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Experimental analysis on a novel frost-free air-source heat pump water heater system

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HIGHLIGHTS

- A novel frost-free ASHPWH system coupled an EHECSD with an ESD is proposed.
- Experiments are carried out to investigate the characteristics of the system.
- The COP increased 7.25% and 46.3% in comparison with HGBD and ERH.
- Test results confirm the expected potential to control the frost-free process.

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ABSTRACT

Air-source heat pumps (ASHPs) are being widely used in residential and commercial buildings and have a huge potential market and development foreground for its energy-savings, high efficiency and environmental friendliness. However, at low temperatures, frost can accumulate on the surface of the finned outdoor coil which will decrease the heating capacity and coefficient of performance (COP). This paper proposes a novel frost-free air-source heat pump water heater (ASHPWH) system, which is coupled to an extra heat exchanger coated by a solid desiccant (EHECSD) with an energy storage device (ESD). To test the system performance, experiments are carried out and the results show that the relative humidity (RH) of the air can be reduced to 52% after dehumidification and the outdoor heat exchanger can be kept frost-free for 34 min at a temperature of 0 °C and relative humidity (RH) of 80%. In addition, the average COP of the system is 2.81 in a single period, which is an increase of 7.25% and 46.3% in comparison with hot-gas bypass defrosting (HGBD) and electric resistance heating (ERH) respectively. With this new technology, it has been proven that frost-free ASHPWH be achieved.

1. Introduction

The air-source heat pump water heater (ASHPWH) system, a water heating device which can provide the same hot water with two or three times the efficiency than traditional gas or electric water heaters [1,2], has recently been drawing extensive attention for its high efficiency, energy-savings and environmental friendliness recently [3,4]. However, during winter operation, the outdoor heat exchanger will be subject to frosting which increases the resistance of the outdoor heat exchanger, leading to a reduction in the performance as well as the reduction in the evaporation temperature of the refrigerant. This results in the decrease of the mass flow rate, leading to the reduction of the heating capacity of the heat pump and the decrease in the COP. Therefore, the problem of frosting in an outdoor heat exchanger is a big obstacle in both promoting and developing the air-source heat pump (ASHP) system in a cold region.

In order to optimize the performance of the ASHP system during winter operation, many studies have been undertaken in an attempt to overcome this weakness of the ASHP system. Examples of these studies include electric resistance heating (ERH) [5,6,7], reverse-cycle defrosting (RCD) [8,9], hot-gas bypass defrosting (HGBD) [10,11] and so on.

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Nomenclature

W	power (kw)
Q	heating capacity (kw)
COP	coefficient of performance (dimensionless)
d	the humidity of air (g H_2O/kg)
c	the specific heat capacity of water (J/kg °C)
t	temperature (°C)
M	the quality of water(kg)
m	the mass of water vapor (g)
RH	relative humidity (%)
Greek letter	
τ	time (min)
η	efficiency (%)
Subscripts	
wv	water vapor
de	dehumidification
re	regeneration
rm	regeneration mode
hm	heating mode
OA	outdoor air
MA	moisture air
DA	dry air

Electric resistance heaters are installed in the indoor coil, which are usually used to supply heat during defrosting. Niederer [12] pointed out that only 15%–25% of the electrical heat was used for defrosting. According to Kazachki [13], refrigerating energy consumption of cold storage with electric heating defrosting method increased by 25%. Kwak [14] used an electric heater in front of an outdoor heat pump instead of an indoor unit to enhance the heating capacity under the frosting condition. Relative to the normal system, the heating capacity and COP were increased by 9.1% and 71.1% respectively. However, the efficiency of electric heating for defrosting is too low which results in high energy consumption.

