IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

Design and experimental study on thermal characteristics of thermal storage flat-plate solar collector

To cite this article: Y T He *et al* 2018 *IOP Conf. Ser.: Earth Environ. Sci.* **188** 012069

Design and experimental study on thermal characteristics of thermal storage flat-plate solar collector

Y T He[1, 2], J F Yang[1], L X Xiao[1] and Y H Yang[1]

[1]Department of Physics and Electronic Science, Chuxiong Normal University, Chuxiong, 675000, China

E-mail: hyt@cxtc.edu.cn

Abstract. A thermal storage flat-plate solar collector is designed to improve working stability of the solar air drying system, which consists of an absorber plate, a transparent cover plate, a heat insulation layer, phase change materials, a tube bank and a shell, etc. The daily thermal characteristics of thermal storage flat-plate air collector system were tested under natural conditions. The results show that heat storage flat-plate solar collector can effectively extend collector heating time, with daily heat efficiency reaching 49.8%, which is 4.6% up as compared to 45.21% of non-thermal storage heat collector.

1. Introduction

In terms of solar thermal utilization, the solar air collector system has wide applications in chemical engineering, material drying projects. Air collectors fall into two types: flat-plate solar air collectors and glass vacuum tube solar air collectors [1]. No matter it is flat-plate solar collector or vacuum tube collector, the traditional collector does not have an energy storage function, with its output temperature greatly affected by the solar irradiance, directly affecting the quality of material drying which limits the promotion and application of solar energy drying to a certain extent. Thermal storage air collector systems have recently been extensively studied and applied [2-5]. For instance: Hua *et al* designed a new tank-free phase change thermal storage solar collector. The results show that addition of 20% phase change storage material to the 34 L collector pipe makes the total heat storage capacity up to 8.2 MJ. The collector pipe has a temperature drop rate of 1.4°C/h based on heat preservation test at night [6]. Wang *et al* experimentally studied the heat transfer characteristics of solar heating concrete heat storage bricks, showing that the use of concrete heat storage bricks in the solar heating system for heat storage can improve the utilization of renewable energy sources [7]. Liu *et al* alleviated the instability of solar hot air heating and improved solar energy utilization efficiency using phase change energy storage wallboards. The composite heating system can increase the average indoor temperature by 7-15°C compared with unheated rooms [8]. Zhao *et al* designed phase change thermal storage solar water heating system and studied the effect of different phase change materials on thermal characteristics of the system. The results show that thermal performance of solar hot water system can be increased by 34% due to the use of PCM heat storage [9]. Wang *et al* proposed a paraffin wax as a phase change thermal storage material for solar air collector, and experimentally studied heat charge and discharge properties of the phase change material, finding improvement in thermal characteristics of thermal storage solar collector system [10]. Wen *et al* introduced a solar thermal collection/ storage system combining phase change thermal storage materials and flat-plate solar air collectors, and estimated the thermal efficiency and heat loss of the entire system. The results show that the system can have thermal storage efficiency of 23% and thermal efficiency of 55% [11].

The above researches show that addition of phase change material heat storage units can increase thermal efficiency and improve thermal properties of solar collectors. However, study on phase change thermal storage solar collectors is still in its infancy, and further study is needed for related theories and experiments [4] In this paper, based on analysis of temperature characteristics of flat-plate solar collectors, thermal storage flat-plate solar collector is designed using solid-solid phase change thermal storage characteristics of mannitol, and its photo-thermal properties are tested and analyzed.

2. Temperature characteristics of flat-plate solar air collectors

The designed flat-plate solar collector mainly consists of an absorber plate, a transparent cover plate, a heat insulation layer and a shell, with its structure shown in figure 1.

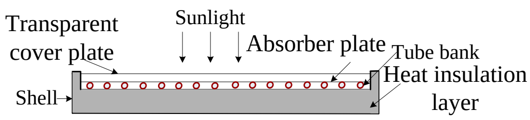


Figure 1. Schematic diagram of flat-plate collector.

