Applied Energy 138 (2015) 133–142

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Energy and environmental comparison of two-stage solutions for commercial refrigeration at low temperature: Fluids and systems

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HIGHLIGHTS

- Possibilities of two-stage systems as future refrigeration systems are analysed.
- Five models of two-stage systems are evaluated with several low-GWP refrigerants.
- Cascades with CO_2 as low temperature fluid are promising systems.
- Direct CO_2 transcritical systems are not recommended for warm countries.
- Performance of cascades does not greatly depend on the high temperature fluid.

ARTICLE INFO

Article history:
Received 29 April 2014
Received in revised form 8 September 2014
Accepted 24 October 2014

Keywords:
Cascade
Two-stage
Low GWP
TEWI
Energy efficiency
R152a

ABSTRACT

International agreements will restrict in the near future the use of high-GWP refrigerants in Europe. These restrictions will favour the implantation of refrigeration systems with low-GWP fluids, especially in applications with high leakage rate. To clarify possible solutions that accomplish the forthcoming F-Gas Regulation, we present simplified models of five two-stage vapour compression refrigeration systems and evaluate them with low-GWP refrigerants (HFC, HFO and naturals). We analyse the energy performance over a wide range of evaporating and environment temperatures and present the TEWI analysis under a same scenario, typical of a centralized commercial refrigeration application. We conclude that, for high-GWP refrigerants, direct emissions have greater weight in TEWI than the indirect ones, so future solutions might be based on low-GWP fluids, in some cases with risk of toxicity or flammability. We observe the indirect two-stage systems (cascades) with CO_2 as low temperature fluid are promising solutions, especially for warm regions.

1. Introduction

Environmental impact associated to vapour compression refrigeration leads a movement among the scientific community towards more environmental friendly solutions, destined to mitigate the direct effect caused by refrigerant emissions and reduce the indirect effect induced by energy consumption of the plants. International agreements, those arisen from the Kyoto Protocol [1], favour the development and implantation of these environmental friendly solutions, since they restrict the use of refrigerants with high Global Warming Potential (GWP). European legislation, the strictest regulation about fluorinated gasses, limited the use of refrigerants with GWP higher than 150 in mobile air conditioning applications [2] and increased the supervision of refrigeration plants and their refrigerant emissions [3]. In addition, some specific state regulations tax the purchase of HFC refrigerants, such in Denmark, Sweden, Germany and Spain. And in March 2014, European Commission approved the final text of the revision of the F-Gas Regulation [4] which will came into force in 2015, whose objective is the partial or total removal of fluorinated gasses with high GWP. This legislation will ban the use of HFC with a GWP higher than 150 in domestic stand-alone systems, in refrigerators and freezers for commercial use and in movable air-conditioning appliances. Also, it will only permit the use of refrigerants with GWP lower than 150 for multipack centralized refrigeration systems for commercial use with a rated capacity of 40 kW or more, except for the primary refrigerant circuit of cascade systems, where gases up to GWP of 1500 could be used. Additionally, it will not permit refilling of systems with a charge size over 40 tonnes of CO_2 equivalent with HFC of very high GWP (higher than 2500). These lasts prohibitions will strongly affect centralized commercial

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http://dx.doi.org/10.1016/j.apenergy.2014.10.069
0306-2619/

Nomenclature

E_{an}	annual energy consumption (kW h)
GWP	global warming potential (100 years integration)
h	specific enthalpy (kJ kg^{-1})
HT	high temperature
h_s	discharge isentropic specific enthalpy (kJ kg^{-1})
h_{fg}	latent heat of phase change (kJ kg^{-1})
HOC	heat of combustion (mJ kg^{-1})
OEL	occupational exposure limit (ml m^{-3})
L	annual refrigerant leakage rate (kg year^{-1})
LT	low temperature
LFL	lower flammability limit (% volume in air)
MT	medium temperature
m	total refrigerant charge of the system (kg)
$\dot{m}$	refrigerant mass flow rate (kg s^{-1})
n	life span of the refrigeration system (years)
P	pressure (bar)
P_C	compressor power consumption (kW)
$\dot{Q}_O$	cooling capacity (kW)
SUB	liquid subcooling degree in subcooler (°C)
t	compression ratio
T	temperature (°C)
$TEWI$	total equivalent warming impact with 100 year integration (ton $CO_{2,equ}$)
w_s	isentropic specific compression work (kJ kg^{-1})

