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Evaluation of different heat pump systems for sanitary hot water production using natural refrigerants

Miquel Pitarch, Emilio Navarro-Peris *, José Gonzálvez-Maciá, José M. Corberán

Instituto de Ingeniería Energética, Universitat Politècnica de València, Camí de Vera s/n, Valencia 46022, Spain

HIGHLIGHTS

- COP dependence on subcooling as a function of condenser size is shown.
- Comparison between two different subcritical prototypes for the production of SHW.
- Subcritical systems have a COP improvement between 5% and 20%.
- Subcritical system able to produce water at 90 °C with higher efficiency (11%).

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ABSTRACT

Heat pumps that work with a high degree of subcooling in subcritical systems have shown a significant margin of improvement when working with sanitary hot water applications. Recently, two different approaches to overcome the high degree of subcooling have been presented in the literature: with a subcooler (separate from the condenser) and by making all the subcooling in the condenser. In this paper, a comparative evaluation between both alternatives is presented, and the obtained results are compared with a representative solution already available on the market using natural refrigerants for this application. The results of this analysis have shown that in a system with subcooling in the condenser, it is possible to obtain a COP comparable to that of transcritical CO_2 heat pump water heaters. Furthermore, the system with subcooling has been demonstrated experimentally as being capable of producing water up to 90 °C and has shown a COP up to 20% higher than some CO_2 commercial products (catalogue data reference).

1. Introduction

An interesting, energy-efficient alternative to conventional sanitary hot water (SHW) systems (boilers), is the use of heat pump (HP) technologies, which is an application that has growing interest [1]. This potential for high efficiency is recognised by the European Directive 2009/28/CE [2], where a portion of the energy captured by a heat pump, having an estimated average seasonal performance factor (SPF) higher than a reference value, is considered as if it were obtained from renewable energy sources.

Since the first heat pump came up to market, engineers have been struggling to find a working fluid (refrigerant) that has to satisfy many requirements, such as thermodynamic, safety and environmental aspects. For instance, some fluorinated gases, such as CFCs and HCFCs have been (or will be soon) phased out [3]. HFCs do not contain chlorine or bromine, hence they are considered a negligible ODP, but are considered to be a greenhouse gas (high GWP), which has motivated counties to reduce HFC emissions [4]. On the other hand, natural refrigerants (carbon dioxide – CO_2 (R744), hydrocarbons (HCs), and ammonia – NH_3 (R717)) are pointed out as harmless to the ozone layer, with no influence on the greenhouse effect, or less so than traditional refrigerants, and with good thermodynamic properties [5].

The SHW application has a high water temperature lift, since the city water temperature is usually at 10 °C and the supplied hot water is at least 60 °C. For these conditions, many researchers have drawn attention to the natural refrigerant, CO_2, working in transcritical conditions as an efficient solution due to the high temperature glide in the refrigerant side. This effort has materialised in projects such as ECO-CUTE in Japan [6]. Works like [7–10] have shown the high efficiency of these cycles at water temperature lifts even higher than 50 K. Pitarch et al. [11] compared, in a theoretical study, the COP penalty of different heat pump systems (CO_2 cycle

* Corresponding author.
E-mail address: enava@ter.upv.es (E. Navarro-Peris).

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Nomenclature

BPHE	brazed plate heat exchanger
CFC	chlorofluorocarbon
COP	coefficient of performance (–)
EV	expansion valve
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HP	heat pump
ODP	ozone depletion potential
Pc	condensing pressure (bar)
Q	capacity (kW)
SHW	sanitary hot water
SMC	subcooling made in condenser
SMCL	subcooling made in subcooler with larger condenser
SMS	subcooling made in subcooler
SPF	seasonal performance factor
T	temperature (°C)
Wc	compressor power (kW)

Subscripts

cond	condenser
disch	discharge
h	heating
sub	subcooling
w	water
w,ci	water condenser inlet
w,co	water condenser outlet
w,ei	water evaporator inlet

with different subcritical refrigerants working at subcooling zero) for SHW production when the water temperature at the HP inlet increases (different water temperature lift). This study shows a higher COP for the CO_2 cycle at high water temperature lift, but its performance has a high dependency with the water inlet temperature to the gas cooler. After a certain value of the inlet water temperature, the COP is higher for the subcritical systems. Transcritical cycles also heavily depend on the optimal control of cycle internal variables like the gas cooler pressure. In the last decade, several authors have studied the optimisation of such a system [12–14]. Although CO_2 systems have an advantage in the SHW production because of the heat rejection in the transcritical region, they bring other problems at a high discharge pressure. Furthermore, it has a low critical temperature (30.98 °C), which makes it an unsuitable refrigerant to work in such applications where high evaporating temperatures can be reached [15], such as solar boosted or waste heat recovery heat pumps [16].

