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Experimental and theoretical study on a solar assisted CO_2 heat pump for space heating

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ABSTRACT

In this paper, a solar combi-system which consists of solar collector and a CO_2 heat pump is investigated experimentally and theoretically. Two experiments are primarily conducted to show the performance of this solar combi-system under different operation conditions. A system model is developed and validated in TRNSYS to analyze the influence of main components parameters. Subsequently, a multi-parameter optimization is carried out in GENOPT to obtain a final optimal result. The simulated results show that the optimized system can save 14.2% electricity and improve the solar fraction by 8%. The solar fraction of the optimized system can reach 71.1%. Finally, the optimized system performance is studied with the weather and load characteristics in Shanghai. Compared with the CO_2 HP heating system alone, the solar assisted system can save 1790.8 kWh electricity on the basis of year round operation.

1. Introduction

Climate change has become a worldwide concern in recent years. In heating, ventilation, air conditioning and refrigeration (HVAC&R) industry, carbon dioxide (CO_2) shows an environmentally friendly advantage over the widely-used hydro chlorofluorocarbons (HCFCs) refrigerants. Due to the characteristic of transcritical CO_2 cycle, CO_2 heat pumps (HPs) can meet the demand of heating systems very well, especially in hot water heater applications. Neksa et al. [1] presented an experimental study of a 50 kW CO_2 HP water heater in 1998. The coefficient of performance (COP) reached 3.6 with the hot water supply temperature of 80 °C. Furthermore, Fernandez et al. [2] conducted a performance evaluation on the overall COP during full tank heating tests in three scenarios typical of residential water heating and results showed that the overall COP was 30% higher for heating a full tank of cold water than reheating a warm tank water after standby losses. Yokoyama et al. [3] investigated the performance of a CO_2 water heating system based on numerical simulation. The daily change in a standardized hot water demand, and some features of the temperature distribution in the storage tank and the system performance criteria are investigated. Petersen et al. [4] presented a high-efficiency R744 heat pump water heater of approximately 35 kW heating capacity for commercial applications with effective utilization of the cooling capability for air conditioning or refrigeration, targeted at commercial use in restaurants, hotels, nursing homes, and hospitals, where some cooling load is typically needed year round. Recent studies have proven that HP water heater is one of the most promising applications of the transcritical CO_2 cycle. The cumulative number of the installed units of the commercial case in Japan, well-known as "Eco-Cute", surpassed 3 million by 2011 [5].

Besides the HP water heater, another application of transcritical CO_2 cycle is a combined heat supply system for space heating (SH) and domestic hot water (DHW). Stene [6] presented an experiment of a 6.5 kW CO_2 HP integrated in a combined heat supply system under different operation conditions. The HP unit gave off heat to a floor heating system at supply/return temperatures of 33/28, 35/30 or 40/35 °C, and the set-point temperature for the DHW was 60, 70 or 80 °C. The results showed that at DHW heating demand ratios above approximately 50%, the CO_2 HP system outperformed the HFC heat pump system. Based on the analyses of results, the author recommended the use of such integrated CO_2 heat pump in low-energy and passive houses [7]. Due to the low space heating demand in such buildings, the heat demand for DHW typically constitutes 50–85% of annual heating demand. These kinds of load characteristics are suitable for CO_2 HP.

In addition to the HP water heaters and combined heat supply

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Nomenclature

A	area of solar collector [m^2]
COP	coefficient of performance[-]
C	specific heat of water[kJ/(kg °C)]
η	solar collector efficiency[-]
G	total incident radiation [W/m^2]
P	power of heat pump[kW]
Q	heat gain [kJ]
ρ	density of water[kg/m^3]
SF	solar fraction[-]
T	temperature[°C]
V	volume [m^3]
W	electricity consumption [kJ]
E	annual electricity consumption[kWh]
F	flow rate[m^3/s]

