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Experimental analysis of an air-source transcritical CO_2 heat pump water heater using the hot gas bypass defrosting method

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HIGHLIGHTS

- Hot gas bypass defrosting method for transcritical CO_2 heat pumps was studied.
- An experimental setup was established in an environmental laboratory.
- The temperature, pressure and energy consumptions in the system were analysed.
- The efficiency of hot gas bypass defrosting method ranged from 30 to 40%.
- The effect of ambient conditions on defrosting efficiency was investigated.

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ABSTRACT

When an air-source CO_2 heat pump water heater operates at low ambient temperatures in cold regions in winter, frost can form on the coil surface of its outdoor evaporator. The frost substantially affects the operating performance and energy efficiency of CO_2 heat pump water heaters and hence periodic defrosting is essential. In this paper, defrosting characteristics of an air-source CO_2 heat pump water heater using the hot gas bypass defrosting method is experimentally studied at different ambient conditions. An experimental setup is developed for this purpose and experimental procedures are detailed. Thereafter, the pressure and temperature in the outdoor evaporator, at the compressor and gas cooler outlets are evaluated during the defrosting period. An energy analysis is then performed of different system components during the defrosting process. Results indicate that 35% of the supplied energy is used for melting the frost, and 7.6% is used to heat the evaporator tubes and fins. About 57.4% of the supplied energy is consumed to increase the internal energy of the gas cooler. The typical efficiency of the hot gas bypass defrosting method applied in the CO_2 heat pump water heater ranges from 30 to 40%. It increases with increasing dry bulb temperature, and decreasing relative humidity.

1. Introduction

Air-source heat pumps (ASHP) have attracted worldwide attention in recent decades due to their significant energy-saving potential and environmental footprint. However, the ASHP performance is substantially affected by freezing outdoor temperatures in most moderate climates in winter. When the ASHP operates at low ambient temperatures in winter, frost forms on the coil surface of the outdoor evaporator. Over time, frost accumulates on the coil surface and reduces the air flow passage through the coil. It acts as a thermal insulator which reduces the heat transfer rate and coil efficiency [1,2], leading to performance degradation or even shutdown of ASHP systems. Periodic defrosting therefore becomes essential. It helps ASHP systems return to the rated performance, although the defrosting itself consumes energy and causes uncomfortable fluctuations of indoor air temperature in a heated place [3,4].

Over the years, some researchers studied frosting mechanisms and processes [5–9] while others researched different defrosting methods and the operating characteristics of ASHP systems with different defrosting methods [10–26]. Sherif et al. [10] developed a defrosting model for an ASHP unit with a cylindrical coil cooler using the electric defrosting method and studied the system performance. Alebrahim and Sherif [11] further evaluated defrosting duration and temperature distribution in the frost layer on a finned-tube evaporator coil when

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Nomenclature

C_P	specific heat capacity, kJ (kg K)$^{-1}$
E	energy consumption, kJ
h	specific enthalpy, kJ kg^{-1}
H	power consumption, kW
L_f	latent heat of frost melting, 334 kJ kg^{-1}
m	mass, kg
$\dot{m}$	mass flow rate, kg s^{-1}
P	pressure, MPa
q	energy consumption rate, kW
Q	heat supply, kJ
t	time, s
T	temperature, °C
V	swept volume, m^3 h^{-1}
W	compressor energy input, kJ
η_{el}	electrical efficiency
η_v	volumetric efficiency
ρ_s	suction gas density, kg m^{-3}
ΔT	temperature difference, °C
$\Delta\tau$	measuring time interval, s

Subscripts

Al	aluminum
comp	compressor
CO_2	refrigerant CO_2
Cu	copper
f	frost
gc	gas cooler
in	inlet
IHX	internal heat exchanger
m	metal
out	outlet

using the electric defrosting method. Mei et al. [12] installed an electric heater in the accumulator of the outdoor unit to heat the refrigerant directly. Results showed that the refrigerant temperature at the compressor inlet increased, and the evaporation temperature also increased to delay the frosting to a large degree. Kwak et al. [13] improved this defrosting method by installing an electric heater at the entrance to the outdoor unit of a small capacity air-to-air heat pump. As reported, this method can maintain the stable heating capacity during normal operation, and improve the heating capacity and COP under frosting conditions.