Subcritical systems (working with zero subcooling) have shown a lower performance for the high water temperature lift in SHW applications, but they have also been used for this purpose. This is the case for the commercial heat pump working with propane, Quantum [17], which warms up the water in sequences using low water temperatures lifts (around 5 K), trying to increase the overall heating COP at the end of the process (warming water at typical temperatures of 60 °C).

The possible benefits of making subcooling have been a concern of many researchers in the last decade. For instance, Justo Alonso and Stene [18] compare the theoretical calculated COP of a CO_2 transcritical cycle with two different systems working with propane; with and without a subcooler, COP is 20% higher when CO_2 is used. Between the two propane cycles, they showed an increase of COP when working with a subcooler with respect to the one with no subcooling, although they do not mention the degree of subcooling.

For a given external conditions, subcooling depends on the active charge of the system (this charge does not include the charge contained in reservoirs like a liquid receiver). In this sense, some authors have indirectly studied the effect of moderate subcooling in the system performance for low temperature lift of the secondary fluid (not for the SHW application), as they studied the influence of charge on the heat pump performance in systems without a charge receiver [19–21]. Of those studies, is important to comment on Corberan et al. [20,21], who studied the role of the charge in the system from a theoretical and experimental point of view; they pointed out that an optimum charge (and subcooling) exists for a given external condition.

For the case of a non-natural fluid, there are also works on SHW production, with no subcooling [22,23], and some concerning subcooling [10,24–26]. Cecchinato et al. [10] theoretically compare a CO_2 transcritical cycle with R134a subcritical cycle working with subcooling. They pointed out that it is possible to increase the energy efficiency of the R134a cycle with an increase in subcooling. In this way, the results for SHW production are similar for both cycles in winter conditions, while CO_2 has a higher performance in the summer [26], studies the subcooling effect on an air conditioner system working with R410A. In that work, the subcooling was controlled with the expansion valve by placing a liquid receiver at the evaporator outlet. An optimal subcooling to maximise the COP was found. This optimum depends on the air inlet temperature to the condenser, but no information about the outlet temperature was reported. To the best of the authors' knowledge, there is no experimental study about the advantages of making subcooling in subcritical systems in order to profit from the high water temperature lift in the SHW application (around 50 K). If a recommendation about subcooling is given, it is usually between 5 K and 10 K.

In recent studies in the frame of the EU project NEXTHPG [27], a new heat pump design for SHW production were proposed, [28] evaluates theoretically the potential SPF of this system, Pitarch et al. [29] presented the experimental results of a propane water-to-water heat pump prototype for SHW production in the application of heat recovery from any water source, which is an application that has recently received considerable attention [30]. The prototype has produced high subcooling in order to profit from the high water temperature lift in the SHW application. The subcooling was made in a separate heat exchanger (subcooler). The results showed a significant improvement in performance compared with the propane cycle with 0 subcooling, especially in the high water temperature lift. In the nominal point, with a subcooling of 44 K and 50 K water temperature lift, the degree of improvement is 31%. The COP in the nominal point was 5.61, which is quite competitive with the CO_2 systems for SHW production. In another study, Pitarch et al. [31] used a different heat pump design in order to produce subcooling. For this prototype, the control strategy used was entirely different because all of the subcooling was produced at the condenser. By means of an additional throttling valve, the active charge on the system can be controlled at any point, and thereby, the subcooling. The experimental results clearly showed an optimum subcooling (active charge) for each external condition (water temperatures). Unfortunately, a direct comparison between both alternatives could not be done, as the size of the condenser area was different for each heat pump.