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Experimental evaluation of R448A as R404A lower-GWP alternative in refrigeration systems

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ABSTRACT

Due to the adoption of EU Regulation No 517/2014, R404A is going to be banned in Europe in most of refrigeration applications, in which is typically used, due to its very high GWP value, 3943. In this paper an experimental comparison between R404A and R448A, a non-flammable alternative with GWP of 1390, is presented. The experimental tests are intended to simulate typical freezing and conservation temperatures and different condensing conditions. Despite cooling capacity of R448A is slightly below that of R404A, R448A energy consumption is even smaller; and R448A COP is higher than that obtained using R404A. Hence, it can be concluded that R448A could be an energy efficient alternative to R404A with a GWP reduction of 70%. Compressor discharge temperature remains at non-dangerous levels.

1. Introduction

Being commercial refrigeration one of the most relevant applications in terms of energy consumption, reducing their Greenhouse Gas emissions (direct and indirect) is essential to help stopping the climate change [1]. R404A is a zero-ODP (Ozone Depletion Potential) refrigerant that has been widely used in previous past in these systems as R22 substitute [2]. Taking advantage of its low Normal Boiling Point (NBP of 226.7 K), it can be used at low evaporating temperatures.

The GWP (Global Warming Potential) limitations in Europe started with the Directive 2006/40/EC [3] and were extended to other systems due to the approbation of EU Regulation No 517/2014 [4], affecting directly to commercial systems where R404A was typically used (Table 1): Refrigerators and freezers (GWP > 2500 in 2020 and GWP > 150 in 2022), multipack centralised refrigeration systems (GWP > 150 in 2022), and stationary refrigeration equipment (GWP > 2500 in 2020).

The solutions proposed to replace high GWP Hydrofluorocarbons (HFCs) are very different and no definitive alternative has imposed yet [5]. The pros and cons of each alternative can be seen at Mota-Babiloni et al. [1]. Specifically, to replace R404A the most feasible options are: cascade refrigeration systems using R134a, or an alternative at high temperature stage [6], and CO_2 at low temperature stage, CO_2 in transcritical systems [7], hydrocarbons [8] or replace directly R404A by using a refrigerant with similar properties (mostly low NBP) [9].

Focusing on direct replacement of R404A, several HFC and HFC/HFO (Hydrofluoroolefin) mixtures have appeared as alternatives.

Three HFC mixtures have been presented as light retrofit replacements for R404A; R407A, R407F and R422A. Despite having approximately half GWP than R404A and higher or similar efficiency [10], these GWP values are still very high and can cause a high acquisition cost due to the GWP taxes approved in some developed countries [11].

HFOs are very low GWP (their values are around 1), zero-ODP and low-flammable fluids proposed to replace HFCs in refrigeration and air conditioning applications [12]. Although that, the most extended HFOs, R1234yf and R1234ze(E), have presented some limitations when they are used as HFC drop-in replacements [13].

Different chemical companies (Honeywell, DuPont, Archema or Mexichem) produced HFO/HFC mixtures to replace R404A [9]. Honeywell first developed two R1234ze(E)-based mixtures known as Solstice™ N40 and Solstice™ L40 [14]. Solstice™ N40 composition was slightly modified and then it was designed as R448A by ASHRAE, it is zero-ODP, non-toxic and non-flammable (A1, [15]) and its GWP value is 1390. It is intended for large commercial

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Nomenclature

COP	coefficient of performance
h	enthalpy (kJ kg^{-1})
$\dot{m}_{ref}$	refrigerant mass flow rate (kg s^{-1})
N	compressor rotation speed (rpm)
P	pressure (kPa)
P_c	compressor power consumption (kW)
$\dot{Q}$	cooling capacity (kW)
SH	Superheating degree (K)
T	temperature (K)
V_G	compressor geometric volume (m^3)

Greek symbols

η_{vol}	volumetric efficiency
$\rho_{suction}$	density at compressor suction (kg m^{-3})

Subscripts

in	inlet
k	condenser
o	evaporator
out	outlet

Abbreviations

DX	direct expansion
GWP	global warming potential
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
IHX	internal heat exchanger
NBP	normal boiling point
ODP	ozone depletion potential
TXV	thermostatic expansion valve

Table 1
Placing on the market prohibitions by the EU Regulation No 517/2014 that affects R404A [4].

