J Therm Anal Calorim (2012) 107:1345–1352
DOI 10.1007/s10973-011-1617-3

Thermal performance evaluation of a solar air heater with and without thermal energy storage

An experimental study

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Received: 24 March 2011 / Accepted: 20 April 2011 / Published online: 11 May 2011

Abstract This communication presents the experimental study and performance analysis of a solar air heater with and without phase change material (PCM) viz. paraffin wax and hytherm oil. There are three different arrangements viz. without PCM, with PCM and with hytherm oil to study the comparative performance of this experimental system. Inlet, outlet temperatures and radiation with respect to time have been recorded and found that the output temperature in case with thermal energy storage (TES) is higher than that of without TES, besides, the outlet temperature with paraffin wax is slightly greater than that of with hytherm oil. Also there is no energy gain in the evening in case of without TES but in case of with TES there is a heat gain for around 4 h in the evening which gives the backup for hot air for around four more hours which is the main advantage of this systems with TES. Based on the data, the efficiency of the system has been calculated and it is noted that the efficiency in the case of heat storage is higher than that of without TES, besides the efficiency in the case of the paraffin wax is slightly higher than that of the hytherm oil case.

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Keywords Thermal energy storage · Phase change material · Solar collector · Solar air heater

List of symbols

A	Projected area of collector tube exposed to the sun light (m^2)
C_p	Specific heat of air (J/kg K)
I_s	Intensity of solar radiation at any particular site (W/m^2)
$\dot{m}$	Mass flow rate of air (g/s)
Q_c	Energy incident on the collector tube (W)
Q_u	Useful energy gained from the collector
Q_f	Energy absorbed by air (W)
ΔT	Temperature difference (K)
T_{in}	Inlet temperature (K)
α	Absorptance of inner surface of evacuated tube collector
τ	Transmittance of the collector tube
η	Thermal efficiency of the collector system
η_{htm}	Thermal efficiency with hytherm oil
η_{pcm}	Thermal efficiency with phase change material
η_{wopcm}	Thermal efficiency without phase change material
T_{htm}	Temperature with hytherm oil
T_{pcm}	Temperature with phase change material
T_{wopcm}	Temperature without phase change material

Introduction

Solar air heaters provide a cost-effective solution for reducing energy consumptions for heating the fresh air and at times can supply useful amounts of heat to spaces that lack passive solar gains. In the interests of improving indoor air quality, fresh air quantities have been increasing, with associated increases in heating energy consumption in cold climates. Solar air heaters are simple devices to heat air by utilizing solar energy. Such heaters are implemented in many applications which require low to moderate temperature [1–4]. The main applications of a solar air heater are space heating and drying for industrial and agriculture purposes [2]. The disadvantages of solar air heaters are the need for handling large volume of air than liquids due to the low density of air and hence low thermal capacity of air. However, the efficiency of solar air heaters is low because of the low Prandtl number of air [4] and low heat transfer coefficient of air [5]. To improve the disadvantages of solar air heaters, a range of theoretical models has been introduced, important design parameters are identified and their appropriateness validated by experimental data [6, 7]. Several investigators have attempted to design more effective solar air heaters by changing the design, orientation and other characteristics of the solar air heaters [9–11]. Several studies have been completed on energy analysis of solar air heaters to define and improve the performance of these systems [8, 12–14].

Phase change materials (PCM) are “Latent” heat storage materials. The thermal energy transfer occurs when a material changes from solid to liquid or liquid to solid. This is called a change in state or “Phase.” Initially, these solid–liquid PCMs perform like conventional storage materials; their temperature rises as they absorb heat. Unlike conventional (sensible) storage materials, PCM absorbs and release heat at a nearly constant temperature. They store 5–14 times more heat per unit volume than those of the sensible storage materials, such as water, masonry and rock [15]. Enibe [16] worked on design, development and performance evaluation of a natural convection solar air heater with PCM-based energy storage. The daytime performance of the system without any load was tested under natural environmental conditions involving ambient temperature variations in the range 19–41 °C. The peak temperature rise of the heated air was about 15 °C, whilst peak cumulative useful efficiency was found to be about 50%. Zhou et al. [17] investigated numerically the performance of a hybrid heating system combined with thermal storage using shape-stabilized phase change material (SSPCM) plates. Considering direct gain passive-solar house in Beijing is which includes SSPCM plates as inner linings of walls and the ceiling. Additional heat supply is employed during load hours at late night and early morning or during the whole day if found to be necessary to keep the minimum indoor air temperature above 18 °C. The results indicated that the thermal storage with SSPCM plates improve the indoor thermal comfort level and saves about 47% of normal-and-peak-hour energy use and 12% of the total energy consumption during winter.