As shown in figure 1, when the flat-type solar collector works, sunlight passes through the transparent cover plate, transmits to the absorber plate, to be converted into heat energy after absorbed by the absorbing coating of the absorber plate. The heat energy is then transmitted through the absorber plate to the heat transfer fluid within the tube bank, so that the heat transfer fluid temperature is increased and output as useful energy of the heat collector.

The incident solar energy for the flat-plate solar collector structure can be expressed as equation (1):

$$Q_A = A_s G(\tau a)_e \quad (1)$$

In the above formula, A_s is the area of the collector's absorber plate, G is the solar irradiance, and $(\tau a)_e$ is the product of transmittance of the transparent cover plate and absorption rate of the absorber plate.

In the steady state, according to the law of conservation of energy, the useful energy output by the collector during a specified period of time is equal to the incident solar irradiance energy on the collector during the same period of time minus the energy dissipated by the collector to the surrounding environment. The available energy of the flat-platecollector can be approximated as equation (2):

$$Q_U = A_s G(\tau a)_e - A_s U_L (T_p - T_a) \quad (2)$$

In the above formula, T_p is the absorber plate temperature, T_a is the ambient temperature, U_L is the heat loss coefficient of the flat-plate collector, which is related to transparent cover plate, absorber plate temperature, ambient temperature, emissivity of the transparent cover plate, thickness and thermal conductivity of heat insulation material. In addition, absorber plate temperature of the collector is not stable owing to factors such as solar irradiance, material parameters of the collector structure, flow rate of the working medium and ambient temperature, etc. For example, for a 2 m^2 flat-plate air collector with air outlet diameter of 3 cm and an air flow rate of 16 m/s, changes in its solar irradiance, ambient temperature, absorber plate and air temperaturewithin a day on November 27, 2017 in Chuxiong is shown in figure 2(a).

It can be seen from the experimental results that during the operation of the flat-plate air solar collector, absorber plate temperature varies greatly with the solar irradiance, which is unstable with a rate of change per unit time (minutes) reaching 46°C and a maximum temperature reaching 131°C.

Thus, the output air temperature of the flat-plate air collector changes with the absorber plate temperature, resulting in unstable outlet air temperature. The high temperature and big variation of the absorber plate of the flat-plate air collector adversely affects its integration with the solar cell to form PV/T solar collector.

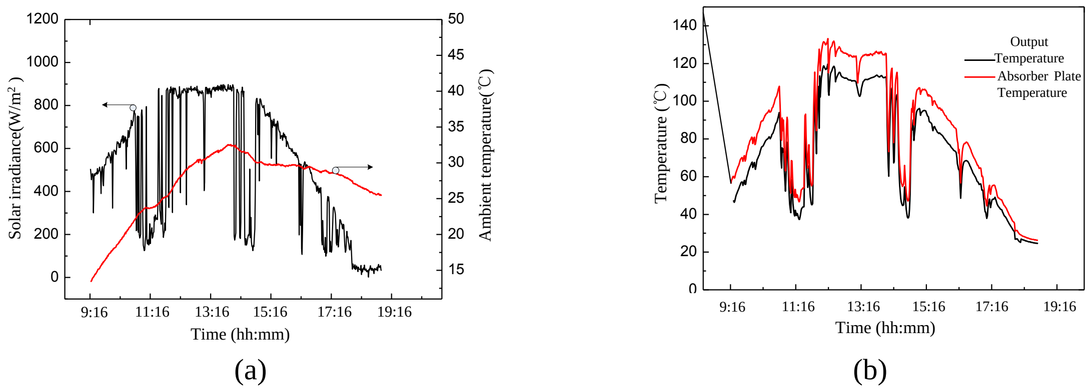


Figure 2. Experimental characteristics of flat-plate solar air collector. (a) Irradiance and Ambient Temperature and (b) Absorber and Output Temperature.

3. Design and thermal characteristics analysis of phase change thermal storage flat-plate collector

3.1. Design ofthermal storage flat- plate collector

The structural diagram of the designed phase change thermal storage solar air collector is shown in figure 3. It comprises: a transparent cover plate, an absorber plate, a circulating tube bank, phase change thermal storage material, a heat insulation layer and a heat collector shell.

