Energy and Buildings 67 (2013) 1–10

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Effect of heat transfer area and refrigerant mass flux in a gas cooler on heating performance of air-source transcritical CO_2 heat pump water heater system

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ARTICLE INFO

Article history:
Received 2 February 2013
Received in revised form 25 July 2013
Accepted 28 July 2013

Keywords:
Transcritical CO_2 heat pump water heater
Gas cooler
The optimal discharge pressure
Heat transfer area
Mass flux

ABSTRACT

This study investigated the effect of geometrical parameters of gas coolers on system performance and the optimal discharge pressure with a developed and experimentally validated numerical model of an air-source transcritical CO_2 heat pump water heater system. This model fully considered actual heat transfer process in the gas cooler and characteristics of major components adopted in the prototype system. Simulation results showed a good agreement with experimental results in terms of heat yields, COP and the optimal discharge pressure. Parametric analysis reveals that a larger heat transfer area of the gas cooler increases heat yields but decreases the optimal discharge pressure while other components in the system remain unchanged. In addition, at the same operating condition with the same heat transfer area, heat yields increase with CO_2 mass fluxes by reducing tube diameters and flow passages of gas coolers, and beyond certain range of mass fluxes, the optimal discharge pressure increases sharply. As one result, the optimal range of CO_2 mass flux in heat exchange tubes should be the range of 155–325 $kg\,m^{-2}\,s^{-1}$ at given condition in this paper.

1. Introduction

With rapid economic development, China has seen a marked increase in energy use in recent decades. Considering the largest population in the world, residential buildings account for a significant amount of the total China energy consumption about 24.1% in 1996, rising up to 27.5% in 2001, and has been projected to about 35% in 2020 [1–3], while more than half of the building energy demand is consumed by space heating, ventilation, and air conditioning (HVAC) system. Utilizing efficient technologies can reduce building energy use as well as greenhouse gas emissions.

Air-source heat pumps (ASHPs) are technologies that have been relatively well documented for heating and cooling buildings [4,5]. Compared to the fluorocarbon heat pump (HP), the carbon dioxide (CO_2) HP has an obvious advantage of environmental protection. Moreover, a continuous and large temperature-glide in the supercritical region can result in an improvement in performance. CO_2 is being advocated as one of the natural refrigerants to replace CFCs and HCFCs in vapor compression systems owing to its environmentally friendly characteristics [6].

Investigations on modern transcritical CO_2 heat pump cycle were initiated in the early 1990s by Lorentzen et al. [7,8]. In their investigations and subsequent study results of researchers, transcritical CO_2 cycle indicates quite different characteristics with conventional refrigerant cycles. In transcritical CO_2 cycle, there is one optimum discharge pressure where corresponding to one maximum COP. Furthermore, comparing with conventional refrigerant cycles, transcritical CO_2 cycle can supply high temperature up to 90 °C without any operating problems [9–11]. For peculiarities of CO_2 transcritical cycle, the thermodynamic and transport properties of CO_2 in supercritical area are the most significant causes.

Vesovic et al. [12] conducted a critical investigation on the thermodynamic and transport properties of CO_2. Fenghour et al. [13] developed the viscosity data with one equation according more accurate experimental data, and Rieberer's work [14] further covered CO_2 properties in both sub- and super-critical regions. With later more work focusing on the critical region, the thermodynamic and transport properties of CO_2 are further improved. Based on more available and reliable CO_2 properties, heat transfer and pressure drop in both the sub- and super-critical regions can be calculated accurately.

Heat transfer and pressure drop correlations for supercritical CO_2 were proposed by Dang and Hihara [15,16] based on new experimental data, which can be used in calculation of actual heat exchange process of supercritical area. In addition, Dang et al.

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http://dx.doi.org/10.1016/j.enbuild.2013.07.078

Nomenclatures

A	heat transfer or expansion valve opening (m^2)
C_D	flow rate coefficient
Cp	specific heat at constant pressure, ($kJ\,kg^{-1}\,K^{-1}$)
COP	heating coefficient of performance
d	diameter (m)
E	compressor input power (kW)
f	frictional factor
G	mass flux ($kg\,m^{-2}\,s^{-1}$)
h	enthalpy ($kJ\,kg^{-1}$)
l	length (m)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
p	pressure (bar)
Q	overall heat yields (kW)
Re	Reynolds number
r	fouling factor ($m^2\,s\,kW^{-1}$)
U	overall heat transfer coefficient ($kW\,m^{-2}\,K^{-1}$)

Subscript

av	average
Cu	copper
exp	expansion valve
eva	evaporator
H	helical coiled
h	high pressure side
i	inner
ihx	internal heat exchanger
in	inlet
m	log mean
o	outer
out	outlet
r	refrigerant (CO_2)
S	straight
s	suction; straight tube
w	water

Greek symbols

α	heat transfer coefficient ($kW\,m^{-2}\,K^{-1}$)
δ	thickness (m)
ε	error
λ	thermal conductivity ($kW\,m^{-1}\,K^{-1}$)
μ	dynamic viscosity ($N\,s\,m^{-2}$)
ρ	density ($kg\,m^{-3}$)

conducted study on effect of lubricating oil on cooling heat transfer of supercritical CO_2 [17]. They found the heat transfer coefficient is affected not only by lubricating oil concentrations, but also by heat flux, temperatures and pressure of CO_2 and other factors.