Alta et al. [18] investigated the energy and exergy efficiency of three different types of solar air heaters, two having fins and one without fins besides one heaters with fins has single glass cover whilst the other two have double glass cover. They found that the heaters with double glass covers and fins are more effective and the difference between the input and output air temperature is higher than that of the other. It is also found that the lower air flow rates will be beneficial in applications where higher temperature differences are more important. Akpinar et al. [19] investigated the performance analysis of a new flat-plate solar air heater (SAH) with several obstacles (Types I, II and III) and without obstacles (Type IV) on the basis of first and second law efficiency. Experiments were performed for two air mass flow rates of 0.0074 and 0.0052 kg/s. The values of first law efficiency varied between 20 and 82%. The values of second law efficiency changed from 8.32 to 44.00%. The highest efficiency were determined for the SAH with Type II absorbent plate in flow channel duct for all operating conditions, whereas the lowest values were obtained for the SAH without obstacles.

Sreekumar [20] developed and tested a roof-integrated solar air heater with a batch dryer. The performance of the dryer was analyzed in detail by three different methods namely, annualized cost, present worth of annual savings and present worth of cumulative savings. The cost of drying 1 kg pineapple found out to US$ 0.25 which is roughly half as compared to that of an electric dryer. The payback period worked out to 0.54 year, much lesser than the estimated life of the system (20 years). Ozgen et al. [12] studied a device by inserting an absorbing plate of aluminium cans into the double-pass channel in different types of flat-plate solar air heater at different mass flow rates. In the first type, cans have been staggered as zigzag on absorber plate, and in second type they were arranged in order whilst in third type is flat plate without cans. Experiments were performed for two different mass flow rates of 0.03 and 0.05 kg/s. The highest efficiency had been obtained for Type I at 0.05 kg/s. Omojaro and Aldabbagh [21] studied thermal performance of a single and double-pass solar air heater with fins using a steel wire mesh as absorber plate, and found that the efficiency increases with increasing the mass flow rate of air. For the same flow rate, the efficiency of the double-pass system is found to be significantly higher than that of a single pass viz. 7–19.4%.

In this experimental study, the performance of evacuated tube collector (ETC)-based solar air heater with and without thermal energy storage (TES) has been carried out in detail. Three different types of arrangements have been evaluated viz. with paraffin wax, with hytherm oil and without TES. It is found that the outlet temperature increases as the time increase, attains its peak and then decreases. The same pattern has also been found for solar radiation with respect to time during the experiment. The outlet temperature in case without TES also exhibits the same pattern but the peak is lower than those of with TES and also optimum temperature in all three cases increases as mass flow rate increases.

