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Experimental study on an integrated collector storage solar air heater based on flat micro-heat pipe arrays

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ABSTRACT

This study investigated the performance of an integrated collector storage solar air heater based on latent heat storage and flat micro-heat pipe arrays. The structure and working principle of the device were explained in detail. The effective area of the collector is 0.93 m^2, and the mass of the phase change material (PCM) is 45.8 kg. An integrated collector storage experimental system was set up, and outdoor experiments were conducted to demonstrate the feasibility of the device for energy storage and air heating. The temperature distribution of the PCM was recorded during charging and discharging to monitor the propagation of the melting and freezing front. Efficiency and power during charging and discharging were also calculated. The integrative device exhibited 59% and 91.6% efficiencies for solar air charging and discharging at 393 and 344 W power, respectively.

1. Introduction

The shortage and inefficient development and utilization of energy have caused serious environmental pollution and hindered sustainable economic and social development in China. Solar energy, an inexhaustible, green, renewable energy source, should be efficiently utilized to solve or improve space heating and environmental issues in remote areas in winter. However, storage of solar energy remains challenging because it is instable, random, and intermittent; as such, the imbalance between energy supply and demand should be resolved. Phase change materials (PCM) exhibit high storage density and constant temperature during charging and discharging and thus can be potentially used for thermal energy storage, particularly for latent heat [1,2].

Inorganic and organic PCMs (mineral salt, fatty acids/esters, and paraffin) and PCM mixtures have been characterized and applied for heat storage. Paraffin-type PCMs are commonly used to store latent heat energy because of their high latent heat of phase change, slight segregation of components, and minimal changes in structure during repeated phase transformation; these materials are also characterized by lack of super cooling and phase separation, good thermal and chemical stability, low vapor pressure, self-nucleating behavior, and low cost [3–5].

Split-type solar energy system (STSES) mainly consists of collector and thermal storage, which are installed separately. Scholars experimentally studied the joint operation of collectors and latent heat storage (LHS). Sharma and Sagara [6] reviewed works on PCM and LHS systems conducted before 2004 and obtained a list of about 250 PCMs and more than 250 references, which can be used to determine suitable PCM for heat exchangers to enhance heat transfer and design. Saman et al. [7] developed a roof integrated solar heating system with storage units as components. The system consists of several layers of PCM slabs, with a melting temperature of 29 °C, for heating homes. The thermal characteristics of the storage during charging and discharging were studied through experimental methods and theoretical calculation. Results showed the effect of sensible heat. The high inlet air temperature and air flow rate increased the heat transfer rate and shortened the melting period. Esakkimuthu et al. [8] investigated the feasibility of an LHS unit with inorganic salt HS-58 to store surplus energy and evaluated the charging and discharging characteristics of the unit. The effects of inlet flow rate during charging and discharging, storage tank configuration, and size of the PCM ball were assessed. The mass flow rate was set to 200 kg/h to provide uniform heat transfer during charging and discharging, utilize the maximum capacity of the storage system, and supply heat for long duration. Devahastin et al. [9] investigated the feasibility of an LHS with paraffin wax as PCM to store excess solar energy. The heat transfer of the PCM during charging and discharging of LHS was also characterized. The effects of the inlet hot air temperature (70 °C–90 °C) and inlet air velocity (1 and 2 m/s) on charging time were determined, and the effect of inlet

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Nomenclature

STSES	Split-type solar energy system
ICS	Integrated collector storage
LHS	Latent heat storage
HTF	Heat transfer fluid
PCM	Phase change material
FMHPA	Flat micro-heat pipe array
HST	Heat storage tank
HIM	Heat insulation material

Dimensional variables

Q	Energy capacity (kJ)
M	Mass (kg)
c_p	Specific heat capacity (kJ kg^{-1} K^{-1})
T	Temperature (K)
P	Thermal power (W)
q_v	Volume flow rate (m^3/s)
A	Area heat transfer (m^2)
ΔT	Temperature difference (K)
I	Solar radiation intensity (W m^{-2})