Stoecker et al. [14] examined conservation of defrosting energy consumption in an industrial refrigeration system using the hot gas defrosting method. It was found that defrosting energy consumption would be conserved if melted frost was drained rapidly. In the same year, Abdel-Wahed et al. [15] investigated the hot water defrosting method applied to a horizontal flat plate cooling surface. They reported that the decrease in the thickness of the frost layer was approximately linear with time. Cole [16] studied heat and mass transfer behavior during the hot gas defrosting of a large commercial freezer, and proposed a theoretical model to estimate the resultant refrigeration loads due to defrosting. Soon after these studies, Krakow et al. [17] established an analytical model to study the dynamics of an ASHP using the hot gas defrosting method. Liu et al. [18] further proposed a distributed model and performed a dynamic simulation of an ASHP using the hot gas defrosting method. Furthermore, Cho et al. [19] experimentally studied the performance of a showcase refrigeration system with multi-evaporators during on-off cycling and hot gas bypass defrosting. It was found that the system with the hot gas bypass defrosting method exhibited greater refrigeration capacity and less temperature fluctuation than the on–off cycling system under frosting/defrosting conditions. Byun et al. [20] applied the hot gas bypass method to retard the formation and propagation of frost in an ASHP. The feasibility of the hot gas bypass defrosting method, and the method's performance, were compared with no defrosting equipment. Results proved that the hot gas bypass defrosting method was very useful for retarding the formation and growth of frost on the outdoor unit. Liang et al. [21] further explained the mechanism and process of the hot gas bypass defrosting method. To guarantee the reliability, a self-organizing control algorithm with self-learning functionality was introduced based on the cardinal fuzzy control algorithm in the study.

More recently, many researchers have studied the reverse cycle defrosting method with different modifications. Ding et al. [22] experimentally investigated the reverse cycle defrosting method on an ASHP with the thermal expansion valve acting as a throttle regulator. Chen and Guo [23] experimentally studied defrosting characteristics of an 11.2 kW split-type ASHP under defrosting conditions. Experimental results showed that the power consumption, defrosting time and indoor endotherm decreased linearly with increasing outdoor air relative humidity (at constant air temperature and velocity). Qu et al. [4] studied the indoor thermal comfort during defrosting with a novel reverse-cycle defrosting method for ASHPs. Room thermal comfort was improved, defrosting period was reduced, and indoor supplied air temperature increased. Qu et al. [24] further experimentally investigated reverse-cycle defrosting performance for a 6.5 kW ASHP using an electronic expansion valve. A different control strategy for the electronic expansion valve was studied and compared. Furthermore, Dong et al. [25] experimentally studied defrosting heat supply and energy consumption during a reverse cycle defrosting operation for an ASHP. The experimental evaluation showed that heat supply from indoor air contributed 71.8% of the total heat supplied for defrosting, and 59.4% of the supplied energy was used for melting the frost. The maximum defrosting efficiency could be up to 60.1%.

From the above review, some experimental and theoretical investigations of ASHP system defrosting methods and their performance are available. However, due to the high operating pressure and unique heat transfer characteristics of transcritical CO_2 heat pumps [26–28], defrosting methods such as reverse cycle are not practical for the transcritical CO_2 ASHP water heater. Minetto [29] investigated a hot gas bypass defrosting procedure for a CO_2 heat pump for domestic hot water and proved that it was effective for systems running in winter at ambient temperature around 0 °C. This method is currently widely applied in commercial CO_2 heat pumps due to structure simplicity and easy operation, but there is still a lack of research on operating characteristics of the transcritical CO_2 heat pump water heater using the hot gas bypass defrosting method. In this paper, the operating characteristics of the transcritical CO_2 heat pump water heater using the hot gas bypass method during the defrosting period was studied under different ambient conditions. An experimental setup was developed for this purpose and the experimental procedure is described in detail. The energy supply and consumption for different system components were analyzed and discussed.