Experimental set-up and procedure

In this experimental study, the solar air heater with and without TES made of an ETC have been investigated. Total 12 number of ETC tubes, 4 filled with PCM, 4 filled with hytherm oil and remaining 4 without TES have been arranged in the series. The copper tubes of 12 mm in diameter have been inserted inside the evacuated tubes using U bends for air circulation. The specifications of the ETC are given in Table 1. The cross-sectional view of a double-walled evacuated glass tubes along with temporary heat energy storage and the schematic of the experimental set-up have been shown in Fig. 1a and b, respectively. Forced air flow is used as a working fluid in the system and PCM/hytherm oil as a heat storage material/fluid so that this stored heat can be used for drying when solar radiation is not available and/or suddenly fluctuates due to any reason in the day time and/or late evening hours. There are four vacuum tubes in each arrangement and a black absorbing coating is done on the outer surface of the inner tube. The tubes are made of glass and the specification is given in Table 1, whilst the length exposed to sunlight is 172 cm and inclined at 45°. There is a vacuum between the annular spaces of double-walled glass tubes to reduce the heat loss by conduction and convection. Out of three arrangements mentioned above, in one arrangement Paraffin wax as a PCM is filled inside ETC tubes and outside copper tube whilst in the second arrangement ETC tubes are filled with hytherm oil, in a way that these temporary heat energy storage materials are coated around the copper tube. Differential scanning calorimeter (DSC) graph of used PCM in this study is shown in Fig. 2. On the other hand, there is no temporary heat storage material in the third arrangement. The heat stored in the TES material is transferred to the copper tube and finally to the blowing air inside it. It also overcomes the sudden drop in the outlet temperature of the hot air, due to fluctuations in the solar radiation throughout the day. Besides, these TES materials (PCM and hytherm oil) also supply heat to the moving air during low insolation and in the late evening hours. The asbestos cloth is used to cover the copper tubes exposed into the open air viz. outside the ETC tubes for insulation purpose to reduce/minimize the heat loss to the ambient air. Calibrated J-type thermocouples made of Copper-Constantine with temperature range −200 to 1350 °C were used to measure air temperature at different state points. Total 13 sensors have been used to get the temperatures at different states of point. In this arrangement, one thermocouple has been used for measuring the input air temperature and other four were used for measuring the outlet temperature of air at different state points. The outlet air temperature of the first tube is the inlet of the second tube and the outlet of the second tube is inlet to the third tube and so on. In this arrangement where TES is used, one thermocouple has been inserted inside the collector tube for measuring the temperature of storage material, besides, the same number of thermocouples have been used at different state points mentioned above. To measure air flow rate, a rotameter of 200 LPM capacity is used, which has been placed between the compressor and inlet of ETC (Fig. 1b). Air was forced circulated through the system using half HP air compressor. For measuring solar radiation, pyranometer with multiplication factor 8.52×10^{-6} V/(W/m^2) has been used in the experiment. The pyranometer is kept on the horizontal surface nearby

Table 1 Details about the solar air heater collector and storage materials

Specification of collector tubes	Values
Total length	179.5 cm
Inner length	176 cm
Coating length	172 cm
Inner diameter	44 mm
Outer diameter	57.5 mm
Properties of the paraffin wax as a PCM	
Melting point	53.04 °C[a]
Specific heat	2.05 kJ/kg °C
Latent heat of fusion	183.1 kJ/kg[a]
Thermal conductivity	0.21 (solid) (W/m K)
Density at 70 °C	0.769 kg/m^3
Properties of HP hytherm 500 oil	
Kinematic viscosity @ 40 °C, cst	27–35
Flash point coc, °C, min	194
Viscosity index	95
Power point c max	0.0
Copper strip corrosion 3 h @ 100 °C (astm), max	1.0
Neutralisation number mg koh/g, max	0.15
260 °C	0.731
280 °C	0.751
300 °C	0.772
260 °C	0.097
280 °C	0.096
300 °C	0.095

