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Thermal performance of solar air collection-storage system with phase change material based on flat micro-heat pipe arrays

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ABSTRACT

In this study, a new type of solar air collection-storage thermal system (ACSTS) with phase change material (PCM) is designed using flat micro-heat pipe arrays (FMHPA) as the heat transfer core element. The solar air collector comprises FMHPA and vacuum tubes. The latent thermal storage device (LTSD) utilizes lauric acid, which is a type of fatty acid, as PCM. The experiments test the performance of collector efficiency and charging and discharging time of thermal storage device through different air volume flow rates. After a range of tests, high air volume flow rate is concluded to contribute to high collector efficiency and short charging and discharging time and enhance instantaneous heat transfer, whereas an air volume flow rate of 60 m^3/h during discharging provides a steady outlet temperature. The cumulative heat transfer during discharging is between 4210 and 4300 kJ.

1. Introduction

Solar energy is a pollution-free renewable source that is distributed widely, and using this energy is an efficient means of energy conservation. Considering seasonality and discontinuity, storing heat generated from solar air collector to latent thermal storage device (LTSD) can extend the time limited by the weather, allowing for prolonged use of solar energy. At present, vacuum tube collector with water as heat transfer medium is an ordinary and recognized technique, but it occasionally leads to freezing and leakage. By contrast, collector with air as the transfer medium is becoming increasingly popular and attractive. To reserve thermal energy coming from the collector, the heat-storing device is necessary. Currently, devices storing thermal energy mostly employ phase change technology. A suitable phase change material (PCM) and device can guarantee efficient operation. A thermal system coupled with efficient collector with LTSD is a valid measure to solve the heating problem during winter.

Heat pipe is an efficient heat transfer component, which features the advantages of thermal homogeneity, stability, and good diathermancy. It is used for heat collecting and charging because of small volume and heat transfer enhancement.

Many scholars at home and abroad have studied solar air collector and LTSD. Zhao et al. [1] conduct an experiment comparing flat plate solar collector with vacuum tube collector, and they conclude that the efficiency of the former is slightly higher than that of the latter, but the efficiency fluctuation of vacuum tube collector is minimal and retains a higher level. Zhu et al. [2,3] investigates a new solar air collector that uses flat micro-heat pipe arrays (FMHPA) as the central transporting component and analyzes the effects of different seasons and airflow rates on thermal efficiency. Xu et al. [4] create a 2D mathematical mode on the basis of heat pipe tubular structure and proper hypothesis of boundary condition and uses FLUENT software to simulate the heat transfer progress and analyze the influencing factors of temperature and flow field.

Thermal energy storage is discussed by many researchers. Wang [5] designs a heat pipe heat exchanger on latent heat storage with paraffin as PCM and analyzes the effects of inlet water temperature and water flow rate on the charging and discharging process. Li et al. [6] create a LTSD using lauric acid as PCM to analyze the heat storage-release performance of storage unit under different inlet temperatures and air flow rates. Agarwal and Sarviya [7] manufacture a shell and tube-type latent heat storage equipment with paraffin wax as heat storage material and study the effect of using latent heat storage equipment on drying food product in hot air during non-sunshine hours. Liu et al. [8,9] set up a heat pipe heat exchanger with latent heat storage, which is operated in three different ways: charging only, discharging only, and simultaneous charging and discharging.

The thermal system combining solar air collector with LTSD is also researched. Esakkimuthu et al. [10] study a solar collector

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Nomenclature

ACSTS	air collection-storage thermal system
FMHPA	flat micro-heat pipe arrays
LTSD	latent thermal storage device
PCM	phase change material
η_c	heat-collecting efficiency
$C_{p,air}$	specific heat capacity of air, kJ/kg·K
ρ_{air}	density of air, kg/m^3
V	air volume flow rate, m^3/h
T_{ci}	collector inlet temperature, °C
T_{co}	collector outlet temperature, °C
A_A	collector area, m^2
I_c	solar insolation, W/m^2
Q_{st}	theory storage energy, kJ
$C_{p,PCM}$	specific heat capacity of PCM, kJ/kg·K
m_{PCM}	mass of PCM, kg
T_f	final temperature of PCM, °C
T_i	initial temperature of PCM, °C
H_m	latent heat of PCM, kJ/kg
m_{Al}	mass of heat pipe, kg
Q_{in}	supplied heat transfer of charging, kJ
T_{si}	storage inlet temperature, °C
T_{so}	storage outlet temperature, °C
Q_{out}	cumulative heat transfer of discharging, kJ
T_{ei}	heating-out inlet temperature, °C
T_{eo}	heating-out outlet temperature, °C
Q_{loss}	heat loss of insulation, kJ
T_{ii}	insulation layer inside temperature, °C
T_{io}	insulation layer outside temperature, °C
A_i	insulation surface area, m^2
h	air convective heat transfer coefficient, W/m^2·K
δ	thickness of insulation layer, mm
λ	heat conductivity coefficient of insulation material, W/(m·K)
x	horizontal coordinate axis x
y	horizontal coordinate axis y
z	vertical coordinate axis z

