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Modelling commercial refrigeration systems coupled with water storage to improve energy efficiency and perform heat recovery

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ABSTRACT

A basic CO_2 transcritical/subcritical commercial refrigeration system is considered, applied to cold rooms and display cabinets in a supermarket. Subcooling of the refrigerant or heat recovery from condensation can be performed, taking advantage of a large fire prevention water tank. The whole refrigeration system is modelled in a TRNSYS environment, taking into account the hourly weather data and calculating the hourly cooling load demand from display cabinets and cold rooms equipment. New *types* have been written to describe display cabinets and cold rooms, CO_2 refrigerating units and a particular water store.

Simulations consider a simple double compression cycle with liquid receiver, and other options among which an auxiliary compressor. Results show that CO_2 plants are feasible and energetically acceptable in mild climates, provided that improvements to standard cycle are adopted. Furthermore, heat recovery can be effectively performed through the employment of a heat storage.

Modélisation de systèmes frigorifiques commerciaux couplés à un accumulateur d'eau pour améliorer l'efficacité énergétique et augmenter la performance de récupération de chaleur

Mots clés : CO_2 ; Froid commercial ; Efficacité ; Modélisation ; Récupération de chaleur

1. Introduction

Commercial refrigeration is being especially affected by the phase down schedule for HFCs, recently forced in Europe through the European "F-gas regulation" (EU Fgas, 2014). In fact, as of 1st January 2022, placing on the market is prohibited for fluorinated greenhouse gases with a GWP of 150 or more used in multipack centralised refrigeration systems for commercial use, with a rated capacity of 40 kW or more. Exception is made for the primary refrigerant circuit of cascade systems, where fluorinated greenhouse gases with a GWP lower than 1500 (like R134a) may be used. This directive represents a step towards a possible full ban of HFCs, as it has already happened in some

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Nomenclature

AC	auxiliary compressor
COP	coefficient of performance
CRU	commercial refrigeration unit
CR	cold room
HX	heat exchanger
LT	low temperature
MT	medium temperature
p	pressure [MPa]
q	heat flux [W]
r	pressure ratio
RDC	refrigeration display cabinet
t	temperature [°C]
ΔT	temperature difference [K]
η_{is}	isentropic efficiency

Subscripts

ap	approach point
aux	auxiliary devices
def	defrost
GC	gas cooler
inf	infiltration
lat	latent
out	outlet
sen	sensible
set	set point
tank	water tank
w	wall

countries (IIR, 2015), thus giving rise to the need for finding alternate solutions (Cavallini et al., 2014). In spite of its low critical temperature as well as high operating pressure levels, carbon dioxide (R744) is receiving growing attention, due to its favourable thermophysical properties, non-toxicity, non-flammability and to its very low GWP, which leads to a negligible direct contribution to the greenhouse effect. On the contrary, the indirect contribution could be negatively affected because of the lower efficiency of R744 systems when compared with those operated by traditional HFCs. This is particularly true for applications in mild and warm climates, where the CO_2 systems operate for a long period of time at transcritical conditions, with a significant decrease in their energy performance. Research is ongoing to face design issues and improve the energy efficiency of CO_2 systems in such conditions (Kim et al., 2004), and various solutions have been identified and tested (Cavallini and Zilio, 2007; Cecchinato et al., 2009; Gullo et al., 2016; Hafner et al., 2014; Sawalha, 2009) also with more in-depth analyses involving system irreversibilities (Gullo et al., 2015).

The main concern at mild/warm climates is related to the high temperature of the refrigerant at the gas cooler exit, which is very effective on the performance of the system (Pettersen, 1997). For this reason many efforts are devoted to investigate configurations where gas cooling can be promoted to the highest level, by means of internal heat exchangers (Cavallini et al., 2007; Ge and Tassou, 2011c; Sawalha, 2008; Yang and Zhang, 2011) with an average increase in the COP of up to 10%, or by means of the “mechanical subcooling”, i.e. performing subcooling thanks to another refrigerating unit (Hafner et al., 2014; Llopis et al., 2015; Qureshi and Zubair, 2012). The effectiveness in terms of global energy consumption of the solution with mechanical subcooling is strictly related to the COP of the additional refrigerating system, and its evaluation on a yearly basis is not so easy. As an example, Wiedenmann et al. (2014) investigated the effect of subcooling performed by an adsorption refrigerator driven by waste heat. Because of the additional investment cost, high payback periods were estimated, with a rather low market potential.

It comes out that an effective improvement could be safely reached while performing subcooling by means of an external device at no or very low expense. Looking for other cold sources for subcooling, Ferrandi and Orlandi (2013) investigated the effect of a cold storage used to cool down the refrigerant at the exit of the liquid receiver in a “booster” cycle. With a water store size from 12 to 27 m^3, they predicted an average reduction in summer daily power consumption around 5% compared to a traditional plant, and a peak refrigerating capacity reduction around 28%.

In this paper, a similar solution is investigated, where a fire prevention water tank is employed as a cold sink for performing subcooling. Of course an application has to be identified for the heat released to the water tank, and this has been found in the HVAC plant. In fact, every supermarket is located in a building or a shopping mall where heating and air conditioning have to be performed, which could take advantage from a heat storage device. The idea of recovering heat from a refrigeration plant in favour of other systems is well known and widespread, especially for hot water production (Hafner et al., 2012; Nidup, 2009; Sawalha, 2013). Much less common is heat recovery for heating purposes (Cortella and D’Agaro, 2016; Cortella and Saro, 2010), both for the great amount of energy required and for the troubles in matching needs and availability. Heat pumps are commonly used for heating purposes in commercial buildings. Their seasonal performance not only depends on their design, but it is definitely affected by the temperature of the secondary fluid at the inlet of the evaporator (Tammaro et al., 2015). For this reason, outdoor air is not the best choice as a heat sink, and geothermal (aquifers or boreholes) or any great capacity heat sources are employed whenever feasible and convenient. A great capacity heat storage like the fire prevention water tank can be a solution to perform subcooling of the refrigeration plant and allow heat recovery in favour of heat pumps for heating purposes, while acting as a buffer and disconnecting heat demand and supply (Polzot et al., 2015).

A thorough evaluation of both the systems is required, by means of a transient state simulation, in order to perform an accurate estimation of their thermal loads and energy use all through the year, and to investigate the effectiveness of various heat recovery strategies, with the aim of reducing the global energy consumption without affecting the performance. Various software codes are available in the literature, able to simulate both the refrigeration and HVAC systems in supermarkets, which can be employed to perform such evaluations. Among all, we mention here *Cybermart* (Arias, 2005; Arias and Lundqvist, 2005), *EnergyPlus* (Stovall and Van Baxter, 2010), and *SuperSim* (Ge and Tassou, 2011a, 2011b). Only *Energy Plus* is freely available, and can be used for the simulation of systems with some