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Experimental evaluation of a CO_2 transcritical refrigeration plant with dedicated mechanical subcooling

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ABSTRACT

CO_2 transcritical refrigeration cycles require optimization to reach the performance of conventional solutions at high ambient temperatures. Theoretical studies demonstrated that the combination of a transcritical cycle with a mechanical subcooling cycle improves its performance; however, any experimentation with CO_2 has been found. This work presents the energy improvements of the use of a mechanical subcooling cycle in combination with a CO_2 transcritical refrigeration plant, experimentally. It tested the combination of a R1234yf single-stage refrigeration cycle with a semihermetic compressor for the mechanical subcooling cycle, with a single-stage CO_2 transcritical refrigeration plant with a semihermetic compressor. The combination is evaluated at two evaporating levels of the CO_2 cycle (0 and −10 °C) and three heat rejection temperatures (24, 30 and 40 °C). The optimum operating conditions and capacity and COP improvements are analysed with maximum increments on capacity of 55.7% and 30.3% on COP.

Évaluation expérimentale d'une installation frigorifique transcritique au CO_2 avec un sous-refroidissement mécanique dédié

Mots clés : CO_2 ; Transcritique ; Sous-refroidissement ; Efficacité énergétique

1. Introduction

After the approval of the bans to the use of fluorinated fluids in the Refrigeration sector by the F-Gas in Europe (European Commission, 2014) the interest for CO_2 as refrigerant has been taken a step forward, especially in commercial refrigeration where its use is not questioned any more. CO_2 in centralized commercial refrigeration systems is mainly put into practice with cascades or pure transcritical systems. According to Shecco

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Nomenclature

COP	coefficient of performance
MS	dedicated mechanical subcooling cycle
t	compression ratio
T	temperature [°C]
TRANS	referring to the CO_2 transcritical cycle
$\dot{m}$	mass flow rate [$kg \cdot s^{-1}$]
P	pressure [bar]
P_C	power consumption [kW]
$\dot{Q}$	heat transfer rate [kW]
q_o	specific cooling capacity [$kJ \cdot kg^{-1}$]
h	specific enthalpy [$kJ \cdot kg^{-1}$]
x_v	vapour title

Greek symbols

η_i	isentropic efficiency
η_v	volumetric efficiency
Δ	increment

Subscripts

CO_2	referring to CO_2 cycle
env	environment
gc	gas-cooler
in	inlet
K	condenser of MS cycle
MS	referring to the dedicated mechanical subcooling cycle
out	outlet
O	evaporator
r	refrigerant
w	water
sf	secondary fluid of the evaporator
sub	referring to the subcooler

Guide (Shecco Publications, 2014), there were 2885 supermarkets operating with pure transcritical systems and 1638 with HFC/CO_2 cascades in Europe in 2013. However, when referring to warm countries, such as Spain or Italy, only 21 supermarkets operate with transcritical systems and 231 with cascades. The preferred solution for warm countries is the cascade, since when the ambient temperature is high the performance of pure transcritical systems is far away from that offered by the cascades (Llopis et al., 2015b).

Different researchers have worked to improve the efficiency of CO_2 transcritical systems trying to reach the performance of other systems. Aprea and Maiorino (2008) and Sánchez et al. (2014a) studied the improvements by using the internal heat exchangers (IHX) in single-stage plants and Cavallini et al. (2007) in two-stage systems. The experimental measurements demonstrated that the IHX can improve the COP up to a maximum of 10%. Others analyzed the effect of extracting vapour from the intermediate vessel to be injected in different points of the cycle, measuring maximum increments of 7% in single-stage plants (Cabello et al., 2012) and 16.5% in double-stage cycles (Cho et al., 2009). The use of expanders (Li et al., 2004), ejectors (Lee et al., 2014) and regulation strategies (Peñarrocha et al., 2014) are also considered. Now, improvements of CO_2 transcritical plants are searched from its combination with other systems, such as desiccant wheels (Aprea et al., 2015) or absorption plants (Arora et al., 2011).

In 1994, Zubair (1994) reintroduced the use of dedicated mechanical subcooling systems. Recently, this option has been studied for supermarket refrigeration systems in warm countries by Hafner et al. (2014) and Gullo et al. (2016). Llopis et al. (2015a) analysed theoretically the use of a dedicated mechanical subcooling system for CO_2 transcritical systems, where the possibilities of increasing the energy performance of a transcritical CO_2 cooling system by subcooling the CO_2 at the exit of the gas-cooler were studied. The CO_2 subcooling, with degrees from 2.5 °C to 10 °C, was done thanks to a dedicated refrigeration system, which rejected heat to the same hot sink than the transcritical. The MS cycle evaporated at a temperature established by the CO_2 conditions at the exit of the gas-cooler, but there it was limited to 10 °C. The pressure drops and heat transfer in pipes were neglected. Evaporating temperature was fixed and a useful overheating of 10 °C was considered. The gas temperature at the exit of the gas-cooler was calculated considering an approach temperature of 5 °C (Kim et al., 2004), as shown in Eq. (1), and of 10 °C at the condenser of the MS cycle, as shown in Eq. (2).

$$T_{gc,out} = T_{env} + 5 \tag{1}$$

$$T_{K,MS} = T_{env} + 10 \tag{2}$$

That work considered simplified models for the compressors, using the same internal and volumetric efficiency curve:

$$\eta_i = \eta_v = 0.95 - 0.1 \cdot t \tag{3}$$

Llopis et al. (2015a) concluded that the MS cycle improves the overall energy efficiency if $COP_{MS} > COP_{TRANS}$, i.e., when the COP of the MS cycle is higher than the COP of the transcritical cycle working together. The advantages that it introduces are a reduction of the optimum working pressure, an increase of the specific cooling capacity and the CO_2 refrigerant mass flow rate, reduction of the CO_2 compressor power consumption and important increments of the overall COP and cooling capacity.

In fact, the theoretical results predicted maximum increments in COP of 9.5%, 13.5% and 13.1% and in cooling capacity of 20.7%, 19.7% and 12.7% at evaporations levels of 5 °C, –5 °C and –30 °C, respectively. However, the improvements that the MS cycle can introduce are higher than those mentioned previously, due to the conservative conditions established in the theoretical study and limited subcooling degrees, which are lower than those analysed experimentally.

This work has been developed in order to evaluate experimentally the impact of a dedicated mechanical subcooling system on a CO_2 transcritical refrigeration plant. The main objective is to quantify the energy improvements that can be achieved with this cycle modification. The evaluation presented in this paper corresponds to the operation of the plant at two evaporating levels (0 and –10 °C) tested at three different heat rejection temperatures (24, 30.2 and 40 °C) covering a wide range of gas-cooler operating pressures. The study has been done without IHX because the mechanical subcooling is supposed to introduce the same benefits without the