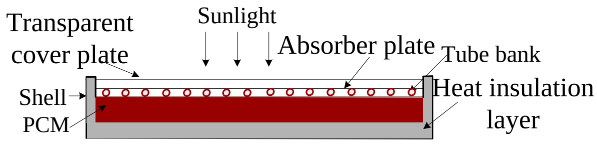


Figure 3. Structural diagram of flat-plate collector with integrated phase change material.

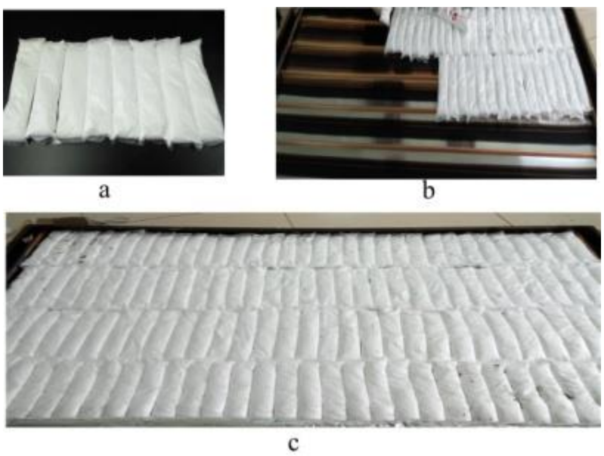


Figure 4. Structure of thermal storage phase change collector. a. Phase change capsule, b. Internal structure of the collector and c. Integrated structure of thermal

storage collector.

According to the temperature and structural characteristics of the flat-plate solar collector, mannitol solid- solid phase change thermal storage material is selected to simplify the encapsulation and integration process of the phase change material, which is then encapsulated intophase change capsule by using polyethylene plastic bag. The phase change material and collector integrated structure is shown in figure 4.

3.2. Thermal characteristics of thermal storage flat-plate collector

In the thermal storage flat-plate solar collector, some heat absorbed by the absorber plate isheated by heattransfer fluid (air), and some is stored in the phasechange material.

Considering that it is convenient to measure the wind speed of the hot air at the hot air outlet in system test, the system output heat is expressed as equation (3):

$$Q_U = C_{air}\rho_{air}VS\left(t_{af} - t_{ai}\right) \tag{3}$$

where V is the wind speed of the hot air outlet (unit: m/s), and S is the cross-sectional area of the hot air collector (unit: m^2).

Thus, the system thermal efficiency can be expressed as equation (4):

$$\eta = \frac{C_{air}\rho_{air}VS\left(t_{af} - t_{ai}\right)}{A_s \cdot E} \tag{4}$$

where A_s is the total area of the collector array (unit: m^2) and E is the solar irradiance (W/m^2).

4. Prototype and experiment of thermal storage flat-plate solar collector

4.1. Prototype of thermal storage flat-plate solar collector

A prototype of thermal storage flat-plate solar air collector system was designed, mainly including a 2 m^2 thermal storage flat-plate solar air collector, a bracket, and a blower, as shown in figure 5. The test system was designed using PT100, temperature transmitter, TBQ solar radiation meter, anemometer and Altay multi-channel data acquisition card to measure the inlet gas flow temperature, outlet gas flow temperature, absorber plate temperature, phase change material temperature, outlet air flow velocity of the collector, and the system test chart is shown in figure 6.

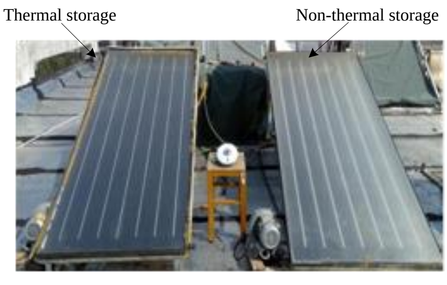


Figure 5. System prototype photo.

