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Performance evaluation of a novel frost-free air-source heat pump integrated with phase change materials (PCMs) and dehumidification

ZhihuaWang[a,b], FenghaoWang[a,b,*], Zhenjun Ma[c], Chun Li[a,b], Yibo Xu[a,b]

[a]*School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi, 710049, China*
[b]*Center for Building Energy Conservation, Xi'an Jiaotong University, Xi'an, Shaanxi, 710049, China*
[c]*Sustainable Buildings Research Centre (SBRC), University of Wollongong, Wollongong 2522, NSW,Australia*

Abstract

Air-source heat pump (ASHP) has been widely used in domestic and commercial buildings because of its energy savings, high efficiency and environmental friendliness. However, the heating capacity of an ASHP system is greatly influenced by the frost accumulation on the surface of the outdoor exchanger. To solve this problem, a novel frost-free ASHP system, integrating with Phase Change Materials (PCMs) and dehumidification, has been developed. In this paper, the schematic design of this system is first presented. The effect of the match relationship between the desiccant materials and PCM thermal energy storage on the performance of the novel system is then studied using a dynamic mathematical model. The simulation results showed that the dehumidification efficiency was increased from 31.8% to 34.7% with the increase of the solid desiccant mass from 1.9kg to 3.5 kg when the volume of the PCM was 1000 ml. The system COP was 2.87 when the desiccant was 2.2 kg and the volume of PCM was 1100 ml at a relative humidity of 80% and ambient temperature of 0°C.In addition, the water temperature was heated to55°C in one cycle which decreased the irreversible loss. Lastly, a correlation of the system COP with the amount of the solid desiccant and the PCM was obtained through a multivariate linear regression. The results obtained can facilitate optimal design and dynamic behavior investigation of this system.

Keywords: Air-source heat pump; Solid dehumidification; Phase change heat storage; Frost-free; System optimization

* Corresponding author. Tel:+86-13227006940; Fax:+86-29-83395100..
*E-mail address:*fhwang@mail.xjtu.edu.cn

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1. Introduction

Energy consumption of buildings has come into a focus around the world. Air-source heat pumps(ASHPs) have been widely used for space heating in both domestic and commercial buildings due to their high energy efficiency and environmental friendliness. However, the major problem of the ASHP system is that the heating capacity and coefficient of performance (COP) decrease at the extreme cold days because of the frost accumulation on the surface of the outdoor exchanger. It is, therefore, important to seek alternative methods to overcome the performance degradation.

To date, the common methods used include the reverse-cycle defrosting (RCD) [1][2],electric heat defrosting(EHD) [3][4], and hot-gas bypass defrosting (HGBD) [5][6].

The efficiency of the traditional EHD method was low, and can cause an unfavourable storage temperature fluctuation. To solve this drawback, a novel defrosting method with air bypass circulation and electric heaters was proposed by Yin et al.[7]. The results from the experiments showed that the defrosting time and defrost energy consumption were reduced by 62.1% and 61.0% respectively, compared with the traditional EHD method. To quantify the performance drop of the ASHP system under the frosting condition, a field test was conducted by Wang et al.[8]. The results indicated that more than 60% frost area of the evaporator was mal-defrosted after five-day operation, and the COP was only 2.3 during the frosting period. To evaluate the effect of different throttle openings on the defrosting performance, a transient mathematical model was developed by Steiner and Rieberer[9]. Huang et al.[10] compared the defrosting performance between the RCD method and the HGBD method. The results indicated that the RCD defrosting time was shorter than HGBD, but the thermal comfortable of using the HGBD method was better than that using the RCD method. Hu et al.[11] performed an energy analysis on the different components during the defrosting period using the HGBD method. The results showed that the energy consumed for melting the frost, heating the evaporator tubes and fins, and increasing the internal energy of the gas cooler were 35%, 7.6% and 57.4%, respectively.

The main focus of these methods is to decrease the defrost effect after the frost accumulated on the surface of its outdoor coil. Recently, some new technologies such as liquid desiccant or solid adsorbent have been developed to dehumidify the outdoor air before entering into the evaporator to prevent the ASHP system from frosting[12][13].

Zhang and Saikawa[14]proposed a frost-free air-source heat pump water heater (ASHPWH) system with integrated a solid desiccant. A numerical simulation was carried out and the results showed that the system COP was 5-30% higher than that of the HGBD method at the temperature of -7-5.5°C and the relative humidity (RH) of 60-80%. Wang et al.[15] discussed a method to prevent the ASHP from frosting by using the solid adsorbent of zeolite. The simulation results showed that the frost problem of the outdoor heat exchanger was resolved and the air pressure loss was low when it passed through the adsorbent bed. Wang et al. [16][17][18][19]proposed a novel frost-free ASHPWH system. The experimental and simulation results showed that the system performance was better than the conventional ASHP system at the low temperature conditions. However, the regeneration efficiency of the extra heat exchanger coated by a solid desiccant (EHECSD) was only 66 % at the temperature of -3.0 °C and the RH of 85%.

For the novel frost-free ASHPWH system, the unreasonable matching between energy storage and dehumidification devices may not only result in a low regeneration efficiency, but also affect the COP of the whole system. Therefore, the primary objective of this study is to investigate the system performance under the different scenarios with different amounts of the PCM ($CaCl_2 \cdot 6H_2O$) and solid desiccant (silica gel).The description of the novel ASHPWH system is first reported. The system performance curves and quantitative analysis are then obtained from the numerical simulation. Finally, a correlation of the system COP with the amounts of the solid desiccant and the PCM used is developed to facilitate the evaluation of the system performance.

2. System description

Figure 1 shows the schematic diagram of the novel frost-free ASHPWH system. It mainly consists of a rotary compressor, a water tank (condenser), four solenoid valves, an energy storage device (ESD), three electronic expansion valves (EEVs), an EHECSD and an outdoor exchanger. The system can operate under the heating mode and the regeneration mode.