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Water-side reversible CO_2 heat pump for residential application

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ABSTRACT

This paper presents the energy assessment of a water/water R744 chiller/heat pump, working according to a transcritical cycle, used for winter heating, summer cooling and tap water production. The different functions (heating, cooling, hot water) are managed water side. The analysis of the R744 chiller/heat pump is based on an original simplified method, which is able to predict the energy performance of the unit based only on its performance data at the nominal rating conditions. The method was validated against experimental data. A comparison with a state-of-the-art R410A unit is presented. The monthly analysis shows that the CO_2 unit is very efficient in hot water production, but penalised in heating and cooling service. The adoption of an ejector in place of the expansion valve makes the CO_2 system reach the same energy consumption as the R410A unit, despite the presence of the water loop only in the R744 lay-out.

Pompe à chaleur au CO2 réversible du côté eau pour une application résidentielle

Mots clés : R744 ; Pompe à chaleur ; Refroidisseur d'eau ; Conditionnement d'air ; Éjecteur

1. Introduction

The effort which has been taking place in the last fifteen years towards the reintroduction of natural refrigerants in vapour compression cycle has recently gained renewed strength by the amended EU F-Gas regulation (Regulation No 517/2014 of the European Parliament and of the Council of 16 April 2014), which included a limit to the HFC quantity that can be launched in the market (phase-down) and a ban of the use of HFC for some

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Nomenclature

COP	heat pump coefficient of performance [-]
EER	chiller energy efficiency ratio [-]
m	mass flow rate [kg s^{-1}]
p	pressure [Pa]
R_p	compressor pressure ration [-]
T	temperature [°C]

Greek letters

η	efficiency [-]
ρ	density [kg m^{-3}]

Subscripts

cr	critical point
DIFF	ejector diffuser
ic	compression
in	inlet
MN	ejector motive nozzle
out	outlet
SN	ejector suction nozzle
tot	total
v	volumetric

applications, with different gradualness according to the specific application and the used refrigerant GWP value.

When Lorentzen (1994) first revived carbon dioxide as a refrigerant, he presented heat pumps as a privileged application for the CO_2 transcritical cycle.

As a matter of fact, carbon dioxide transcritical cycle is nowadays regarded as an energy efficient option for tap water heat pumps: the gas cooling process well fits the warming up of a finite stream of water, resulting in a quite large temperature lift in water without significant penalisation in COP, as it was clearly demonstrated in the technical literature (Lorentzen, 1994; Minetto, 2011; Nekså, 2002; Nekså et al., 1998). The peculiarities of the transcritical cycle require the use of once-through heat exchangers (gas coolers) in association with storage tanks; in this way the best energy performance can be achieved, as it was demonstrated by Cecchinato et al., 2005. The reason lays on the fact that, whereas for a common cycle the condensation temperature is linked to the water maximum temperature (and so it is for COP), for transcritical cycles energy efficiency is instead strongly linked to the water inlet temperature (Cecchinato et al., 2005; Nekså, 2002).

Heinz et al. (2010) demonstrated that CO_2 might offer an efficient solution if low temperature heating is required, especially if applied to low energy buildings.

In order to take advantage from the temperature of the water from the main, solutions with two or three gas coolers in series have been proposed (Heinz et al., 2010; Stene, 2005), providing simultaneously hot water for the tap and the heating system. Efficiency of such systems depends very much on the ratio between the tap hot water and heating demand, and their management might result complicated. Arteconi et al. (2014) analysed a CO_2 heat pump for space heating and hot water production, installed in Shanghai; they focused on load management, applying several demand side strategies by means of a dynamic simulation model with the aim of analysing the overall performance (i.e. thermal comfort and energy consumption) of the system in heating mode. Jin et al. (2015) recently proposed a CO_2 hybrid ground-coupled heat pumping system, analysing the behaviour of the suggested configuration at full and partial load and at different climatic conditions; they demonstrated that the combined COP for space conditioning and service hot water varies from 3.0 to 5.5 with 65 °C of hot water supply.

For the same mentioned reasons related to the intrinsic inefficiency of the transcritical cycle at high temperature of the heat rejection fluid, stationary air conditioning with CO_2 is rarely considered; Calabrese et al. (2015) analysed an air-to-air rooftop system for air conditioning Rooftoop CO_2 unit, finding out that expected performances are significantly poorer than HFCs units at external air temperature higher than 16 °C.

However, when simultaneous heating and cooling are required, CO_2 might offer good efficiency, as illustrated Sarkar et al. (2006) for an industrial application. CO_2 heat pumps for simultaneous heating and cooling are also available on the market, for industrial or commercial purposes, such as Envitherm by Star Refrigeration (2015) and Eco Cute “unimo W/W” by Mayekawa (2015); heat recovery for space heating is also common practice, as it happens in CO_2 commercial refrigeration plants, representing an example of simultaneous heating and cooling.

When dealing with residential applications, the heating and cooling demand is often not concurrent, while the hot water demand is normally concentrated in the morning and evening. Byrne et al. (2009) proposed a CO_2 chiller/heat pump for space heating and cooling and hot water heating, which can provide heat and cold water simultaneously or use external air as a heat source for heating and as a heat sink while cooling. They compared R407C and CO_2 performances for a hotel thermal load profile and hot water storage with weak stratification, estimating a slightly higher annual energy consumption (+4%) for CO_2.

As Lorentzen (1994) pointed out in the early stages of R744 revival, if the CO_2 heat pump is intended for space heating, modifications to the simple vapour compression transcritical cycle should be put in place to limit the efficiency losses of the cycle which occur as the gas cooler outlet temperature increases. The potentialities of using two-phase ejectors in CO_2 transcritical cycle was foreseen by Lorentzen in 1984, due to the inherently high expansion losses of the transcritical cycle; in 2011, Elbel (2011) reviewed the research effort which had been done so far to develop and evaluate ejectors and their interactions with the other circuit components, when used in a transcritical cycle.

Nowadays, ejectors are gaining popularity for CO_2 heat pumps as well as for refrigeration systems; limiting to manuscripts providing experimental results, Nakagawa et al. (2011), Lee et al. (2011), Banasiak et al. (2012), and Minetto et al. (2013) recently showed significant COP improvement when replacing expansion valves with ejectors, experimentally founding improvements ranging from 8% (Banasiak et al., 2012) to 26% (Nakagawa et al., 2011) with reference to the single compression-isenthalpic expansion unit. Elbel and Lawrence (2015) have just reviewed the last developments in ejector technology, present-