Many researchers [18–21] have investigated the optimal discharge pressure in order to improve transcritical CO_2 heat pump water heater system performance, based on an assumption that local heat transfer coefficients were almost constant; they proposed similar functions of optimal discharge pressure with CO_2 gas cooler exit temperatures and evaporator temperatures. However, in a real gas cooler, the assumption is over simplified since heat transfer coefficient could be varied significantly under different operating conditions and heat exchanger geometries. Thus, it could cause large deviation of predicting optimal discharge pressure in a real system by those oversimplified functions. Yamaguchi et al. [22] developed a detailed heat pump system model with an emphasis on considering transcritical CO_2 heat transfer within heat exchangers. Their modeling results showed that, with their

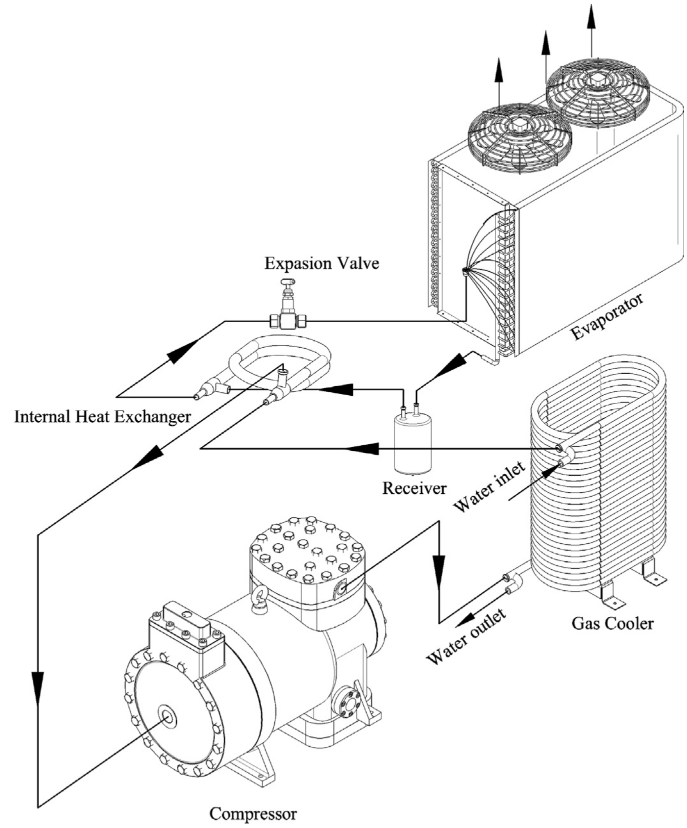

Fig. 1. Schematic diagram of the prototype of air-source transcritical CO_2 heat pump water heater.

simulation model, actual operating process of a transcritical CO_2 heat pump water heater plant could be predicted accurately.

In authors' preceding paper [23], a prototype of air-source transcritical CO_2 heat pump was established, and its performances (heat yields & COP) were investigated at various operating conditions. Based on the experimental results, an empirical correlation of the optimal discharge pressure was proposed as a function of ambient temperatures and water outlet temperatures. An experimentally validated system model was developed to interpret the existence of optimal discharge pressure in a theoretical basis. It was found that the optimal discharge pressure is also affected by system components such as gas cooler, but this aspect was not fully investigated in the previous paper.

Therefore, the objective of this study aims to quantify the effects of gas coolers geometrical parameters on the COP and the optimal discharge pressure in a transcritical CO_2 heat pump system by using an advanced system model. In this work, main effort is placed on considering heat transfer and pressure drop in the gas cooler. Two categories of gas coolers with different geometric parameters are compared in the model and their impact on system performance and optimal discharge pressure are identified.

2. Gas cooler and cycle simulation models

2.1. Air-source transcritical CO_2 heat pump water heater

Fig. 1 shows the classic cycle of air-source transcritical CO_2 heat pump water heater, which consist of a transcritical CO_2 compressor, a gas cooler, an internal heat exchanger, an evaporator and an expansion valve, etc. And in every component, refrigerant CO_2 flows following the sequence of arrows as shown in Fig. 1.