Products and equipment		Date[a]
Refrigerators and freezers for commercial use (hermetically sealed equipment) that contain HFCs with:	GWP ⩾ 2500 GWP ⩾ 150	2020 2022
Stationary refrigeration equipment, that contains, or whose functioning relies upon, HFCs with GWP ⩾ 2500 except equipment intended for application designed to cool products to temperatures below 223 K		2020
Multipack centralised refrigeration systems for commercial use with a rated capacity ⩾40 kW that contain, or whose functioning relies upon, fluorinated greenhouse gases with GWP ⩾150, except in the primary refrigerant circuit of cascade systems where fluorinated greenhouse gases with a GWP < 1500 may be used		2022

[a] 1 January.

refrigeration centralized systems with DX (Direct Expansion) in public area. Besides, L40 is zero-ODP, non-toxic but low-flammable and with a GWP value around 250. Because its GWP is over 150 (this limitation was tighten than expected), another blend with GWP fewer than 150 was developed: HDR-110. It is targeting small refrigeration applications, as self-contained units or hermetically sealed systems (R290 or CO_2) with or without suction-line/liquid-line heat exchanger [16].

Recent researches have shown that R448A can compete with R404A in various applications. Mota-Babiloni et al. [17] have studied theoretically six R404A alternatives in four vapour compression configurations (where refrigerants with high glide can be used). Better energy efficiency is obtained with all replacements compared to R404A under all conditions studied. Yana Motta et al. [18] concluded that R448A performs better than R404A in a walk-in freezer/cooler, with acceptable pressures and discharge temperatures. In a DX supermarket lab test [19], R448A energy consumption is 3–8% lower than R404A at different evaporating and condensing conditions. Therefore, R448A can reduce energy consumption compared to R404A in a DX supermarket system with minor modifications.

In this paper, R448A is evaluated as R404A alternative using data obtained from several drop-in tests performed in a vapour compression system test bench. The rest of the paper is organized as follows: In part 2, the main considerations of using these refrigerants are explained. Later, in part 3, the experimental setup is shown. Then, in part 4, the experimental procedure is detailed. Next, in part 5, results are presented and discussed. Finally, in part 6, the conclusions of the study are summarized.

2. Properties of refrigerants analyzed

R448A is a non-azeotropic mixture of R32 (26%), R125 (26%), R1234yf (20%), R134a (21%) and R1234ze(E) (7%). It is selected as R404A alternative because of its similar properties that ensures good adaptation to existing systems, Table 2.

Although R448A NBP is higher than that of R404A, it accomplishes freezing requirements (operating evaporator pressure above atmospheric at low temperatures). R448A glide is very high and cannot be simplified to near-azeotropic mixture, but, as pointed by Rajapaksha [21], taking advantage of this characteristic and redesigning the systemto adapt to a non-azeotropic mixtures as R448A could lead to energy improvement. Furthermore, it cannot be used in systems with components where liquid can be collected e.g. suction line accumulators, flash tanks, receivers or pool boiling/flooded evaporators [22]. The critical temperature for R448A is also higher, so the power required for compressing vapour decreases [23]. The vapour density is lower for R448A and it affects suction volumetric flow rate. Vapour line pipes design should be revised due to great differences in vapour density and liquid. Great difference in liquid thermal conductivity could affect heat exchangers design.

R448A accomplish the GWP limitation for stationary refrigerant equipment and also can be used in cascade multipack refrigeration systems [24]. However, it will not be allowed in refrigerators and freezers or in direct expansion multipack refrigeration systems [4].

Table 2
Characteristics of refrigerants selected [20].

	R404A	R448A	Rel. dev.
ODP/GWP_{100-yr}	0/3943	0/1390	
ASHRAE Safety Class	A1	A1	
Glide[a] (K)	0.75	6.27	
Critical Pressure (kPa)	345.20	356.81	3%
Critical Temperature (K)	3728.85	4674.93	25%
NBP (K)	227.41	233.05	2%
Liquid density[a] (kg m^{-3})	1150.59	1192.39	4%
Vapour density[a] (kg m^{-3})	30.32	22.09	−27%
Liquid c_p[a] (kJ kg^{-1} K^{-1})	1.39	1.42	2%
Vapour c_p[a] (kJ kg^{-1} K^{-1})	1.00	0.98	−2%
Liquid therm. cond.[a] (W m^{-1} K)	$73.15 \cdot 10^{-3}$	$92.41 \cdot 10^{-3}$	26%
Vapour therm. cond.[a] (W m^{-1} K)	$12.82 \cdot 10^{-3}$	$12.01 \cdot 10^{-3}$	−6%
Liquid viscosity[a] (Pa s^{-1})	$179.70 \cdot 10^{-6}$	$188.35 \cdot 10^{-6}$	5%
Vapour viscosity[a] (Pa s^{-1})	$11.00 \cdot 10^{-6}$	$11.42 \cdot 10^{-6}$	4%

[a] Temperature = 273 K.