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Theoretical comparison of low GWP alternatives for different refrigeration configurations taking R404A as baseline

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ABSTRACT

Six refrigerants are evaluated as low GWP replacements for R404A using different configurations, including two-stage system architectures. These refrigerants are selected according to similar characteristics to R404A, and they are the mid-term alternatives R407A and R407F, and the long-term alternatives: L40 and DR-7 (with very low GWP and low flammability), N40 and DR-33 (with low GWP and no flammability). In order to have a complete comparison range, various operating conditions are considered, covering low and medium evaporator temperatures and two levels of condensation temperatures. Configurations selected are presented and the equations used to simulate the expected performance are shown. From a given cooling capacity, volumetric flow rate and COP are compared, taking R404A as baseline. The most efficient alternatives are the low-flammable refrigerants, L40 and DR-7, and when no flammability is acceptable, N40 and DR-33 are also very good options.

Comparaison théorique des alternatives à faible GWP pour diverses configurations frigorifiques prenant le R404A comme point de référence

Mots clés : Réfrigération ; Configurations ; Remplacements du R404A ; GWP ; Coefficient de performance (COP)

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Nomenclature

COP	coefficient of performance (–)
h	specific enthalpy (kJ kg^{-1})
$\dot{m}$	refrigerant mass flow rate (kg s^{-1})
P	pressure (MPa)
$\dot{Q}$	heat transfer rate (kW)
SH	Superheating degree (°C)
T	temperature (°C)
$\dot{V}$	volumetric flow rate (m^3 s^{-1})
$\dot{W}_c$	compressor power consumption (kW)

Greek symbols

ε	effectiveness
η	efficiency
ρ	density (kg m^{-3})

Subscripts

disc	discharge
HP	high pressure stage
IHX	Intermediate Heat Exchanger
in	inlet
IP	intermediate pressure stage
k	condenser
liq	saturated liquid
LP	low pressure stage
out	outlet
suc	suction
SC	subcooler
o	evaporator

1. Introduction

To avoid the reduction in the atmospheric ozone, according to the terms of the Montreal Protocol, a total phase-out for chlorofluorocarbon (CFC) by 2010 and hydrochlorofluorcarbon (HCFC) by 2040 in all countries (UNEP, 2007) has been established. In this way, hydrofluorocarbon (HFC) gases became relevant in all refrigeration fields (Calm, 2008) because of their zero Ozone Depletion Potential (ODP). And while they are non-ozone depleting substances, they have great values of global warming potential (GWP). So, after being approved the Kyoto Protocol in 1997 (Kyoto Protocol, 1997), HFC refrigerants were considered as greenhouse gases (GHGs) and they would be progressively removed.

Through the European Directive 2006/40/EC (Directive, 2006/40/EC) fluids with GWP>150 are banned for new mobile air conditioners (MAC) since 2011 and for the rest MAC systems will be excluded onward 2017. Additionally, in 2012 a tightening of the F-gas regulation was proposed, where a reduction reaching 21% of the levels sold in 2008–2011 by 2030 is established. In this way, in 2013 in Spain, a tax focused on refrigerants with high GWP (Ley 16/2013) was also approved.

So, because of the relevance of the refrigerant gas leakages from vapour compression systems (in UK supermarkets around 13% of refrigerant from circuits is lost (Cowan et al., April 2010)), research efforts in the refrigeration industry are focused on finding non-toxic fluids with low GWP and with low flammability to replace high GWP working fluids used in existing vapour compression cycles (U.S. Environmental Protection Agency, September 2013).

Analysing low and medium temperature commercial refrigeration applications, due to Montreal Protocol, there was a retrofit process from R22 and R502 to zero-ODP refrigerants, mainly R134a, R404A and R507A (Mohanraj et al., 2009; Yang and Wu, 2013). R404A and R507A are very similar and they can be used both for a very wide range of evaporation temperatures, R404A being mostly used in Europe. R404A shows excellent properties: non-flammable and non-toxic, easy retrofit in R22 systems, a similar range of operating conditions and presents good energy efficiencies (Spatz and Yana Motta, 2004; Llopis et al., 2010; Ge and Cropper, 2008; Arora and Kaushik, 2008; Ge and Cropper, 2004). However, R404A presents high GWP (3922) (IPPC, 2001) and probably is going to be phase-out over the next years (Jürgensen, 2013).

Currently, HFC mixtures are prevailing as medium GWP replacements for R404A. In this way, non-flammable mid-term solutions like R407A (GWP = 2107) or R407F (GWP = 1825) are available (Linde Gases Division, September 2013; Linde Gases Division, September 2013). Despite having half the GWP of R404A, these refrigerants are presented with a better performance in light retrofit processes. In order to work with refrigerants with even lower GWP values, long-term solutions are being developed by Honeywell (Solstice™ N40 and L40) (Honeywell International Inc, September 2012) or DuPont (DR-7 and DR-33) (Minor and Rinne, October 2012), developing HFC and HFO blends.

While N40 and DR-33 are non-flammable refrigerants with relatively low GWP values (1205 and 1410, respectively), L40 and DR-7 have a low GWP (285 and 246, respectively) even though they would be classified as A2L by ASHRAE Standard 34 (American Society of Heating Refrigerating and Air-Conditioning Engineers 2010). Yana Motta et al. (2012) suggest using in future studies flammable refrigerants in high side of secondary fluid systems (chillers), cascade systems (CO_2 in the low stage), small close-coupled systems, and even distributed systems.

Moreover, Yana Motta et al. (2012) tested low GWP refrigerants (R407F, N40, N20 and L40) in a refrigeration system designed for R404A. All alternatives showed superior performance, acceptable pressures and discharge temperatures below the limits. On the other hand, they recommended some changes when using flammable refrigerants. Minor and Rinne (2012) experimented with DR-7 and DR-33 in a double-door unit designed for R-404A. The conclusions were that both replacements presented similar (DR-33) or slightly minor (DR-7) energy consumption, similar pressures and compression ratio, and the increase in discharge temperature was about 13–16 °C.

Besides using low GWP alternatives, it is also important to look for more efficient systems. In this way, applying some modifications to the basic cycle (Minh et al., 2006) should be considered. For example, the refrigerating effect in the evaporator can be enhanced using an internal heat exchanger (IHX)