[a] Measured by DSC

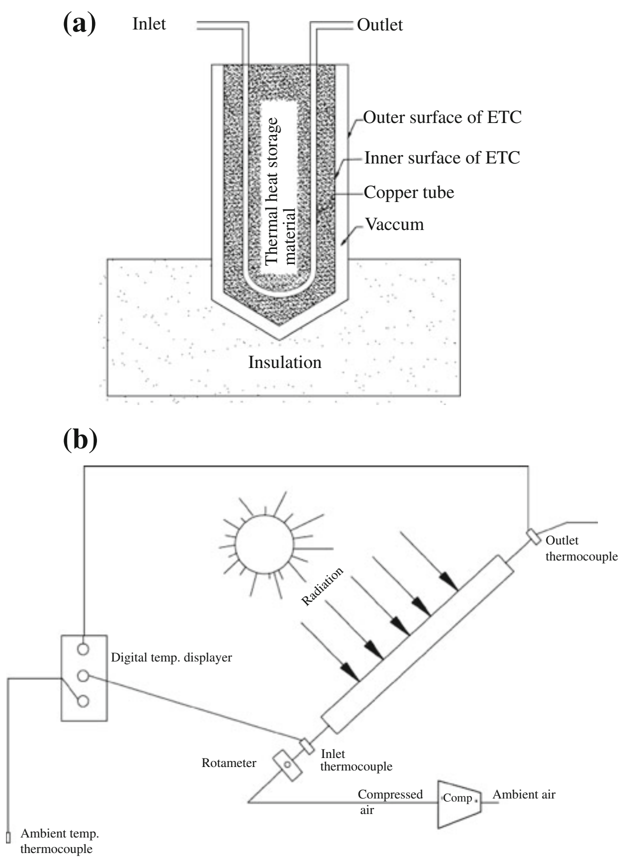

Fig. 1 **a** Cross-sectional view of ETC tube with TES, **b** schematic of the experimental set-up

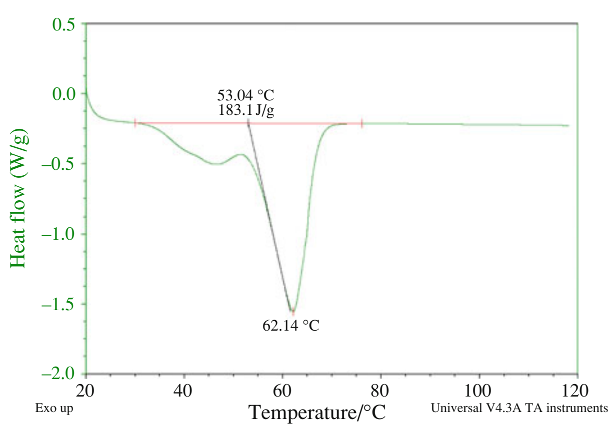

Fig. 2 DSC graph of the PCM used in study

the experimental set-up in the open air, so that no shadow and/or reflection of solar radiation from any other surface/object falls on it. For collection of data, HP data acquisition unit attached with a computer has been used in this study. The volume flow rate of the circulating fluid is measured by volume flow meter before it enters the first tube. Whenever fluid enter in the first tube its temperature rises, which can be identified by measuring temperature with the help of thermocouple provided at inlet and outlet of each tube. Volume flow rate of the fluid in the system is specified and the schematic description is shown in Fig. 1b. Data was collected from the system for few days in different months by varying the volume flow rate of air and has been evaluated to find out the efficiency of solar air heater with and without TES.

Analysis

Energy analysis is necessary part of any system to get the real performance of the particular system. The energy analysis is based on the first law of thermodynamics and the corresponding thermal efficiency has been calculated based on the recorded data. The energy analysis is based on the fact that it is an upper limit of efficiency with which the solar radiation can be converted into heat and the heat can be used for different applications at a given frequency spectrum and intensity. Energy incident on the collector is given by:

$$Q_c = AI_s,$$

where Q_c (W) is the energy incident on the collector tube, A (m^2) is the projected area of collector tube exposed to the sun light and I_s (W/m^2) is the intensity of solar radiation at any particular site. Useful energy gained from the collector can be written as:

$$Q_u = \alpha\tau I_s A,$$

where α is the absorptance of inner surface of ETC and τ is the transmittance of outer surface of the collector. The useful energy transmitted into the evacuated tubes is absorbed by moving fluid and can be calculated by the following equation:

$$Q_f = \dot{m} C_p \Delta T,$$

where Q_f (W) is the energy absorbed by air, C_p (kJ/kg K) the specific heat of air and ΔT (K) is the temperature difference and $\dot{m}$ (kg/s) is the mass flow rate of moving fluid viz. air. The thermal efficiency of the collector system is defined as the ratio of useful energy transferred by fluid to that of energy incident on the collector i.e., the ratio of useful energy gained by the working fluid to the energy incident on the collector and is given by:

$$\eta = Q_f/Q_c = \dot{m}C_p\Delta T/AI_s,$$

where η is the abbreviation used for thermal efficiency of the system

Results and discussion

The performance of an ETC-based solar air heater with and without TES has been evaluated for three different configurations. Three different arrangements viz. solar air heater without TES, with PCM and with hytherm has been taken for performance evaluation of solar air heater. The inlet, outlet temperatures and solar radiation with respect to time for different mass flow rates (i.e., 10, 20, 30, 40 and 50 LPM) with and without TES recorded and the performance has been illustrated in Figs. 3, 4, 5, 6, and 7. It is noted that in case of without TES, the outlet temperature increases as time increases attains its peak at nearly about 13:00, 14:20, 12:00, 13:40 and 13:00 h for different mass flow rates viz. 10, 20, 30, 40 and 50 LPM, respectively, and then decreases gradually after 16:30 h. The similar trend has been observed for solar radiation but with fluctuations throughout the daytime.

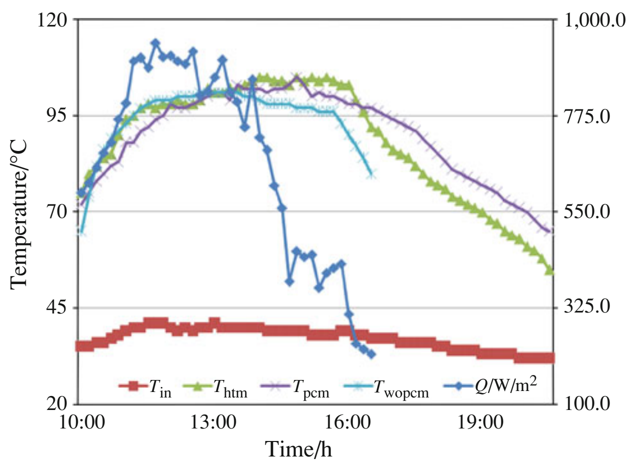

Fig. 3 Time versus inlet, outlet temperatures and solar radiation for 10 LPM

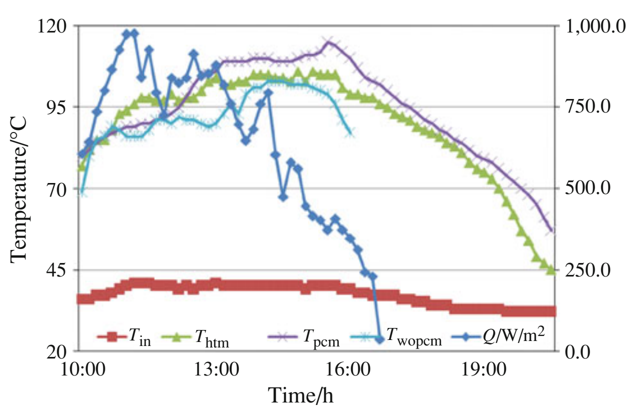

Fig. 4 Time versus inlet, outlet temperatures and solar radiation for 20 LPM

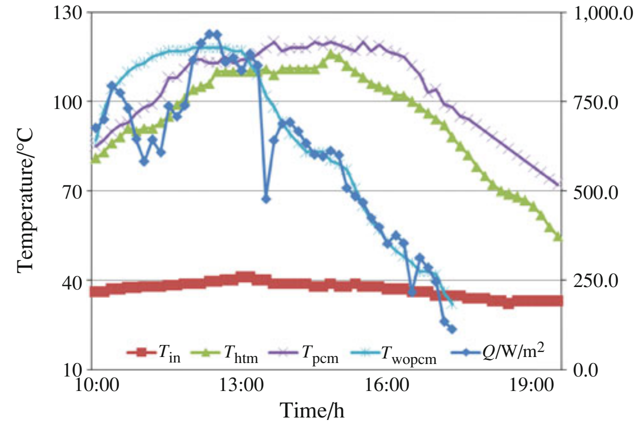

Fig. 5 Time versus inlet, outlet temperatures and solar radiation for 30 LPM

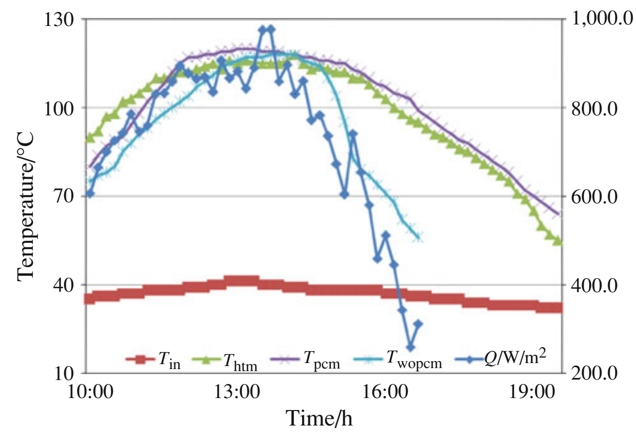

Fig. 6 Time versus inlet, outlet temperatures and solar radiation for 40 LPM

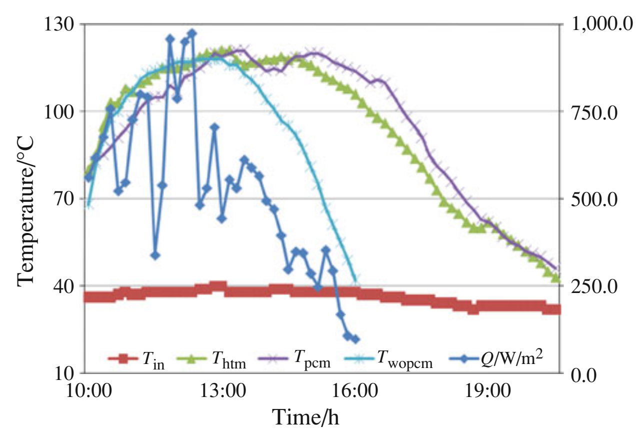

Fig. 7 Time versus inlet, outlet temperatures and solar radiation for 50 LPM

In arrangements with TES, the outlet temperature increases as time increases attains its peak at 14:50, 15:40, 14:30, 13:30 and 13:30 h for different mass flow rates viz.

10, 20, 30, 40 and 50 LPM, respectively, and decreases afterwards slowly. But as heat is stored in the PCM during the day time it is also supplied to the working fluid during low insolation and/or in the absence of solar radiation, generally after 16:30 h during winter time. The heat released by TES to the working fluid is nearly up to 20:30 h, which gives back up of approximately 4 h every day. As can be seen from Table 1, temperatures is good enough even after 16:30 h, it is very useful for many low and medium temperature heating applications. This shows the usefulness of thermal energy systems for such devices. Also, as the mass flow rate increases, the