP
R134a	CH_2FCF_3	102	101.1	40.59	-26.0	A1	0	1430
HFO1234ze	$CHF = CHCF_3$	114.04	79.0	36.32	-20.0	A2L	0	6

HFO1234ze exhibits zero ODP and an extremely low global warming potential which ensures a shorter life cycle in the atmosphere. HFO1234ze belongs to A2L safety classification which implies that it has low toxicity but slightly flammability. HFO1234ze can be considered a near drop-in replacement of R134a and it can be used in existing equipment design with minimal changes. A Vapor Compression Plant (VCP) generates 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, which originates from CO_2 emissions in the atmosphere due to the energy production processes. Hence, the employment of refrigerants with low direct impact doesn't guarantee consequentially a low indirect impact in the VCP. Thus, the introduction of environmental parameters reveals itself helpful in taking over refrigerant with low GWP. Next to TEWI (Total Equivalent Warming Impact), LCCP (Life Cycle Climate Performance) is one of the most comprehensive parameters which takes in account all the relevant indirect emissions related to the whole process of VCP and refrigerant manufacturing and transportation. In this paper are reported the results of an experimental comparative analysis between R134a and HFO1234ze, when they are employed in a domestic refrigerator as refrigerants. Under sub-tropical conditions, it have been measured the energy consumptions in accordance with the UNI-EN-ISO15502 [16]. For each test it have been estimated TEWI and LCCP to assess the environmental impact due to HFO1234ze when used as replacement of R134a.

2. The TEWI and LCCP concepts

A number of methods for calculating [17,18] the total incidence of global warming by a vapor compression plant, has been developed. The 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 [19]:

$$\mathrm{TEWI} = \mathrm{CO}_{2,\mathrm{dir}} + \mathrm{CO}_{2,\mathrm{indir}} \quad (1)$$

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

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

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 LCCP is a more comprehensive evaluation of the VCP impact on global warming than TEWI. It includes all the direct and indirect emissions generated by the system during its complete lifetime from "cradle to grave." To do this, in addition to TEWI, LCCP accounts for energy embodied in the product materials, greenhouse gas emissions from chemical manufacturing and end-of-life disposal of the unit. LCCP can also account for minor emission sources that are not accounted for in TEWI such as transportation leakage, manufacturing leakage, and refrigerant manufacturing emissions. The LCCP index is calculated as [20]:

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

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

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

The LCCP direct contribution includes the TEWI one (2) with, in addition, the refrigerant leakages due to accidents, system servicing operation and refrigerant production and transport. The last term take into account the atmospheric reaction products from the breakdown of refrigerants in the atmosphere, by means of GWP_{adp}, which is measure of the effects of refrigerant decomposition in the atmosphere and the degradation effects of that refrigerant. (6) is the LCCP indirect contribution which 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 for end-of-life recycling/recovery of system and refrigerant. In the evaluation of TEWI and LCCP indexes 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 CO2 emission rate per kWh has been estimated by Ecometrica 2011 [21], whereas through the RAEE standard [22], based on the refrigerator net mass (81 kg), it has been estimated the amount of all materials composing the tested VCP. Both the GWP (Table 1) and the GWPadp ($GWP_{adp,R134a}$=1.6; $GWP_{adp,HFO=}$3.3) index values are provided by the Europ. Dir. 517/2014 [23].

3. Experimental tests and results

All the experimental tests have been carried out by an experimental apparatus which includes a refrigerant system under test, an investigation apparatus and a virtual instrument for performance and criticality evaluation. As refrigerant system it has been considered a Samsung domestic refrigerator which has double port and which belongs to the A+ class for energy efficiency. As a matter of fact EU Directive 92/75/EC [21] established an energy consumption EU Energy Label scheme for refrigerators, revised in 2010, where A+++ is the most energy efficient whereas G the least. Temperature measurement have been carried out by 7 PT100 thermo-resistances placed in the circuit, as shown in Fig. 1, by the 4-wires voltamperometric technique; whereas the VCP pressures have been measured through 2 piezoelectric absolute pressure gauge. Table 2 summarize the characteristics of the sensors employed and the accuracy of the measurements performed. Moreover Frigocheck 2.0, a virtual instrument developed in Labview area, has been utilized for real time monitoring of pressure and temperature evolutions in the whole domestic experimental apparatus.

Table 2. Characteristics of the sensors used and the accuracy of the measurements performed.

Quantity	Transducer	Range	Uncertainty
Temperature	PT100 4 wires	-100 ÷ 500 °C	0.15°C
Humidity	Protimeter System 996	-100 ÷ 70 °C / 0 ÷ 100%	0.15°C / 1.0%
Pressure	Piezoelectric absolute pressure gauge	1 ÷ 10 bar;	0.2%
		1 ÷ 30 bar	0.5% F.S
Energy	Energy Test	0 ÷ 1 MWh	1 %
Weight	Balance	0÷100 kg	0.1 g

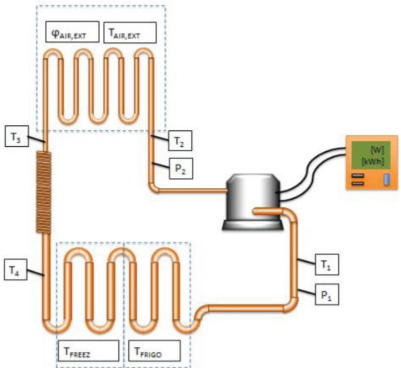

Fig. 1. A block diagram scheme of the vapor compression cycle under investigation with the relative sensors for the measurements.

