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Research Paper

# The evaluation of optimal discharge pressure in a water-precooler-based transcritical $CO_2$ heat pump system

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## HIGHLIGHTS

- A novel subcooler-based transcritical $CO_2$ heat pump was studied.
- The existence of the optimal discharge pressure was discussed theoretically.
- Different control strategies of the optimal discharge pressure were compared.
- A correlation was proposed to evaluate the optimal discharge pressure.

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## ABSTRACT

A water-precooler-based transcritical $CO_2$ system is presented for promoting the modified $CO_2$ system to the space heating fields in which the water return temperature is too high to the standard transcritical $CO_2$ systems. The theoretical results found that the optimal discharge pressure, similar to the standard system, is also a remarkable parameter for the water-precooler-based system. Furthermore, four prediction approaches for the standard system are cited and the comparison of the optimal discharge pressure between the standard and the water-precooler-based system is carried out. Upon the results, it can be concluded that the optimal discharge pressure of the water-precooler-based system is higher than that of the standard system in all the simulation range. Moreover, on the basis of abundant simulation data, an empirical correlation for the water-precooler-based $CO_2$ system is proposed to evaluate the optimal discharge pressure by the ambient, water return and supply temperature as the independent variables.


## 1. Introduction

In recent years, a mass of cities and districts were suffered from the infringement of the haze in northern China in winter. Most researches believed that the aggressive haze which occurred normally in northern China in winter was mainly caused by the space heating used coal-fired boilers. Without treatment in waste gases, the small-size distributed coal-fired boilers leaded to immeasurable inhalable particles thereafter unquantifiable air pollution in winter. As a very promising approach, some researchers proposed to introduce the air-source heat pump (ASHP) into the application of space heating and replace the coal-fired boiler. According to the Chinese national standard of space heating, the water supply temperature should be more than 60 °C in both domestic and commercial fields, which is too high to the conventional refrigerants-based heat pumps. Thus, the air-source transcritical $CO_2$ heat pump system is presented widely to the space heating fields.

Decades ago, several pioneering researches have been carried out to assess the system performances and environmental attractive characteristics of using $CO_2$ as refrigerant in the cooling and heating refrigeration systems [1–3]. The research results found that the hot water supply temperature could be very high with effective COP by the transcritical system due to the $CO_2$ working mode in the transcritical region which caused the huge temperature glide in the gas-cooler. Similar experimental prototypes and theoretical models were studied by Nekså et al. [4] and White et al. [5], Nekså et al. found that the system COP in heating mode could be 4.3 at 0 °C in ambient temperature and the water could be heated from 9 °C to 60 °C. Furthermore, White et al. simulated that the hot water supply temperature could be more than 120 °C if the pressure of the water circulated system can be controlled well.

It is well known that there is an optimal discharge pressure in the $CO_2$ system due to the distinct working mode in the transcritical region [6], and absolutely, lots of studies have been carried out to analyze the reason why the optimal discharge pressure exist and evaluate the value of the optimal discharge pressure in various

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**Nomenclature**

| | |
|---|---|
| A | heat transfer area ($m^2$) |
| $c_p$ | specific heat capacity (kJ $kg^{-1}$ $K^{-1}$) |
| h | enthalpy (kJ $kg^{-1}$) |
| K | heat transfer coefficient (W $K^{-1}$ $m^{-2}$) |
| $\dot{m}$ | mass flow rate (kg $s^{-1}$) |
| N | number of discrete elements |
| P | pressure (MPa) |
| Q | heat transfer rate (kW) |
| R | fouling resistance (K $m^2$ $W^{-1}$) |
| T | temperature (°C) |
| V | theoretical displacement ($m^3$) |
| W | power dissipation (kW) |
| X | water flow ratio |
| $\alpha$ | convective coefficient (W $K^{-1}$ $m^{-2}$) |
| $\rho$ | density (kg $m^{-3}$) |
| $\eta$ | efficiency |
| $\xi$ | dehumidification coefficient |
| $\gamma$ | heat leakage coefficient |
| $\lambda$ | conductivity (W $K^{-1}$ $m^{-2}$) |