Subscripts

c	Charging
pa	Paraffin
i	Initial
f	Final
Al	Aluminum
st	Stainless steel
d	Discharging
air	Air
in	Inlet of duct
ind	Indoor
hl	Heating load
out	Outlet of duct
e	Extraction
s	Storage
r	Release
b	Black film
g	Glass cover-plate
col	Collector area
C	Convection
R	Radiation
su	Supply
au	Auxiliary
a	Ambient

Greek letters

γ	Latent heat capacity (kJ/kg)
τ	Time (s)
$\Delta\tau$	Time interval
η	Efficiency (%)
λ	Thermal conductivity (W K^{-1} m^{-1})
δ	Thickness (m)
θ	Slant angle (rad)
ε	Emissivity of object surface (%)
σ	Stefan-Boltzmann constant (W m^{-2} K^{-4})

ambient air velocity was evaluated during discharging. The effect of LHS on the drying kinetics of sweet potato and the capacity of the unit to conserve energy during drying were evaluated. The drying rate of sweet potato increased with decreasing inlet ambient air velocity. The amounts of energy extracted from the LHS were 1920 and 1386 kJ/(min kg), and the energy savings were 40% and 34% when using inlet ambient air velocities of 1 and 2 m/s, respectively.

STSES presents several limitations, such as large space requirement, complexity, presence of secondary heat transfer, and low thermal efficiency. The heat loss of the system should be reduced to increase the thermal efficiency and reduce the occupied area. Scholars have developed compact PCM solar collectors and integrated collector storage (ICS) devices to reduce secondary heat transfer and heat loss in pipelines. The use of ICS has been widely studied in solar water heaters [10–20] but has been rarely investigated in solar air heaters. Bansal et al. [21] developed a thermal analysis model of a collector cum system for quasi-steady-state conditions by using stearic acid as PCM. The applicability of the mathematical model was assessed using numerical methods, and the results showed the advantages of the system over STSES. Enibe et al. [22] proposed a natural circulation solar heating system with PCM as energy storage. The system consists of a flat plate solar collector integrated with paraffin PCM, prepared in modules and equispaced across the absorber plate, for energy storage. Modeling and experimental verification were conducted. The predicted performance of the system was compared with the experimental data obtained under daytime no-load conditions at an ambient temperature of 19 °C–41 °C and daily accumulated total radiation of 4.9–19.9 MJ/m^2. The predicted temperatures at specific locations on the absorber plate, heat exchanger plate, glazing, and heated air, with values of 10 °C, 6 °C, 8 °C, and 10 °C, respectively, are consistent with the experimental data. The maximum predicted cumulative and overall efficiencies of the system are within 2.5%–13% and 7.5%–18%, respectively. Su et al. [23] designed and tested a flat-plate solar air collector/storage system integrated with PCM. The experimental results and calculation indicated that the thermal storage efficiency of the device is 23%. The thermal efficiencies of the collector/storage system and the regular collector are 55% and 19% respectively. Hence, the solar collector/storage system can significantly decrease the thermal loss and increase the thermal storage efficiency.

The ICS system can be used in solar air heater to reduce the system floor area, simplify the system, reduce the heat loss, and improve the thermal efficiency; as such, ICS has become a new research direction for solar energy systems. However, in solar air heater with ICS, solar energy absorbed by the collector cannot be rapidly transferred to the heat storage medium, resulting in inefficient thermal collection and storage and difficulty in extracting the stored energy. The development of integration technology is not mature yet and must be further improved.

This study proposes a new type of ICS solar air heater that uses a novel highly efficient heat transfer element, namely, flat micro-heat pipe array (FMHPA) [24]. The feasibility and performance of the device was tested in an outdoor experiment. The FMHPA is connected to the solar air collector and LHS. This renewable energy heating technology uses an absorber with high absorption rate and FMHPA with efficient heat transfer characteristics; as such, solar energy can be stored in the PCM, and the stored energy can be extracted from the air duct at nighttime or when needed. In addition, the combined heat storage and collector not only conserves energy but also improves the performance and reliability of a wide range of energy systems, especially those for intermittent energy sources, such as solar energy.

2. Experimental investigation

2.1. Details of experimental setup

An experimental system of the new type of ICS solar air heater was designed with LHS and FMHPA and used for charging and discharging tests in an outdoor environment in Beijing. Fig. 1 shows