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Performance and thermal charging/discharging features of a phase change material assisted heat pump system in heating mode

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HIGHLIGHTS

- We introduced an integrated heat pump with a triple-sleeve energy exchanger.
- Experiments were carried out to investigate the performance and thermal behavior.
- Dynamic balance was observed between water and refrigerant with a PCM interlayer.
- The system with a PCM interlayer had a high COP value.

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ABSTRACT

At low ambient temperature, air-source heat pump suffers from decrease in both heating capacity and coefficient of performance (COP), and increase in compressor's pressure ratio. A parallel triple-sleeve energy storage exchanger with phase change material (PCM) for storing thermal heat was designed to ensure the reliable operation of a heat pump under various weather conditions and enhance the system performance at low ambient temperature. The innovative device also includes a solar thermal collector loop for utilizing free solar energy. Thermal heat can be transferred into and stored by the PCM using water as the heat transfer medium. Controlled experiments were carried out to investigate the performance and the simultaneous thermal charging and discharging behavior of this enhanced heat pump system. Transient operating characteristics, including the temperatures, pressures and heat transfer rate, were analyzed. The COP value in an operating mode with a constant heat transfer fluid water temperature and flow rate increased until the system entered into the stable operating stage. The final COP can reach up to 3.9 when the three heat transfer mediums (water/PCM/refrigerant) achieved the steady-state. The experimental results show an interesting phenomenon that the heat transfer process between water and refrigerant with a PCM interlayer was a dynamic balance. The PCM temperature and the difference of the water temperature at the inlet and outlet of the evaporator regularly fluctuated around some balance points. In this study, the measured PCM temperatures in the dynamic steady-state were 12.8 and 14.2 °C. The difference of the water temperature at the inlet and outlet of the evaporator balanced around 2.8 °C. The findings in the research implied more study is needed to explore the PCM charging/discharging mechanisms and improve the operation of the PCM assisted thermal system.

1. Introduction

With the rapid development of economy and the increasing energy demand, energy conservation draws more and more public attention. Compared to those traditional gas or electric water heater, air-source heat pump (ASHP) can serve the same purpose with two- to three-time higher efficiency [1,2]. Therefore, ASHP is gradually used in residential and commercial buildings for heating applications, providing significant economic benefits. In southern China, especially in the Yangtze River delta, extreme low surrounding temperature can reach −10 °C in winter. Supposing the set point of outlet water temperature is 55 °C, the working temperature range of ASHP would reach to 65 °C. At low ambient temperatures, the heating capacity of ASHP drops rapidly. The high pressure ratio on the refrigerant side is likely to cause high/low

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Nomenclature

ASHP	air-source heat pump
COP	coefficient of performance
HTF	heat transfer fluid
PCM	phase change material
TRESE	triple-sleeve energy storage exchanger

pressure protection and trip off the system. In addition, the low operating temperature of the outside air heat exchanger can cause frosting on the surface and lead to decrease in the performance. Therefore, some assisted devices and technologies such as auxiliary heaters have been researched and applied to the ASHP for improving the performance under the low temperatures [3–5].

