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Experimental research of an air-source heat pump water heater using water-PCM for heat storage

Deqiu Zou[a,*], Xianfeng Ma[a], Xiaoshi Liu[a], Pengjun Zheng[a], Baiming Cai[b], Jianfeng Huang[b], Jiangrong Guo[a], Mo Liu[a]

[a] *Faculty of Maritime and Transportation, Ningbo University, Ningbo 315211, Zhejiang, China*
[b] *Guangdong Cheery Air-conditioner Manufacturing Co., Ltd., Foshan 528313, Guangdong, China*

HIGHLIGHTS

- An air-source HPWH using water-PCM for heat storage was designed.
- Heat storage capacity of the HPWH was increased.
- The *COP* of the HPWH was improved.
- The operation time of the HPWH was shortened.

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ABSTRACT

With the improvement of energy saving and environmental protection requirements, the market share of heat pump water heater (HPWH) is gradually increasing. In order to increase the heat storage capacity and improve the performance of the system, an air-source HPWH with storage tank using water and finned phase change material (PCM) for heat storage is designed and experimentally studied. Performances of the HPWH for the first operation when the PCM is in heat storage and the second operation when the PCM is in heat discharge were compared and discussed. Furthermore, performances between the HPWH using water-PCM for heat storage and conventional HPWH with standard water tank were compared. The results show that the volume of the storage tank has little increase, but the heat storage is increased by 14%. Besides, when water is heated from 15 to 55 °C, the first operation time for the HPWH is almost the same as the normal operation time of the conventional HPWH, but the second operation time is shortened by13%.The results also show that the HPWH has good water temperature uniformity and its *COP* was improved.

1. Introduction

Water heating is a major energy consumer all around the world [1]. It is the fourth largest energy user in the commercial buildings sector, after heating, air conditioning, and lighting [2]. Most water heaters are equipped with conventional heaters generating heat by consuming fossil fuels or electricity. Those water heaters are not desirable in view of environment protection and energy utilization efficiency. So, developing clean and energy-saving hot water devices becomes a focus all over the world.

Heat pumps water heater (HPWH), based on the principle of inverse Rankine cycle, is recognized as a promising prospect technology due to its energy-saving, low-cost and safety. Performances of HPWH are influenced by refrigerants, system structure, ambient temperature, water temperature, etc. [3,4]. So, many studies have focused on the system optimization [5–11], defrosting [12–14] and performance improvement through the improvements in compressors, evaporators, condensers, expansion valves and working fluid [15–24]. With the increasing demand for hot water, higher requirements for coefficient of performance (*COP*) and heat storage capacity have been put forward. As the *COP* is the key technical indexes of HPWH, many studies have been conducted to obtain high *COP* by optimizing the HPWH system. For example, Ibrahim et al. [5] have developed a dynamic model of HPWH to compare the performance of three similar systems that differ only with the condenser geometry. The results show that using mini-condenser geometries increase the *COP*. Bin Hu et al. [13] presented an ESC based self-optimizing control scheme for maximizing the *COP* of an air-source CO_2 heat pump water heater system while satisfying the hot-

* Corresponding author.
E-mail address: zoudeqiu@nbu.edu.cn (D. Zou).

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water outlet temperature setpoint. Ghoubali et al. [19] presented a *COP* optimisation study depending on the refrigerant charge for a R290 heat pump water heater with three different types of condensers. All the three condensers were tested and the best performance is obtained by the roll-bond HPWH.

One of the most widely used is air-source HPWH which absorbs heat from air at lower temperature, and transfers it into a water tank at higher temperature. As a core component of air-source HPWH, a storage tank is commonly used to store the required hot water at the preferred temperature to the end uses. Conventional water heaters using water as heat storage media have advantages of simple structure, high heat transfer rate and low cost, but its heat storage density is low due to sensible heat storage. To solve this issue, HPWH using phase change material (PCM) as storage medium has attracted more and more attention in recent years [25–33]. PCM is a latent heat energy storage media, which can absorb or discharge high amount of latent heat with small temperature variations. It has a higher energy storage density compared to water, so a smaller storage volume is needed to store the same amount of heat. More importantly, PCM can charge and discharge heat at a constant temperature which would make HPWH run smoothly. Long et al. [34] have developed an air-source HPWH with Paraffin (56#) for thermal storage to take advantage of off-peak electrical energy. In their studies, the water tank was replaced by PCM unit completely. The latent heat storage capacity, the melting point temperature and the density are 254.9 J/g, 56.03 °C and 0.770 g/ml, respectively. Agyenim et al. [35] have conducted an experimental system with a longitudinally finned RT58 PCM in a horizontal cylinder to evaluate its heat transfer performance. The results have demonstrated that with an improvement in heat transfer techniques to charging and discharging heat effectively from the store, store size can be reduced by 30%. Wu et al. [36] have designed a cascade air-source HPWH with PCM for thermal storage application to ensure the reliable operation under various weather conditions and enhance the system performance at low ambient temperature. Experimental results showed that the heating coefficient of performance (*COP*) values in single stage mode ranged from 1.5 to 3.05, while in cascade mode, the heating *COP* values ranged from 1.74 to 2.55.