RCD is one of the more common methods of defrosting for ASHP systems. Using the four-way valve, the normal heating operation and the refrigerant flow is reversed. The indoor heat exchanger becomes the evaporator and the outdoor heat exchanger becomes the condenser. During the defrosting process, hot gas is pumped into the outdoor heat exchanger to melt the frost. Dong [15] studied the sources of heat supplies and the end-uses of the heat supplied during a reverse cycle defrost operation. Qu [16] investigated the performance of RCD through two control strategies: the electronic expansion valve (EEV) being fully open and the EEV being regulated by a degree of refrigerant superheat controller. The results showed that when the EEV was regulated by a degree of refrigerant superheat controller during defrosting, a higher defrosting efficiency was obtained. However, this method is only provides intermittent heating during defrosting and absorbs heat from the indoor unit, making the user feel uncomfortable. To solve this problem, Hu [17] proposed a novel PCM based RCD method for ASHP which takes PCM as a low temperature resource during defrosting to reduce the impact of deficient heating capacity for comfort.

For the HGBD method, a portion of the high temperature refrigerant is injected from the outlet of the compressor into the inlet of the outer heat exchanger to retard frost formation. The average COP and heating capacity were improved by 8.5% and 5.7% respectively, in comparison with a conventional heat pump [18].Cho [19] investigated the performance of the showcase refrigeration system with three evaporators with on–off cycling and hot gas bypass defrosting. In addition, Jang [20] utilized a hot-gas bypass valve to remove the frost from the outdoor heat exchanger, but it was differentiated from the common high pressure hot-gas bypass methods by its use of low pressure. However, the HGBD method reduced the heating capacity and produced a longer defrosting time of 272 s, 2.89 times than the RCD time of 94 s [21].

Some new methods of defrosting and delaying frost formation were proposed. Outdoor air can be dehumidified by a solid adsorbent or liquid desiccant before entering the evaporator to prevent ASHP system from frosting [22,23]. Zhang [24] added an extra heat exchanger coated with a solid desiccant (EHECSD) in a traditional ASHP system to prevent the system from frosting, using regeneration air to regenerate the desiccant. However, the moisture from the desiccant-coated heat exchanger was still causing frosting in evaporator in regeneration mode when the temperature of the refrigerant fell below 0 °C. For this problem, this paper proposes a novel frost-free ASHPWH system, coupled with an EHECSD and an energy storage device (ESD). This system not only prevents frosting because the air is dehumidified by a solid adsorbent before entering an outdoor heat exchanger, but also avoids frost formation and continuous heating in regeneration mode. In this study, the working principle of this kind of heat pump water heater is introduced and experiments are carried out to investigate the system performance. Graphical results including changes of air temperature and RH with time during heating and regeneration process as well as time-wise variations of stored and released thermal energy of PCM, COP, system pressure, suction temperature and discharge temperature are presented and discussed.

2. Experimental system and procedure

2.1. System description

A schematic diagram of the novel frost-free ASHPWH system is illustrated in Fig. 1, with the process shown on a p-h diagram of the refrigerant in Fig. 2. It consisted mainly of a rotary compressor (1), overload protection devices (2, 14), a Four-way valve (3), a condenser which wraps around outer of the water tank (4), solenoid valves (5, 13, 15, 18), an ESD (6), Filter driers (7, 10, 16), electronic expansion valves (EEVs) (8, 11, 17), an EHECSD (9) and an outdoor heat exchanger (12). This system contains two kinds of operation mode, namely heating mode and regeneration mode.

During heating mode, the solenoid valves (5, 13) are opened while the solenoid valves (15, 18) and EEV (17) are closed. The discharged refrigerant from the compressor unit (1) flows into the condenser, which wraps around the outer wall of the water tank (4), and rejects the heat to the cold water in the tank. The refrigerant proceeds to flow through the ESD (6) where the condensation waste heat is absorbed. The refrigerant, which is one-stage throttled by the EEV(8), enters the EHECSD (9), absorbing part of the latent heat of water vapor before entering the outdoor heat exchanger (12), in which the refrigerant absorbs heat from the air after two-stage throttled by the EEV (11). Finally, the superheat refrigerant re-enters the compressor unit to complete the heat cycle. Outdoor air (OA) flows through the EHECSD (9) where water vapor from the air is absorbed and sensible heat is released. Because the dew point temperature of dry air (DA), dehumidified by the solid desiccant, is lower than the evaporation temperature, the frost-free ASHPWH can be realized. Finally, the air is removed from the outdoor heat exchanger (12) at state EA. When the moisture of the solid desiccant increases, the vapor partial pressure