Greek symbols

α	recycling factor of the refrigerant
β	indirect emission factor (kgCO$_2$ kWh^{-1})
η_i	isentropic efficiency of the compressor
ε	subcooler thermal effectiveness
Δ	increment

Subscripts

$casc$	cascade heat exchanger
env	environment
H	high-temperature cycle, second compression stage
I	intermediate level
K	condensing level
L	low-temperature cycle, first compression stage
l	saturated liquid
O	evaporating level
opt	optimum value
s	subcooling mass flow rate
sf	secondary fluid
v	saturated vapour

refrigeration, especially supermarket refrigeration systems, where the use of R404A and R507A will be forbidden. As can be deduced, in a near future we will find limitations about the use of high-GWP HFCs, which limits the direct effect, however, no actions are taken by reference to more energy efficient systems, which will also reduce the indirect effect.

According to UNEP [5], the most used refrigerants in commercial refrigeration are R404A for medium and low temperatures and R134a for high temperatures. R404A is a very high-GWP refrigerant and R134a a high-GWP refrigerant (Table 1). Their use will be limited by future regulations, therefore alternative refrigerants are currently being explored. The considered options among the naturals are ammonia (R717), carbon dioxide (R744) and some hydrocarbons, being all of them very-low-GWP fluids. Due to safety considerations, R717 is experimented with indirect two-stage [6,7] or secondary fluid systems [8–10]. R744 is evaluated with direct transcritical single [11,12] or two-stage plants [13,14], as low temperature fluid in cascade systems [15] or as secondary fluid [16,17]. And hydrocarbons, specially R290, are analysed as high temperature refrigerants in indirect two-stage plants [18] and with secondary fluids [19]. In addition to the naturals, we can consider some other candidates, such as the recently developed very-low-GWP hydrofluoroolefins R1234yf and R1234ze(E), and one low-GWP HFC, the R152a, all of them with some characteristics of flammability. However, we have not found any reference regarding experimental evaluation of these last fluids in semihermetic compressors yet. The main properties of above mentioned fluids [20,21] are presented in Table 1.

From the analysis above presented of current and future options of refrigerants for commercial refrigeration, we suggest from the point of view of safety that all low-GWP fluids, except CO_2, cannot be recommended for centralized direct expansion systems since all of them present characteristics of flammability or toxicity, therefore the security of the end users will not be guaranteed. The most logical option for these fluids is to implement indirect systems, for example cascades with CO_2 as LT refrigerant or secondary fluid indirect systems with CO_2 or another fluid. We can consider single-stage and two-stage systems, but we will discuss here only two-stage systems because their higher energy performance. Accordingly, the discussion of the systems leads us to only five systems: direct two-stage systems with CO_2 (with subcooler or flash tank), indirect two-stage systems with a low-GWP fluid in the HT side and CO_2 in the LT side, and direct two-stage systems (with subcooler or flash tank) with a low-GWP refrigerant combined with a secondary fluid loop. Direct two-stage plants were analysed with HFC fluids with the subcooler inter-stage system in [22–24] and those with CO_2 with a flash tank in [25] and without inter-stage systems in [26]. Regarding indirect two-stage systems or cascades, they were studied experimentally with NH_3/CO_2 in [7,27] and with R134a/CO_2 in [15]. Finally, regarding secondary fluid systems, Wang et al. [28] present some experimental investigations using CO_2. As can be observed, we can state that initial works have been done in order to provide environmental friendly solutions from an experimental point of view. However, it is not clear which refrigeration system with the possible combinations of low-GWP refrigerants will be the most interesting.

Literature provides few works comparing those refrigeration solutions. Girotto et al. [29] presented energy consumption of a supermarket with two solutions, one CO_2 transcritical system (single-stage compressors for MT and two-stage compound compressors for LT) with a two-stage direct expansion system with R404A. They observed lower energy efficiency for CO_2 solution, but stated it could reach the same efficiency of R404A with cycle improvements. They not provided TEWI considerations. Da Silva et al. [30] presented an experimental comparison of a supermarket centralized system working at −30 °C with a R404A/CO_2 cascade and with a direct expansion single-stage with R404A and R22. They considered energy, environmental and cost analysis, and concluded that the cascade system reduces energy consumption about 13–24%. However, they do not provided data about environmental implications. Mumanachit et al. [31], from a theoretical approach, presented the energy and cost comparison of a NH_3/CO_2 cascade system with a two-stage ammonia system, concluding that the cascade system is more efficient at low evaporating temperatures. Finally, Messineo [32] presented a theoretical analysis of a NH_3/CO_2 cascade system with a two-stage R404A system, stating that