optimum temperatures also increases in all the three cases as can be seen from Figs. 3, 4, 5, 6 and 7. It is also found that the optimum outlet temperature of the working fluid at different mass flow rates is slightly higher in the case of PCM than those of with hytherm oil, but, in general the optimum outlet temperature with TES is better than those of without TES.

Figures 8, 9, 10, 11 and 12 illustrates the thermal efficiency and solar radiation with respect to time for different mass flow rates of the working fluid with and without TES as mentioned above. It is noted that the efficiency in all the three cases with and without TES increases as the time increases with some fluctuations attains their peaks and decrease slowly towards evening time without TES as can be seen from Fig. 8. On the other hand, the thermal efficiency in the case of TES systems (viz. PCM and hytherm oil) attains their first peak nearly mid of the day and the second peak towards evening time when solar radiation falls sharply and the major heat is supplied by the storage system. However, during the first half the instantaneous efficiency of the latter cases is lower than the former case (without TES) because the major part of the energy supplied by solar radiation is observed by the TES material (PCM and hytherm oil), yet the overall efficiency in the latter cases is significantly higher than that of the former case (without TES). Besides, the thermal energy system supply heat for the late evening hours for useful applications and hence, is quite beneficial for many application including heating and space conditioning applications. Because of the intermittent nature of the solar radiation, the TES enhances not only the efficiency but also prolongs/extends the duration of the availability of hot air for useful purposes. From Figs. 8, 9, 10, 11 and 12, it is clear that the higher peak with TES occurs at around 16:30 h, which is due to the fact that solar radiation goes down sharply at that time, whilst circulating air gets heated by temporary storage material at almost constant temperature for some time as explained earlier. As a result, the output to input ratio with TES increases sharply and hence, the efficiency attains its peak during low solar radiation. Thus, the TES not only supply energy with less fluctuation but also shift the peak towards evening hours and hence, increases the usefulness of the solar air heater system in the evening time.