In this paper, the energy performances of R134a are compared with HFO1234ze. Furthermore, TEWI and LCCP analysis for both refrigerants have been conducted, when they are employed in a domestic refrigerator. 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, empty, was working with a charge of 101g for R134a experiments and of 136g for HFO1234ze. All the tests have been evaluated while the freezer cell (T_{FREEZ}) and the cold cell (T_{CELL}) were set, respectively, at average values of -18°C and 5°C. In Fig. 2(a) and 2(b) are shown the temperature trends at the evaporator and the evaporator superheating, during an operation time of 24h, respectively. In Figure 2(a) which exhibits the temperature trends at the evaporator (86400 seconds) for both fluids, one can observe the two fluids exhibiting quite the same behaviors, but HFO1234ze shows always lower values of the evaporating temperature. In Figures 2(b) tests with HFO1234ze register a small decrease of evaporator superheating, with respect to R134a, due the greater charge of the former refrigerant (136g) than the latter (101 g). In both the above mentioned figures, i.e. 2(a) and 2(b), for every tests an high peak, due to defrost cycle, is clearly visible. In Fig. 3(a) and 3(b) are reported the air temperatures of the freezer (T_{FREEZ}) and the cold (T_{CELL}) cells, set at -18°C and +5°C respectively. In Figure 3(a) one can appreciate the good response of both fluid, oscillating around the desired value (-18°C). Figure 3(b) reveals that both the fluids swing around T_{CELL} = +4°C, rather than the required value of +5°C. 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} = -18°C, it could happens that the air flux from freezer to cold cell cools more than needed and T_{CELL} falls below +5°C when the damper effect takes place. Moreover, from the Figures 3(a) and 3(b) one can identify the time where the defrost cycle takes place, represented by the great jumps of the temperature.

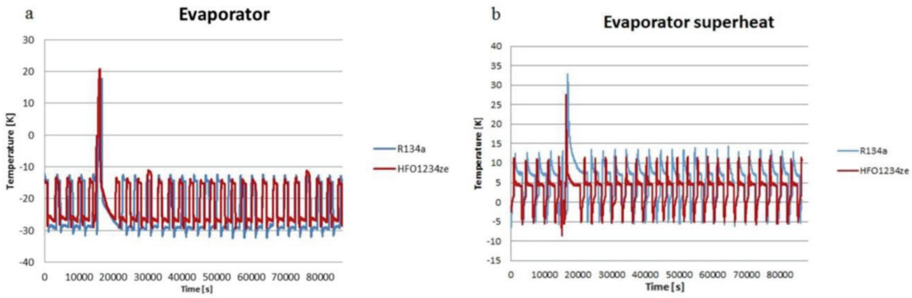

Fig. 2. (a) Temperature at the evaporator and (b) evaporator superheat during 24-hour test for R134a and HFO1234ze.

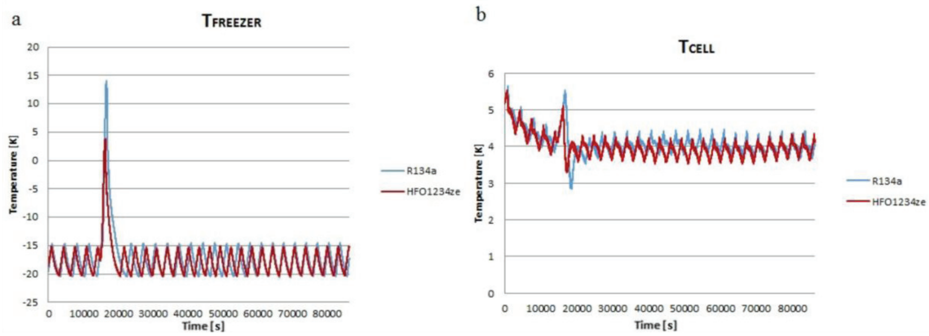

Fig. 3. (a) Air temperature in 24 hours of the freezer cell set at -18°C; (b) Air temperature in 24 hours of the cold cell set at +5°C.