Greek symbols

τ	time

Subscripts

HP	heat pump
FCU	fan coil unit
I	inlet
O	outlet
OT	operation tank
ST	storage tank
SP	supply pump
DP	delivery pump
SCP	SC pump
S	whole system
SC	solar collector

systems, some studies paid attention on solar-assisted CO_2 HPs to further reduce the electricity consumption. Chaichana et al. [8] presented a comparative study of natural working fluids with R-22 for solar-boosted heat pumps. The results showed that CO_2 may be unsuitable for solar-boosted heat pumps because of its low critical temperature and high operational pressures. Kim et al. [9] conducted a simulation study of a solar-assisted CO_2 HP system, in which a CO_2 HP is used as an auxiliary thermal source. The impact of various operation conditions, especially expansion valve (EEV) opening, is analyzed. Kim et al. [10] did a simulation study of hybrid solar-geothermal heat pump system for residential applications. The influence of different operation conditions on the system parameters is conducted. Deng et al. [11] proposed a study on optimization of a solar combi-system with CO_2 HP via TRNSYS [12] simulation model. The system was optimized and analyzed by using both single and multi-parameter optimization. However, only a few studies, particularly experiment studies, have been conducted to analyze the characteristics of a solar combi-system with a CO_2 HP.

The main purposes of this study are: (1) to conduct an experiment study on the performance of a pre-existing solar combi-system with a CO_2 HP; (2) to do an optimization analysis based on the pre-existing system. The influences of main components in the system are studied and the performance of the final optimized system is analyzed.

2. System description

Fig. 1 shows a schematic diagram of the proposed solar combi-system in the residential building and Fig. 2 shows the main components. The 40 m^2 solar collector (SC) array (vacuum tube solar collector with micro CPC reflector at the back) is installed on the roof with an installation angle of 30°. The captured solar energy is delivered to the 500 L storage tank by the SC pump. The delivery pump is used to bring the hot water in the storage tank into the 300 L operation tank. The DHW (set point: 40 °C) is heated by an immersed heat exchanger in the operation tank with a mixing valve to adjust the temperature. A 6 kW CO_2 HP is employed as an auxiliary heater, which is connected with the operation tank. The CO_2 HP consists of a fin-tube evaporator with fan, a smooth tube in tube gas cooler, a fixed speed swing compressor and an electronic expansion valve. The discharge pressure of the compressor is controlled by adjusting the effective flow area of the expansion valve. Two switching valves are installed to switch the heat source between storage tank and CO_2 HP. 5 fan coil units (FCUs) act as the indoor terminal units for SH, with the hot water delivered by supply pump from operation tank. The main parameters of the system components are listed in Table 1. This system separates the operation tank from the storage tank. The storage tank acts as the main storage of the captured solar energy and delivers energy to the operation tank only when the temperature level is achieved. In this way, the storage volume is separated and the operation tank volume can be much smaller. The CO_2 HP will consume less electricity to maintain the temperature in the small volume operation tank when the solar radiation is poor. The operation tank is also a buffer of heat for the whole system since the temperature of the solar system changes obviously with the solar radiation. It can weaken the temperature fluctuation of the heat source.

The temperatures of the system are measured by a group of PT100 sensors (A class, error: 0.1 °C). The water flow rate is measured by an integrating flow meter with an accuracy of ±5% (of full scale 10 m^3/h) in the range 0–10 m^3/h. The ambient condition is monitored by a micro weather station (Davis 6152c) and Kipp & Zone CM22 pyranometer, and the accuracies of the radiation and temperature are ±5% (of reading) and ±0.5 °C, respectively. The electricity consumption and transient power are measured by one single-phase meter (QINGZHI ZW3415) and one three-phase meter (QINGZHI ZW3432). The accuracies of measurements are ±1% (of reading). All the data is captured and handled by a Graphtec GL800 acquision system.

The control strategy is as follows: (1) CO_2 heat pump heating mode: as long as the water temperature at the middle position of operation tank is lower than 45 °C, the CO_2 HP starts to operate until the temperature reaches 50 °C; (2) Solar heating mode: the switching valves switch to storage tank and the delivery pump operates when the temperature at the top of storage tank is higher than the temperature at the bottom of the operation tank and the middle position of operation tank is higher than 45 °C; (3)Room temperature for the heat supply is set at 18 °C for starting and 22 °C for stopping; (4) The SC loop is controlled by an on/off differential controller with the set value of 8/4 °C.

Fig. 3 and Fig. 4 are the floor plan and the inside view of the test apartment. The total area of the building is 90 m^2, consisting of a 19.2 m^2 bedroom A, a 16 m^2 bedroom B, a 46.8 m^2 living room with open kitchen, a 5 m^2 bathroom and a 3 m^2 storage room. The north, south and east building envelops are exterior walls and the west building envelop is adjacent to another apartment. The heat transfer coefficients of the building envelop are listed in Table 2.