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The drop-in of HFC134a with HFO1234ze in a household refrigerator

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ABSTRACT

This paper reports the results of a comparative experimental analysis between HCF134a and HFO1234ze. The experimental apparatus consists of a domestic, commercial refrigerator operating with HCF134a and for which a drop-in substitution with HFO1234ze has been realized. A series of experimental trials have been taken out to evaluate: the pull-down time for the identification of the optimal charge of HFO1234ze and 1-day electric energy use. All the tests have been taken under sub-tropical conditions in conformity with the UNI-EN-ISO15502. The results show that the refrigeration cycle performance of HFO1234ze is as good as that of HFC134a. In particular, the cycle working with HFO134ze with the optimal charge shows an energy saving of 9%.

1. Introduction

In a world where nearly 17% of the overall energy consumption originates from refrigeration [1] and where R134a is still the most employed refrigerant for domestic scopes, a substantial conversion to the utilization of environmentally friendly refrigerants has become a "must". As a matter of fact, most modern refrigeration units are even based on Vapour 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 [2] because of their significant Ozone Depletion Potential (ODP). So, from the first United Nations Framework Convention on Climate Change (1987), it has been delineated the guidelines to be followed by all over the world nation, to mitigate the greenhouse gas 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 HFC134a, shows a relevant direct impact on global warming, who has been quantified through a parameter called GWP (Global Warming Potential).

Human activities have increased the concentration of greenhouse gases in the atmosphere. This resulted in a substantial heating of the land surface and atmosphere that adversely affected the natural ecosystem. Therefore, nowadays the use of environmentally friendly refrigerants has become a "must" to mitigate the global heating. The Kyoto Protocol [3], under 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. Founded 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 limitations are forcing the transformation to the fourth generation of refrigerants with both ODP and GWP regulations [4].

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 HFC134a 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 the development of new refrigerant, with zero ODP and GWP as low as possible, whom should exhibit an environmentally friendly behavior. Hydrocarbons (HCs) especially propane, butane, isobutane and isobutane blends are recommended [5] as benign environmental refrigerants. They present many advantages like zero ODP, negligible GWP, low critical pressures and high enthalpy difference during the evaporation process. Nonetheless, main disadvantages associated with their use are interrelated to their high flammability and in not have a drop-in refrigerant nature because of its mismatching in volumetric cooling capacity and working pressure. HCs are flammable and classified [6] in the range of low toxic, highly flammable

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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 [ml m^{-3}]
S_{cab}	external surface of the cabinet [m^2]
U	Thermal transmittance 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 compressor
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	surround
ON	phase of working of the compressor
OFF	phase of stop of the compressor

refrigerants (A3). Despite the high flammability, these refrigerant fluids are employed in new domestic refrigerators in Europe but are forbidden in the USA and Japan. HFO refrigerants are unsaturated HFC refrigerants and widely recognized [7–10] 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, HFOs are miscible in Polyester (POE) type lubricating oils; the miscibility of HFOs with POE lubricants is comparable to that HFC134a.