integrated with the PCM based thermal storage unit, which is evaluated according to the charging and discharging performance of the storage unit. Low air flow rate can utilize maximum thermal energy. A phase change thermal storage unit for a roof-integrated solar heating system is analyzed based on transient thermal behavior by Saman et al. [11] based on experimental results and the 2D mathematical model of the PCM during charging and discharging. Arkar [12,13] design a solar air heating system that consists of an air vacuum tube solar collector and latent heat storage and find that 54–67% of the heat produced by solar air heating system during daytime can be used for creating heat at night. Enibe [14,15] constructs a passive solar powered air heating system, which is made up of a single-glazed flat plate solar collector integrated with PCM heat storage device. The system can be operated for crop drying applications successfully, and the predicted performance of the system is compared with experimental data. Kabeel et al. [16] experimentally investigates flat and V-corrugated plate solar air heaters (SAHs) with paraffin wax as thermal energy storage material and presents parameters affecting the thermal performance of the flat and V-corrugated plate SAH with and without PCM. Khadraoui et al. [17] conducts an experimental study to enhance the efficiency of a simple fabricated Solar Air Heater (SAH) integrated with thermal heat storage. Two similarly designed solar air collectors (with and without PCM) are used to evaluate the importance of PCM unit. Fath [18] studies solar air collector with built-in latent heat thermal energy storage system. PCMs with different melting temperature are studied, and those under 51 °C and 43 °C show the best performance.

A new type of solar air collection-storage thermal system (ACSTS) is studied based on vacuum tube air heater and the novel LTSD with lauric acid used as PCM, in which the heat transfer core component of the collector and LTSD is FMHPA [19,20]. The performance of ACSTS is tested in a collection-storage working condition with different air volume flow rates. A reference is provided to investigate solar air heater integrated with the thermal storage of PCM.

2. Experimental investigation

2.1. Structure and theory of collector

The collector combining FMHPA with vacuum tubes consists of collecting units, a bracket, induced draft fan, and an air duct made in iron with insulation board pasted. The collector includes 20 collecting units, which is formed by uniformly sectioned straight ribbed aluminum fin, FMHPA, and vacuum tube. The size of the aluminum fin is $55 \times 25 \times 80$ mm, and the FMHPA is $2000 \times 40 \times 3$ mm, and the vacuum tube is $\Phi 58 \times 1800$ mm, respectively. The absorptivity of vacuum glass tube film coating is 0.95, and emissivity is 0.05. And borosilicate glass transmittance is 0.91, heat conductivity coefficient is 1.2 W/(m·K), and heat capacity is 0.82 kJ/(kg·K). Fig. 1a illustrates the schematic of the experimental setup. FMHPA connected to aluminum fin by heat-conducting glue is placed in a vacuum tube. To guarantee the gas tightness between vacuum tube and iron air duct, a rubber ring is utilized to link them with pasted sealant. The aluminum fin is installed in a rectangular duct with reducing nipple used to connect the induced draft fan. The collecting device is placed in the bracket in a 45-degree angle from the ground.

The collector includes 20 collecting units. The collecting unit, combined with FMHPA and vacuum glass tube, is presented in Fig. 1b. During the working process, the vacuum glass tube coating film absorbs solar radiation energy. The air in the vacuum glass tube is then heated, and thermal energy is transferred to the evaporation section of FMHPA. The working fluid with 20% liquid-filled ratio in the evaporation section absorbs thermal energy to evaporate. When steam flows up to the condensation section, it becomes liquid and releases thermal energy and then reflows to the evaporation section by gravity and capillary force. This cycle is continuous, reciprocating phase change process [2]. Given the efficient heat transfer performance of FMHPA, it can transfer thermal energy to aluminum fins attached in the condensation section of FMHPA. Finally, the air in low temperature driven by fan-1 takes away thermal energy from aluminum fins by convection heat transfer and becomes high temperature.

2.2. Structure and theory of FMHPA LTSD

FMHPA LTSD comprises thermal storage tank, heat transfer component, PCM (lauric acid), and iron air duct. The thermal storage tank is made with a 3 mm corrosion-resistant steel plate, and the size is $388 \times 105 \times 800$ mm. The height of the thermal storage section and air duct is 480 and 160 mm, respectively. The heat transfer component consists of FMHPA and a V-model aluminum fin by the welding technology. FMHPA is filled with acetone, whose filling rate is 20%. The working principle of thermal storage unit is