Based on the above analysis, researchers are constantly trying to use various methods to improve the *COP* of conventional HPWH. However, in the present study, the *COP* of HPWH using PCM for heat storage is lower than that of conventional HPWH. For example, in the studies of Long et al. [34] and Wu et al. [36], the *COP* of water-PCM heated HPWH were 3.08 (average value) and 3.05 (maximal value) respectively, while the minimum value is 3.4 for static heating regulated by China National standard GB/T23137-2008. Because of this, the practical application of water-PCM heated HPWH is still limited due to its lower *COP*. At present, most researchers are concerned with high heat storage capacity using PCM for storage in HPWH, there is little literature on how to improve its *COP*. According to our analysis, there are two main reasons for the lower *COP* of water-PCM heated. One is that the unreasonable structure of storage tank leads to a great deal secondary heat exchange between water and PCM, the other is that the low thermal conductivity of PCM reduces the heat transfer efficiency. To solve the above problems, we have proposed a storage tank using water-PCM for heat storage [37]. Fig. 1 shows the schematic configuration of the storage tank.

As shown in Fig. 1, the storage tank consists of water tank, PCM, fin, steel casing and condenser coil. The PCM is filled in the annular cavity between the outer wall of the water tank and steel casing. Fins are welded on the outer wall of the water tank to increase the heat transfer performance of the PCM. Condenser coil is wrapped around and affixed to the outside of the water tank which is coated by PCM. The storage tank is better than traditional water-PCM storage tank: Firstly, heat storage capacity is increased without reducing the volume of water. So, heat transfer performance of the water tank could not be weakened by the PCM, on the contrary, when the latent heat stored in the PCM is discharged into water, electrical power of HPWH could be reduced which may improve the *COP*. Besides, compared to common PCM storage tank, the secondary heat exchange can be reduced as the volume of water tank is not changed. Secondly, the effective heat transfer areas are increased when the condenser coil is completely coated with PCM. While in conventional water tank, only a part area of the condenser coil contacted with the outer wall of the water tank can be used. Finally, fins can improve heat transfer rate of PCM. So, HPWH with storage tank can not only has higher heat storage capacity, but also has higher *COP*.

In this paper, to increase the heat storage capacity and improve the performance of the system, an air-source HPWH using water-PCM for heat storage was designed. An experimental study on the performance of the air-source HPWH was conducted. Furthermore, performances between the HPWH using water-PCM for heat storage and conventional HPWH with standard water tank were compared.

2. Experimental system and process

2.1. Design of the storage tank with finned PCM

2.1.1. Standard water tank

The storage tank with finned PCM was improved from a standard water tank. The standard water tank was 996 mm high and 400 mm in diameter shown in Fig. 2. The condenser coil with outside diameter of 7 mm, wall thickness of 0.25 mm is wrapped around and affixed to the outside of the water tank divided into two branches. The axial distance between two coils is 20 mm. A temperature sensor (5 K) was installed in the middle of the water tank with a170 mm higher than the lowest coil for measuring the average temperature of the water in the water tank.

2.1.2. Selection of PCM

The melting point and latent heat of PCM are the most important determinants in selecting an appropriate PCM. In the present study, according to appropriate melting point and large latent heat for HPWH, paraffin ((RT44HC)) is used as a latent heat storage material. Its thermal properties were tested by Differential Scanning Calorimetry (DSC). The characteristic parameters of the selected PCM are shown in Table 1.

2.1.3. Structural design of storage tank with finned PCM

The structure of storage tank with finned PCM was designed according to the idea of Fig. 1. Steel fins with a thickness of 0.25 and a height of 5 mm were added at the middle of two coils and middle part of outer wall of the water tank. The photo of the water tank without PCM was shown in Fig. 3.

The space between outer wall of the water tank and casing was filled with 9.1 kg of PCM. The casing exceeds only 7 mm from the condenser coil with volume increase of 6%. Besides, it was coated with 50 mm thickness of thermal insulation material. So, the volume increase could be negligible because the radial diameter increase was small relative to the thickness of the insulation material, and the thermal insulation material could be thinner as the temperature of the PCM was lower than the coil. The photo of the storage tank with finned PCM was shown in Fig. 4.

2.2. Description of the experimental plant

As shown in Fig. 5, the air-source HPWH system was located in enthalpy difference laboratory.

The enthalpy difference laboratory was measured at 7.0 m (L) × 5.5 m (W) × 5.5 m (H). There was an air conditioning system including electric heaters, a humidifier and a cooling coil to simulate the outdoor environment. The ambient conditions include temperature and relative humidity. These ambient conditions could be maintained at its designed value by adjusting electric heaters and chillers (refrigerating compressor unit). The experimental air-source HPWH used