The most investigated HFOs are HFO1234ze and HFO1234yf. To date, such fluids have been widely investigated under different points of view. Kondo et al. [11] showed the flammability limits of HFO1234yf and HFO1234ze depend on the humidity of the air. In particular, HFO1234ze, which is non-flammable in dry air, becomes flammable if humidity becomes larger than 10%. Yang et al. [12] tested out the flammability limits of HFO1234ze and its mixtures: HFO1234ze/HCFC161 and HFO1234ze/HCFC152a. They showed that R1234ze possessed a slight flame suppression effect on both HCFC161 and HCFC152a but could not make it unburnt completely under the experimental concentration range. Schuster et al. [13] investigated the effect of the inhalation exposure of HFO1234ze on mice and rats. The quantified amounts of the metabolites eliminated in urine in both mice and rats suggest only a low extent (< 1% of the dose received) of biotransformation of HFO-1234ze and 95% of all metabolites were expelled within 18 h after the end of the exposures. About the thermodynamic properties of HFOs, several researchers have carried out relevant results. In particular, Akasaka [14] and Lai [15] provided equations of state for HFO1234yf and HFO1234ze(e), while Akasaka et al. [16] proposed a fundamental equation of state for HFO1234ze(z). Tanaka et al. [17] carried out experimental measurements of the vapour pressures and pressure, density, and temperature for HFO1234ze (e). Lai [18] modelled the thermodynamic properties of HFO1234zf with an accurate molecular-based PC-SAFT equation of state. Other researchers focused on the heat transfer and pressure drops for HFOs: Righetti et al. [19] carried out a comparative performance analysis of HFO1234yf, HFO1234ze(e) versus HFC134a. They found that the refrigerants HFO1234yf and HFO1234ze(e) exhibit vaporization performance similar to HFC134a. Therefore, each of them can be surely considered an environmentally friendly substitute for HFC134a. Also, HFO1234yf exhibits vaporization performance similar to HFC134a at a similar mass flow rate. Then, it can be regarded a direct drop-in alternative for HFC134a in domestic refrigeration. Jankovic et al. [20] present two different analyses of R1234yf and R1234ze(E) as drop-in replacements for R134a in a small power refrigeration system. They found that R1234yf seems as an adequate drop-in refrigerant for R134a, but R1234ze(E) may perform better when an overridden compressor can be used to match the refrigerating system cooling power. McLinden et al. [21] explore as possible substitutes of HFC fluids for refrigerants having low global warming potential (GWP). Between these fluids they considered both HFO1234yf and HFO1234ze.

Looking at the system performances the theoretical works are more popular than those experimental. Fukuda et al. [22] analyzed the coefficient of performances (COP) of heat pump working with HFO1234ze (e) and HFO1234ze (z). Their simulations suggested that HFO1234ze(z) is suitable for high-temperature applications rather than in typical air conditioners. Llopis et al. [23] presented simplified models of five two-stage vapour compression refrigeration systems and evaluated them with low-GWP refrigerants (HFC, HFO and naturals). Molés et al. [24] reported a comparative study concerning energy performance of different single-stage vapour compression configurations using HFO1234yf and HFO1234ze(e) as working fluids. Because the adoption of HFOs in some situations leads to a decrease of the energy performances, they proposed various technical solutions to overcome this issue. They suggested the best option is the adoption of an internal heat exchanger. Yataganbaba et al. [25] developed an exergy analysis of HFO1234yf and HFO1234ze in a two evaporator vapour compression refrigeration system. Wang [26] carried out a state of the art of the drop-in of HFC134a with HFO1234yf. He evidenced the COP and heat capacity of HFC134a system might suffer from a direct drop-in replacement of HFO1234yf. The deterioration is around 0–27%, depending on the operational conditions. The major part of the theoretical suggestions have been confirmed by the experimental works carried out by Mota-Babiloni et al. [27] and Navarro-Esbrí et al. [28]. The Spanish authors performed several experiments to analyze the consequences of the direct drop-in of HFC134a with HFO1234ze (e) and HFO1234yf. Sethi et al. [29] analyzed both theoretically and experimentally the influences of the replacement of HFC134a with HFOs for a refrigerated vending machine. In et al. [30] tested an optimized heat pump working with HFOs.

The compatibility of the oils has been investigated as well. Akram et al. [31] presented the tribological performance of grey cast iron with different lubricants, namely PAG (Polyalkylene glycol), POE (Polyolester), and Mineral oil, in the presence of environmentally friendly HFO-1234yf refrigerant. They found PAG/HFO1234yf exhibited better tribological performance compared to the other systems. Series and Barbosa [32] evaluated experimentally the relative permittivity (dielectric constant) of mixtures of a POE ISO VG 10 lubricating oil and