As the TES has finite heat capacity and limited mass due to available space in evacuated tubes, the instantaneous

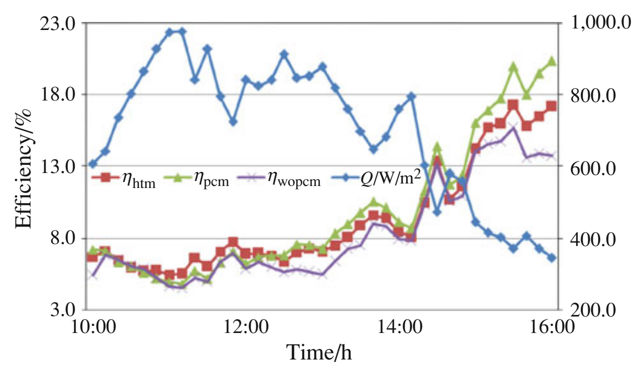

Fig. 9 Time versus solar radiation and thermal efficiency for 20 LPM

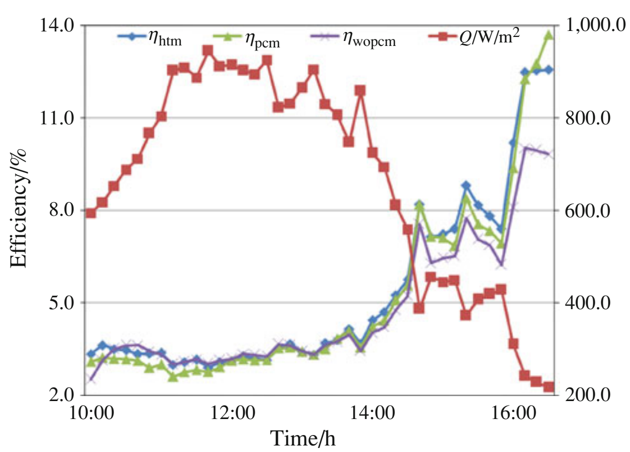

Fig. 8 Time versus solar radiation and thermal efficiency for 10 LPM

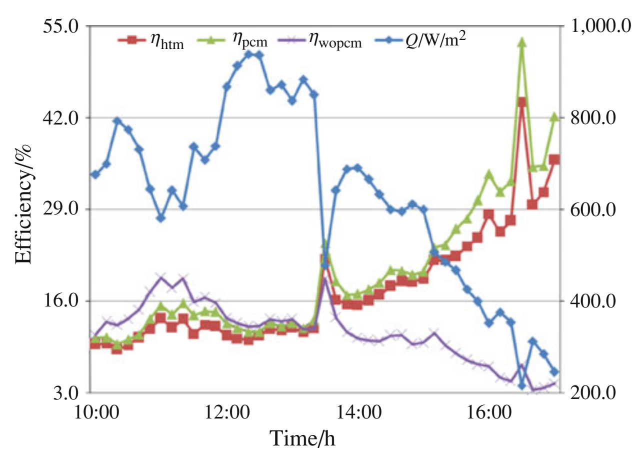

Fig. 10 Time versus solar radiation and thermal efficiency for 30 LPM

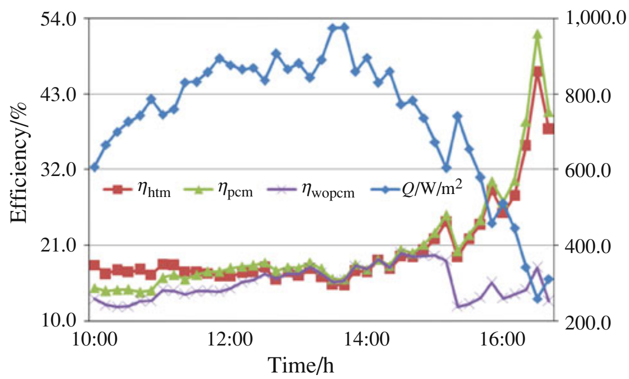

Fig. 11 Time versus solar radiation and thermal efficiency for 40 LPM

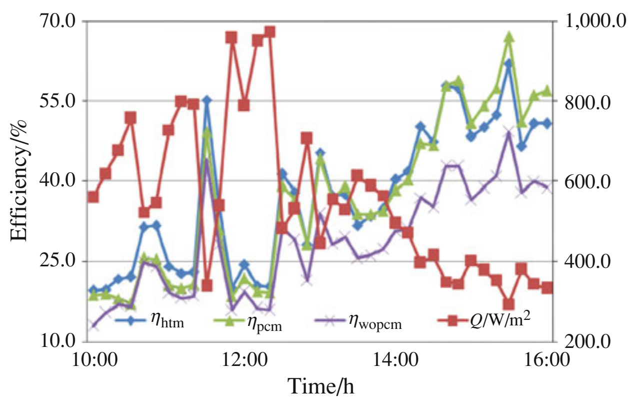

Fig. 12 Time versus solar radiation and thermal efficiency for 50 LPM

fluctuation is compensated by the storage material which supplies heat at almost constant temperature. However, if the solar radiation fluctuates more often and/or for longer time due to weather constraint, the fluctuations are also found in the outlet air temperature and the thermal efficiency of the system. But in the case of without TES, the fluctuation in both the efficiency and the outlet temperature are found to be more frequent and significant. It is also noted from Figs. 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12 that, as the mass flow rate of the working fluid increases, the thermal efficiency and the outlet temperatures in all the three arrangements increases which is due to the fact that heat gain by the moving fluid in the ETC also increases. Efficiency of solar air heater using paraffin wax is slightly better than that of with hytherm oil, but, in general the efficiency with TES is observed to be much better than that of without TES.

Conclusions

The performance evaluation of an ETC solar air heater with and without TES has been carried out at different mass flow rates using hourly solar radiation. This experimental study can be concluded as follows:

- The optimal outlet temperatures in the case of with TES are found to be higher than those without TES. Also in general, the optimal outlet temperature of arrangement with paraffin wax is found to be higher than those of with hytherm oil for all the mass flow rates with TES.
- As mass flow rate increases, the optimum outlet temperatures as well as the thermal efficiency in all the three cases, mentioned above, increases which can be explained in terms of higher energy gain and lesser heat loss.
- From the study, it is found that the thermal efficiency fluctuates throughout the day as can be seen from the graphs shown in the article, which is obviously due to the fact that the solar radiation also fluctuates over the period of time. Also as time increases, the thermal efficiency as well as the outlet temperature first increases attains their peaks at nearly about mid day and then decreases in the case of without TES, which is found to be the same is found for the solar radiation. However, in cases with TES, the thermal efficiency and the outlet air temperature increases with time, attain their peaks at nearly about 16:30 h with a small fluctuation and then decreases smoothly for all the mass flow rates. This is due to the fact that the solar radiation sharply decreases in the late afternoon and heat is supplied only by TES for some time. But due to the limited mass and capacity of the storage material, this supply also decreases slowly after a certain time.
- As the mass flow rate increases, efficiency increases peak of efficiency slightly shifts towards origin in case without TES. However, in case with TES, there is a small shift in the peak due to different mass flow rate of the working fluid.

Acknowledgements One of the authors (V.V. Tyagi) highly acknowledge the financial assistance in the form of Research Associateship due to CSIR, New Delhi, India.

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