In recent years, thermal energy storage is playing an increasing important role in energy conservation applications. Since PCM has high heat storage density and a narrow range of operating temperature during a phase change, it is widely used in thermal systems for storing thermal energy [6]. Many experiments have been conducted to study the thermal performance of PCM storage system [7–9]. According to these publications, paraffin waxes can be found in many applications and is the most widely used one. However, its inherent disadvantage of low heat transfer rate during the charging/discharging process limited the improvement of thermal performance. For various circumstances, composite materials consisting of a PCM and at least one other material might be applied instead. The other material serves to improve one or more the PCM properties (e.g. melting temperature, specific heat, etc.). For example, the use of graphite particles and fibers PCM has been proposed about ten years ago to enhance the thermal conductivity [10]. Since then, numerous publications have experimentally proved this concept with different composite PCM. A new supported phase change material made of paraffin impregnated by capillary forces in a compressed expanded natural graphite matrix was presented by Py [11]. Composite PCM/CENG thermal conductivities were found to be equivalent to those of the sole graphite matrix from 4 to 70 W/(m K), much higher than 0.24 W/(m K) of the pure paraffin. Zhang and Fang [12] experimentally studied the thermal performance of a paraffin/expanded graphite composite phase change material. The heat transfer rate of the paraffin/expanded graphite composite was observed higher than that of the paraffin due to the high thermal conductivity of the combined expanded graphite. The prepared paraffin/expanded graphite composite PCM had a large thermal storage capacity and did not experience liquid leakage during its solid–liquid phase change. Medrano et al. [13] experimentally investigated the heat transfer process during melting (charge) and solidification (discharge) of five small scale heat exchangers working as latent heat thermal storage systems. Results showed that the double pipe heat exchanger with the PCM embedded in a graphite matrix is the one with higher values, ranging from 700 to 800 W/(m^2 K). It could be concluded that increase of the heat transfer coefficient was more important than increase of heat transfer area. Sole et al. [14] conducted several charging tests to investigate the performance of a hot water tank with about 90 vol.% of sodium acetate trihydrate and 10 vol.% graphite as PCM. Energetic and exegetic analyses were conducted for the charging of the water tank, with and without PCM, to clarify the contribution of PCM. Since the 1950s, many researchers have studied various solar assisted heat pumps [15–18]. Han et al. [19] built up a mathematical model for a solar assisted ground-source heat pump with an energy storage device, and studied the effect of the heat storage device on the performance of the solar assisted ground-source heat pump. Ozgener and Hepbasli set up a greenhouse heating system based on a solar assisted ground-source heat pump and studied its operating characteristics [20]. The effect of pipe work arrangement on the performance of the solar assisted ground-source heat pump heating system was also investigated. A direct-expansion solar assisted heat pump system, which could offer space heating in winter and air conditioning in summer and supply hot water throughout a year, was also studied [21]. Xu et al. [22] proposed a new type of solar-air source heat pump water heater, whose flat-plate heat collector/evaporator with spiral-finned tubes could extract energy from both solar irradiation and ambient air for hot water heating. The operating performances of the system were simulated. Li et al. [23] built up a direct-expansion solar assisted heat pump water heater, studied experimentally the system performance and finally proposed some measures for system optimization.

It is a new idea to combine an ASHP with thermal storage technology and solar collecting system. The integrated system utilizes the PCM for heat storage and improves the performance of the heat pump at low ambient temperatures. In addition, a solar energy system is included to collect solar energy for thermal storage and directly space heating. Based on the idea, the authors designed a novel integrated heat pump system with triple-sleeve energy storage exchanger (TRESE) [24]. This novel compact heat pump system cannot only make use of off-peak electricity to provide low-cost space heating/cooling and hot water, but also ensure the reliable operation under various weather conditions. In our previous work, experiments on thermal performance of triple-sleeve energy storage exchanger have been carried out to verify the feasibility of the integrated heat pump system. In this paper, we presented and discussed the transient operating characteristics, including the temperatures, pressures and heat transfer rate, of the system.

In the following sections, we first briefly introduced the structure of the integrated heat pump system. Then we described the settings and the testing procedure of the experiments. The results of the trended data and the derived variables are then presented to interpret the performance of the system. The paper finally concluded with a brief discussion on the observed phenomenon.

2. Integrated heat pump system (with triple-sleeve energy storage exchanger)

2.1. The structure of TRESE

A new integrated heat pump system with TRESE has been proposed. Its key component TRESE had a special structure. Fig. 1 shows the detailed structure of an energy storage cell used in the TRESE. It consisted of three passes of concentric copper tubes. PCM was embedded inside the space between the outer tube and the inner tube. Refrigerant flowed inside the inner tube and heat

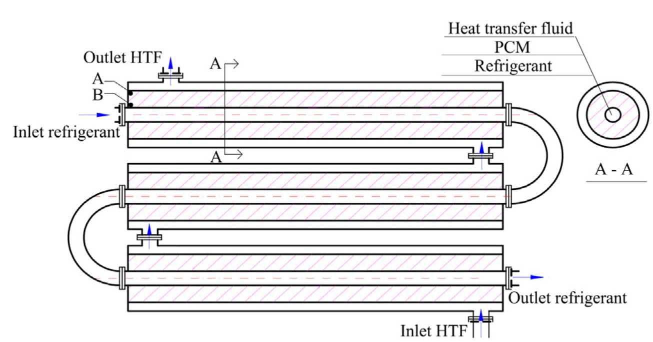

Fig. 1. Structure of an energy storage cell used in the TRESE [24].