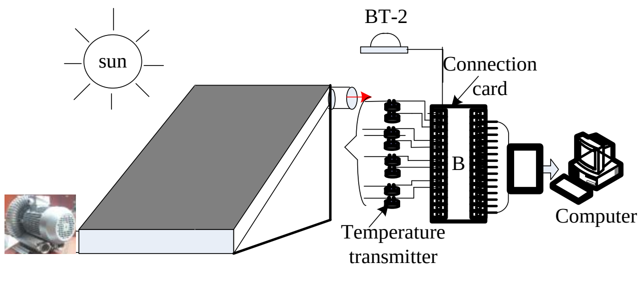
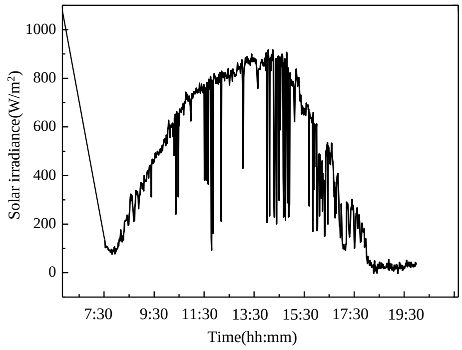


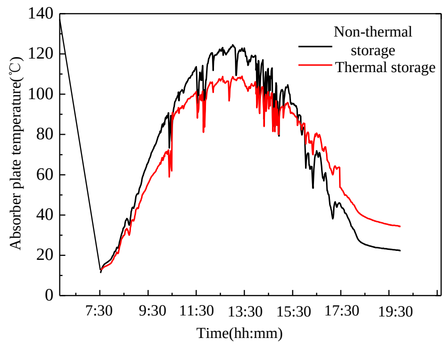
Figure 6. System test chart.

4.2. Experiments and analysis

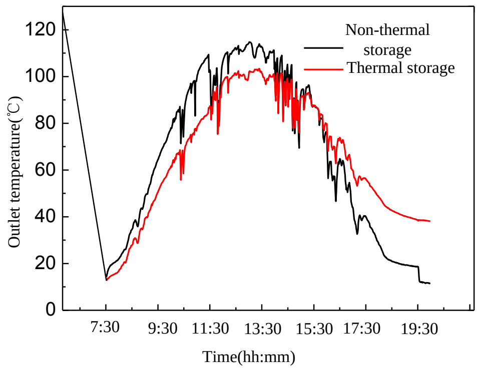
Chuxiong is located on the Yunnan Guizhou Plateau, with low atmospheric density, high sunshine transmission rate, long sunshine duration, and annual solar radiation above 5800 MJ/sq m. Solar air and water collectors are widely used in production and life.On January 12, 2018, the designed thermal storage flat-plate air collector was experimentally tested. Anon-thermal storage flat-plate air collector system with the same structural parameters as the thermal storage flat-plate air collectorwas designed to study the influence of phase change heat storage material on thermal characteristics of the collector. The wind speed of collector's hot air outlet is 20.8 m/s, and the hot air outlet radius is 1.2 cm. The test results are shown in figure 7.



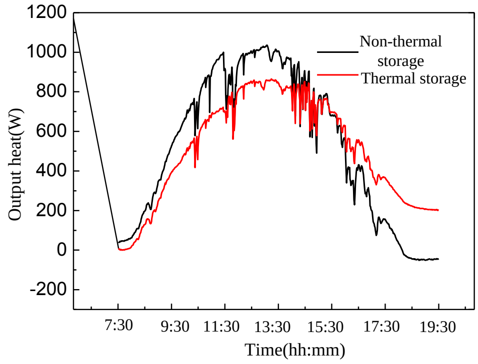
(a)



(b)



(c)



(d)

Figure 7. Daily thermal characteristics of flat-plate air collector. a. Solar irradiance b. Absorber plate temperature, c. Collector outlet temperature and d. Collector output heat.

