

***Mechanical and Energy Engineering***

**Experimental Study on Double-Pass Solar Air Heater with and without using Phase Change Material**

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**ABSTRACT**

In this paper, an experimental study was conducted to enhance the thermal performance of a double-pass solar air heater (SAH) using phase change material (PCM) for thermal storage at climatic conditions of Baghdad city - Iraq. The double-pass solar air heater integrated with thermal storage system was manufactured and tested to ensure that the air heating reserved after the absence of the sun. The rectangular cavity filled with paraffin wax was used as a latent heat storage and incorporated into the lower channel of solar air heater. Experiments were carried out to evaluate the charging and discharging characteristics of two similar designed solar air collectors with and without using phase change material at a constant air mass flow rate of (0.0375 kg/sec). The parameters that affect the thermal performance of the SAH with and without the PCMs presented by solar radiation, the difference in air temperature, outlet air temperature, instantaneous thermal efficiency, and daily efficiency are evaluated. The experimental results show that when using the PCM, the temperature of the outlet air was enhanced and increased over the ambient temperature by (1.5 - 6.5 °C) after sunset for 5 hours period. It was found that the instantaneous thermal efficiency of the heater using thermal storage exceeds 100% after sunset, this is due to a large amount of heat stored in the paraffin wax that has been released during the discharge process. Also, it was found that the daily efficiency of the double pass SAH integrated with and without thermal energy storage unit was (56, 47%) respectively.

**Key Words:** double-pass solar air heater (SAH), latent heat storage, phase change material, paraffin wax.

**دراسة تجريبية لسخان الهواء الشمسي ثنائي المجرى في حالة استخدام و عدم استخدام المادة المتغيرة الطور**

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**الخلاصة**

في هذا البحث تم اجراء دراسة تجريبية لتعزيز الاداء الحراري لسخان الهواء الشمسي ثنائي المجرى بأستخدام مادة متغيرة الطور للخن الحراري في ظل الظروف المناخية لمدينة بغداد - العراق. تم تصنيع واختبار سخان هواء شمسي ثنائي المجرى متكامل مع نظام تخزين حراري لضمان تسخين الهواء بعد غياب الشمس. تم استخدام تجويف مستطيل مملوء بشمع البارافين كخازن حرارة

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كامن ودمجها في القناة السفلية لسخان الهواء بالطاقة الشمسية. وأجريت التجارب لتقييم خصائص الشحن والتفريغ لمجموعتين متشابهتين لمجمع الهواء بالطاقة الشمسية مع وبدون المادة المتغيرة الطور عند معدل تدفق كتلة ثابت للهواء (0.0375 كغم / ثانية). تم تقييم المعلمات التي تؤثر على الأداء الحراري من سخان الهواء بالطاقة الشمسية مع وبدون المادة المتغيرة الطور والتي تتمثل ب: الإشعاع الشمسي، والفرق في درجة حرارة الهواء، ودرجة حرارة الهواء الخارجة، والكفاءة الحرارية اللحظية والكفاءة اليومية. وأظهرت النتائج التجريبية أنه عند استخدام المادة المتغيرة الطور تم تعزيز درجة حرارة الهواء الخارجة وزادت على درجة الحرارة المحيطة بمقدار (1.5 - 6.5 درجة سيليزية) بعد غروب الشمس لمدة 5 ساعات. وقد وجد أن الكفاءة الحرارية اللحظية للسخان مع استخدام التخزين الحراري تتجاوز 100%. بعد غروب الشمس، ويرجع إلى أن كمية كبيرة من الحرارة المخزنة في شمع البارافين تم الإفراج عنها أثناء عملية التفريغ. أيضا، وجد أن الكفاءة اليومية لسخان الهواء الشمسي ثنائي المجرى مع وبدون وحدة تخزين الطاقة الحرارية كانت (56%، 47%) على التوالي.

