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System design and energy performance of a solar heat pump heating system with dual-tank latent heat storage

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ABSTRACT

Thermal energy storage is widely regarded as one of the most promising technologies for ensuring that solar applications provide maximum energy efficiency and reliable energy supply. Phase-change materials (PCMs) can store latent heat energy during the phase-change process. The main objective of this study is to illustrate the energy-efficiency benefits of dual-tank latent heat storage (DLHS) installed in a solar heat-pump heating system (SHPHS). We designed and constructed an SHPHS–DLHS and tested it in the meteorological conditions of Beijing, China. As a result of this research, we defined a new performance parameter, the daily average collection efficiency (η). This parameter, combined with coefficient of performance (COP), can be used to evaluate the design of PCM thermal storage system and to maximize the use of the thermal storage media. We also tested thermal efficiency under different conditions and found that collection efficiency increases by up to 50% with the use of latent heat storage. The peak COP of the SHPHS–DLHS system was 10.03, roughly 3.5 times higher than that of the system using sensible heat water storage only. We conclude that PCMs improve an SHPHS system's energy efficiency.

1. Introduction

Solar energy is a clean, renewable solution to many of the environmental problems associated with energy production and consumption. However, solar energy's intermittent availability is a disadvantage. An effective way to address the availability problem is to install thermal storage in solar systems. Stored energy allows a system to maintain a continuous supply and thus meet users' seasonal or daily demand when the solar resource is not available [1–3]. There has been much research on reliable, high-quality thermal storage materials [4–8,3,9]. Thermal energy storage can be classified by mechanism (sensible, latent, or chemical) and by storage concept (single-medium or dual-media). Three types of systems are generally used for thermal energy storage: sensible, latent, and hybrid [10–14]. Water is generally used as the sensible heat carrier for reasons of simplicity and easy availability [15,16]. However, water has intrinsic shortcomings as a heat carrier, including low energy density and temperature instability during the energy charge and discharge processes. The average coefficient of performance (COP) of an indirect-expansion solar-energy-system assisted heat pump using water as the storage carrier was 4.83 in an experimental and numerical study [17]. The authors of that study concluded that COP cannot reflect system performance precisely. They analyzed collector thermal performance and found that collection efficiency was not sufficient. The main reasons for low collection efficiency are that solar radiation is abundant in midday, which causes the heat-transfer fluid (HTF) temperature in the energy storage tank to rise to its highest level. At the same time, midday is usually the time of lowest heating demand because it is the warmest time of day.

Because the temperature difference between the energy storage tanks and the solar collector, which is the unique parameter that turns the hot water circulation pump switch on or off, is not high enough to switch on the pump, no energy is stored at this time.

Phase-change materials (PCMs) are latent heat energy storage media, which can absorb or release high amount of latent heat when they change phase from solid state to liquid state (endothermic process) or vice versa (exothermic process) with small temperature variations. This main feature makes PCMs particularly attractive for solar thermal energy storage. PCMs have a higher energy storage density than water, so a smaller storage volume is needed to store the same amount of heat when using PCMS than when using water as the heat-transfer fluid. More importantly, PCMs can charge and discharge thermal energy at a constant temperature. Therefore, many researchers use PCMs as a daily storage medium instead of water and have investigated the performance of solar heat pump

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Nomenclature

PCMs	phase-change materials
DLHS	dual-tank latent heat storage
SHPHS	solar heat pump heating system
COP	coefficient of performance
HTF	heat-transfer fluid
WST	water-storage tank
PST	PCM storage tank
TTSTs	two thermal storage tanks
HCL	heat-collection loop
HRL	heat-release loop
C_P	specific heat [J/(kg K)]
P	consumption of electricity (W)
Q_c	solar energy collection (W)
Q_w	heat stored in WST (W)
Q_{pcm}	heat stored in PST (W)
Q_{so}	heat released to thermal units (W)
I_β	solar radiation intensity (W/m^2)
A_c	effective collection area of solar collector (m^2)
m_c	mass flow rate of collection loop (kg/s)
m_s	mass flow rate of heat pump P_2 (kg/s)
η	daily the average collection efficiency
T_{si}	the inlet HTF temperature of end-user (°C)
T_{so}	the outlet HTF temperature of end-user (°C)
T_1	the inlet HTF temperature in the solar collector (°C)
T_2	the outlet HTF temperature in the solar collector (°C)
T_3	the HTF temperature in the WST (°C)
T_6	the HTF temperature in the PST (°C)
T_n	the heating threshold temperature (°C)
T_d	antifreeze threshold temperature (°C)