*Subscripts*

| | |
|---|---|
| air | air |
| cond | condenser |
| com | compressor |
| $CO_2$ | $CO_2$ subunit |
| d | discharge |
| e | evaporator |
| gc | gas-cooler |
| h | heating |
| i | inner |
| in | inlet |
| is | isentropic |
| I,j,k | Iteration number |
| o | outer |
| opt | optimal |
| out | outlet |
| pre | presented |
| r | refrigerant |
| s | suction |
| sta | standard system |
| sub | water-precooler-based system |
| tot | total |
| v | volumetric |
| w | water |
| w,f | water return |
| w,s | water supply |
| 134a | R134a subunit |

working conditions. Kauf [7] studied a standard transcritical $CO_2$ heat pump system and concluded an empirical correlation by the simplified system model upon the ambient temperature or the gas-cooler outlet temperature as the independent variable. In Kauf's research, the optimal discharge pressure is in direct proportion to the gas-cooler outlet temperature. Similarly, Liao et al. [8] analyzed and simplified the transcritical system and the heat transfer process before obtaining their empirical correlation. Comparatively, the evaporating temperature was taken into consideration in Liao's research as another independent variable to evaluate the optimal discharge pressure. Besides, analogous conclusion has been summarized by Sarkar [9] using both the ambient temperature and gas-cooler outlet temperature as the independent variables. Differently, the optimal discharge pressure is inversely proportional to the evaporating temperature in Sarkar's study instead of direct proportion which can be found in Liao's study. However, Chen et al. [10] support the argument from Kauf that only the gas-cooler outlet temperature should be taken into consideration as the independent variable. They summarized another empirical correlation which was very similar to Kauf's correlation to evaluate the optimal discharge pressure in the transcritical system.

However, on the basis of these researches displayed above, it can be observed that the performances of the transcritical $CO_2$ system deteriorated sharply with the increase in water return temperature thereafter gas-cooler outlet temperature, which was not suitable in the space heating fields with more than 40 °C in water return temperature. Thus, Yang et al. [11] and Song et al. [12] proposed a combined system with an R134a refrigeration cycle as the water-precooler. This modified system can be used to provide hot water stably and effectively under the operated conditions with quite high water return temperature (up to 50 °C) and very low ambient temperature (low to −20 °C). As an innovative system that is suitable to the space heating application fields, this kind of modified system cannot be found in any other literatures and the existence and evaluation of the optimal discharge pressure in the modified system is never been discussed in detail.

In this study, the water-precooler-based transcritical $CO_2$ heat pump is proposed and discussed theoretically in detail for the utilization of the proposed system in the application of space heating. Furthermore, the optimal discharge pressure both in the water-precooler-based system and the standard system are analyzed in detail in order to compare the difference between the optimal discharge pressures in the standard system and in the proposed system. Finally, on the basis of abundant simulated data, an empirical correlation is proposed in this study to evaluate the optimal discharge pressure in the water-precooler-based system.

## 2. System description and theoretical analysis

### 2.1. System description

Fig. 1 displayed the system schematic diagram of the water-precooler-based transcritical $CO_2$ heat pump system with components of a conventional R134a subunit, a transcritical $CO_2$ subunit, a shunt valve, a confluence tank and a water supply cycle. The ambient temperature which transfers heat with the $CO_2$ evaporator can be controlled from −20 to 0 °C to simulate the conditions in China in winter as well as the return water (from space heating users) temperature can be controlled from 40 to 50 °C according to China National Standard for space heating. Flowing through the shunt valve, the return water flow is splitting into two streams. On the one hand, due to the quite high temperature of the return water, the portion of return water that flows into the $CO_2$ gas-cooler is channeled into the R134a evaporator first and cooled to an acceptable state with lower temperature. On the other hand, the heating capacity of the R134a subunit is also absorbed by another water flow in the R134a condenser. Finally, the two portions of streams mingled up with each other in the confluence tank before being pumped to users.

### 2.2. Theoretical analysis

The pressure-enthalpy (P-h) diagrams of the two subunits in the water-precooler-based system are shown in Figs. 2a and 2b. As dis-