It can be seen from figure 7 that for the thermal storage flat-plate air collector, due to the addition of the phase change heat storage material, the absorber plate temperature, outlet temperature and output heat of the collector is lower than those of non-thermal storage collector in the first half of the day (before 3 pm), and less heat is output, some heat is stored in phase change material. However, in the second half of the day, due to the weakened solar irradiance and heat release of the phase change material, the absorber temperature, outlet temperature, and the output heat of the collector is higher than those of non-thermal storage collector, which extends the collector heating time. Statistics of daily thermal characteristics of the collector system is shown in table 1.

Table 1. Heat output parameters of flat-plate air collector.

Collector type	Irradiance (w/m^2) (one day)	Total output heat (J)	Maximum outlet temperature (°C)	Solar heat conversion efficiency
Non-thermal storage collector	431940.45	195292.37	112.00	45.21%
Thermal storage collector	431940.45	211650.82	103.00	49.80%

Although the phase change thermal storage solar collector has a significant effect on improving the heat performance of the collector, the cost of the collector will be increased to a certain extent due to the increase of the phase change thermal storage material. In practical applications, it is necessary to select the phase change heat storage solar collector based on the comprehensive consideration of the thermal stability and cost of the solar drying system.

5. Conclusion

The thermal storage flat plate solar collector integrating mannitol phase change material and flat plate collector is feasible.During operation of thermal storage flat-plate air solar collector, on the one hand, itssystem daily heat efficiency can reach 49.80%, as compared to 45.21% of ordinary flat-plate solar collector. On the other hand, as the solar irradiance changes, the temperature change rate of the absorber plate decreases, and thermal storage flat-plate solar collector can extend the heating time. In addition, integration of mannitol solid phase change material as a heat storage unit with flat-plate solar collector enables simple structure and easy encapsulation of phase change materials, which facilitates itspromotion and application in the solar drying system.

Acknowledgments

The authors thank National Natural Science Foundation of China (No. 51566001) and Education department Major Project Foundation of Yunnan province (No. ZD2014014) for their financial supply.

References

[1] Wang H, Hu X H and Cheng H Z 2013 *Introduction to Solar Thermal Utilization* (Beijing, China: Tsinghua University Press)
[2] Sun H T, Gu Q J, Liu G Y, Xue A K and Xu F 2016 An extremum search method for optimal design of solar collector *Anhui Science &Technology* **7** 51-3
[3] Xu Y B, Zhao M, Qiu Y L, *et al* Solar CaO high-temperature thermal storage assisted CO_2 capture coal-fired power generation system *Acta Energiae Solaris Sinica* **1** 180-5
[4] Mohammed M A, Khan N I, Ibrahim *et al* 2018 Evaluation of solar collector designs with integrated latent heat thermal energy storage: A review *Sol. Energy* **166** 334-50
[5] Elbahjaoui R, El Qarnia H and Naimi A 2018 Thermal performance analysis of combined solar collector with triple concentric-tube latent heat storage systems *Energy and Buildings* **168** 438-56
[6] Hua W S, Zhang X L, Liu F and Du X D 2017 A novel tank-free phase change thermal storage solar collector and its thermal performance *Renew. Energ. Res.* **3** 395-400
[7] Wang Y, Jian Y F, Bai F W *et al* 2014 Characteristics of concrete heat storage blocks in solar heating system *Energy Storage Science and Technology* **3** 244-9
[8] Liu X, Feng G H and Huang K L 2015 Analysis of the composite heating system of solar air collector and phase change energy storage wallboard *Energy Storage Science and Technology* **6** 632-7
[9] Zhao J, Ji Y S and Yuan Y P 2018 Energy-saving analysis of solar heating system with PCM storage tank *Energies* **11** 881-93
[10] Wang Z Y, Diao Y H, Zhao Y H, *et al* Heat transfer characteristics of flat-plate micro heat pipe array type solar air collection-storage integrated device *J. Eng. Thermophys.* **3** 625-34
[11] Su W J, Zuo R, Zhang Z Q, *et al* 2008 Solar flat-plate heat collection/storage system *Acta Energiae Solaris Sinica* **4** 449-53