heating systems with latent heat storage [18–22]. Kaygusuz et al. [23] performed a series of studies on solar heat pump systems using $CaCl_2{\cdot}6H_2O$ as the PCM. They investigated the performance of combined solar heat pump heating systems both experimentally and theoretically and found that a dual-source heat pump system combines the best features of series and parallel systems. Yumrutas and Koska [24] proposed a structural configuration for an experimental solar-assisted heat-pump space-heating system with a daily energy storage tank and investigated the effects of climate conditions and certain operating parameters on system performance. Kaygusuz [25] claimed that the average seasonal heating performance values of the combined solar-heat pump system with energy storage in encapsulated PCM packing for residential heating in Trabzon are 4.0 and 2.5 for series and parallel, respectively. Jiang [26] simulated a solar energy application system that uses $CaCl_2{\cdot}6H_2O$ as the PCM, for a home in the Harbin area of china. The simulation results suggested that the temperature of the PCM in a storage tank was much lower than that of water in a central solar heating system with hot-water heat storage, and that the temperature could be maintained at around the melting point of the PCM.

Through summarizing the previous investigations of solar energy storage, it can be found that they only focused on using either water or PCM as daily energy storage. Little consideration has been placed to the studies of combining water and PCM. In order to investigate this combined approach, our group designed and constructed an SHPHS–DLHS system. In addition, the differences between the SHPHS–DLHS system and the water energy storage system are systemically researched in this paper. The specific research content of this paper is organized as follows: Section 2 describes the structural configuration of an efficient DLHS system. Section 3 describes the mathematical modeling of system evaluation coefficients. Section 4 presents our experimental results, theoretical analyses and system cost, while Section 5 presents the conclusions.

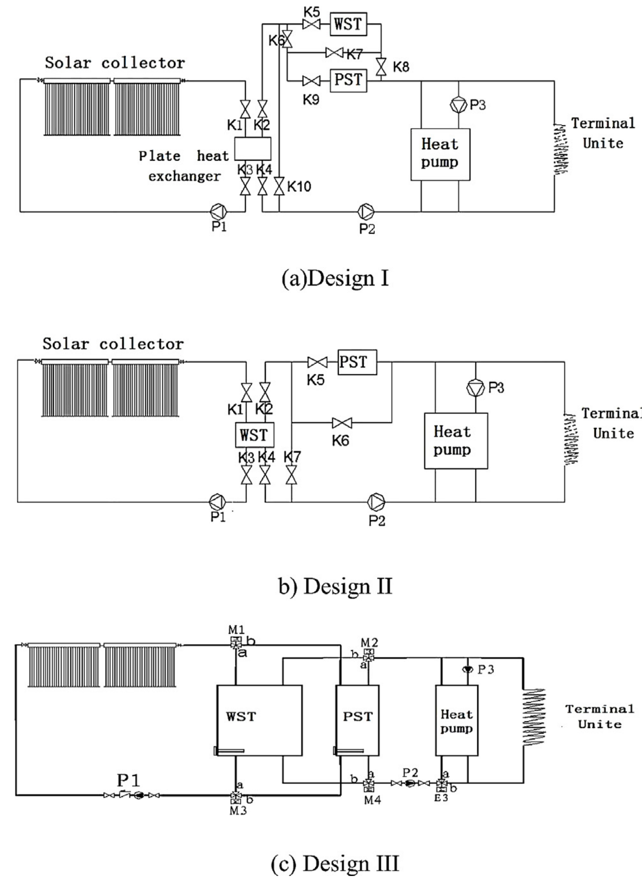

Fig. 1. Schematic diagrams of three dual-tank latent heat storage system configurations. (a) Design I, (b) Design II, (c) Design III.

2. System description

2.1. System design methodology

In this section, we describe three methods of designing the dual-tank arrangement for a latent heat storage system (Fig. 1).

As shown in Fig. 1, the systems are composed of solar collectors, the dual tanks, a heat-pump unit, circulating water pumps and terminal units (floor plate tubes), and other elements. The operating strategies of the different systems showed in Fig. 1 are as follows:

Design I: Fig. 1(a) shows two thermal storage tanks (TTSTs) separated from the collector by a plate heat exchanger. Operational strategies of this system could be:

- Strategy I: When the solar energy meets the heating demand perfectly, the collector directly supplies heat, and no energy is stored in or released from the TTSTs (valves k6, k7, and k8 are open; valves k5 and k9 are closed).
- Strategy II: When there is surplus solar energy generated, the TTSTs will store heat individually. Valves can be set so that they connect in series (valves k5, k7, and k9 open, and valves k6 and k8 closed) or in parallel (valves k5, k6, k8, and k9 open, and valve k7 closed) by being switched on or off.
- Strategy III: When the solar energy is not sufficient to meet heating demand, the TTSTs release heat individually.

Design II As shown in Fig. 1(b), the water-storage tank (WST) is an important connecting component installed between the solar