Fig. 4 shows the refrigerator average power during an operation time of 24h for both the tested. From the figure 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 HFO1234ze is 9% lower than with R134a. Such behavior is due to the similar values of temperature at the evaporator, shown by the two tested fluids, but with R134a sub-cooling is greater than HFO1234ze that leads to a greater value of the latent heat of evaporation. Table 3 exhibits daily and annual energy consumptions for the test performed, the average power and duty cycle amplitude both for R134a and HFO1234ze. The average power is the energy consumption during a whole ON-OFF compressor cycle, divided the amplitude of such time period. The duty cycle is considered as the ON/(OFF+ON) time percentage. When the refrigerator is working with 136g of HFO1234ze an annual energy consumption 8% lower than operating with 101g of R134a, has been estimated. In the evaluation of TEWI and LCCP indexes it has been considered 101g of R134a and 136g of HFO1234ze as refrigerant charges. In Table 4 are reported the references values for evaluation of TEWI and LCCP direct contributions, whereas all the leak rates and the CO_2 emissions per material kilo and per kWh, needed to estimate the indirect contribution, come from scientific literature. In particular it has been considered α=0.435 kg_{CO2}.kWhyr^{-1}. By means of the RAEE standard [21], based on 81kg as the refrigerator net mass, it has been estimated the amount of all materials from which it is made. Table 5 provides the details concerning the materials that compose the refrigerator. Table 6 contains TEWI and LCCP indexes, together with the single CO_2 direct and indirect contributions, for both the tested refrigerant. Both indexes reveal that a domestic refrigerator working with HFO1234ze, provides a lower environmental impact despite of employing R134a. Furthermore, from the table one can notice that for both refrigerants LCCP is always greater than TEWI; as a matter of fact LCCP is more comprehensive than TEWI, since that the former takes in account all the relevant indirect emissions related to the whole process of VCP and refrigerant manufacturing and transportation.

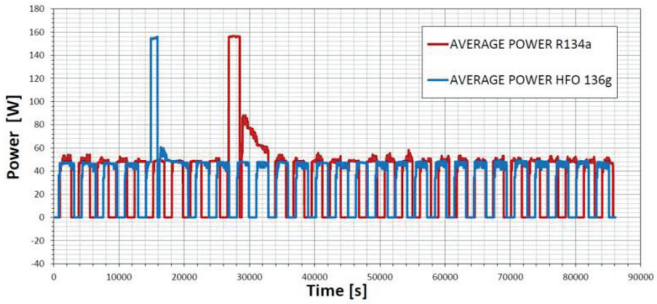

Fig. 4. 24-hours average power for R134a and HFO1234ze.

Table 3. Energy consumption and average power for the test performed.

Refrigerant	Daily consumption *(kWh)*	Annual consumption *(kWh)*	Average Power *(W)*	Duty cycle *(%)*
R134a	0.793	289.4	33	60
HFO1234ze	0.724	264.3	30	62

Table 4. All the reference values needed to estimate TEWI and LCCP direct contribution.

Refrigerant	m *(kg)*	p_L *(%/yr)*	p_{acc} *(%/yr)*	REC *(%)*	V *(yr)*	N_{serv} *(-)*	P_{serv} *(%)*	P_{prod} *(%)*
R134a	0.101	2.5	10	85	15	1	5	0
HFO1234ze	0.136	2.5	10	85	15	1	5	0

Table 5. Materials composing the refrigerator.

Material	m *(kg)*	m/m_{tot} *(%)*	$co_{2,eq\ mat}$ *(kg_{CO2}/kg)*
Aluminum	5.2	6.5	12.6
Copper	2.2	2.7	3.00
Plastic	8.1	10.0	2.80
Polyurethane	12.5	15.4	4.02
Steel	53.0	65.4	1.80

Table 6. TEWI and LCCP indexes.

Refrigerant	$CO_{2,dir}$ *(kg_{CO2})*	$CO_{2,indir}$ *(kg_{CO2})*	TEWI *(kg_{CO2})*	$CO_{2,dir,t}$ *(kg_{CO2})*	$CO_{2,indir,t}$ *(kg_{CO2})*	LCCP *(kg_{CO2})*
R134a	75.8	1888.3	1964.1	306.0	2101.2	2407.2
HFO1234ze	0.4	1724.6	1725.0	17.7	1938.1	1955.8

4. Conclusions

In this paper an experimental comparative analysis between R134a and HFO1234ze, implemented in a domestic refrigerator, is introduced. It have been estimated TEWI and LCCP to assess the environmental impact from a global point of view, due to HFO1234ze employed as a substitute of R134a. R134a has a relevant direct global warming effect stemming from its absorption power of long-wave radiations, that depends on its GWP and on the fraction of refrigerant charge released in the atmosphere. In a no longer future, a possible substitute of R134a can be HFO1234ze, 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 HFO1234ze, it have been demonstrated that the latter is a valid substitute of R134a. Indeed, both TEWI and LCCP evaluations shows that HFO1234ze has a very low direct impact on global warming, since it presents a very small GWP with respect to R134a, whom is more than one hundred higher. Regards to the indirect impact, for R134a and HFO1234ze, it is approximately the same. In conclusion both indexes reveal that a domestic refrigerator working with HFO1234ze, provides a lower environmental impact despite of employing R134a. Therefore the relative calculated TEWI and LCCP for HFO1234ze are always lower than the corresponding indexes for R134a. Furthermore, it happens that for both refrigerant TEWI index has a lower value than LCCP, confirming that an environmental impact investigation based on LCCP is more comprehensive than basing on TEWI, since the former takes in account all the relevant indirect emissions related to the whole process of VCP and refrigerant manufacturing and transportation.

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