**الكلمات الرئيسية :** سخان الهواء الشمسي ثنائي المجرى، تخزين الحرارة الكامنة، المادة المتغيرة الطور، شمع البارافين.

## 1. INTRODUCTION

Solar energy is considered to be one of the renewable energy sources and most commonly used today, where the benefits from the sun sources (heat and light) are through converting them into electrical energy as well as in various thermal applications. Solar air heaters (SAHs) have an important role in the application of the solar thermal energy techniques. They can be widely used in many major applications like drying of agricultural products and heating in buildings with hot air in the winter. The SAH can be simply designed and constructed with low costs. The SAH absorbs the solar energy by the black absorbent surface and converts it into thermal energy and then takes advantage of this energy and transfers it to the heat transfer medium. Using the solar energy in applications such as heating or drying process continuously may face a big problem after the absence of solar radiation. So, it has been proposed to use the storage system for energy by phase change materials (PCM) to meet the energy needs during the night hours. Thermal energy can be stored in different forms such as sensible heat storage, latent heat storage, and chemical energy storage when the latent heat storage of fusion by using phase-changing materials plays an important role for this purpose. These materials store the heat energy received from the sun rays during daylight hours the and then re-used it after sunset under a constant temperature with high storage density.

In the past years, many types of research have been conducted on the SAHs and integrated it with a packed bed and energy storage systems in order to improve their thermal performance. **Yeh, et al., 1999**, used a double-pass solar air heater to increase the heat transfer area and thus improve thermal performance. It was found that increasing the thermal energy causes improvement in the thermal performance for the SAHs. **Enibe, 2003**, constructed and studied a natural convection solar air heater using paraffin wax as an energy storage material under natural environmental conditions which had ambient temperature changes in the range 19 - 41°C and daily global irradiation in the range 4.9 - 19.92 MJ/m<sup>2</sup>. When the maximum air flow rate is 0.01 kg/sec., it was found that the peak temperature rise for the heated air was about 15°C and the peak cumulative useful efficiency reached about 50%. The results show that this system can be successfully used for drying agricultural crops. **Mettawee, and Assassa, 2006**, conducted an experimental investigation of the SAH by using paraffin wax as a latent heat storage material. It was found that when the thickness of the PCM layer increases below the absorber plate, this will lead to increase the convective heat transfer coefficient and discharging time. **El-Sebaili, et al., 2007** carried out an investigation of a double flow SAH with and without a packed bed. It was found that the efficiency of the SAH with the packed bed was 22-27 % higher compared with those without a packed bed. **Alkilani, et al.,**



2009 performed an experiment on a SAH with using paraffin wax as a PCM and 0.5 % aluminum powder. It was found that the freezing time of the PCM is inversely proportional to the air mass flow rate and reached about 8 hr at 0.05 kg/sec. **Aldabbagh, et al., 2010** made an investigation and comparison study between the single and double pass SAHs with wire mesh as packed bed. The efficiency of the double pass SAH was found to be (83.65%), while it was (45.93 %) for single pass SAH. **Dhiman, et al., 2011** conducted an experimental study on the double-pass solar air heater using packing material on the upper channel. An analytically model had been developed to describe the different temperatures and heat transfer characteristics of a parallel flow packed bed for SAH in order to study the effects of the mass flow rate of the air and different porosities of packed bed material on their thermal performance. It was found that the thermal efficiency of parallel flow packed bed for the SAH was 10-20 % higher than the double pass SAH without packing materials. **Hosseini, et al., 2012** conducted an experimental investigation to evaluate the behavior of melting of the PCM in the horizontal shell and tube heat storage. They found that the region that exists in the uppermost section was of high temperatures, this is because of the buoyancy effects. They claimed that the total time for melting reduced to 37% when the temperature increased from 70 to 80 °C. **Krishnananth, and Murugavel, 2013**, carried out experiments to evaluate the thermal performance on the double-pass SAH with and without thermal energy storage for different configurations. Paraffin wax with aluminum capsules had been used as the phase change energy storage material. The results show that the SAH with the use of paraffin wax as a phase change energy storage material delivers high air temperature throughout the day. Also, it was found that the efficiency was higher through the evening hours. It is concluded that the double-pass SAH when the paraffin capsules were placed on the absorber plate is the efficient one. **Shalaby and Bek, 2014** experimentally performed an investigation on the thermal performance of the solar dryer with and without the PCM. After using the PCM, they found that the drying air temperature was higher than ambient temperature by 2.5 - 7.5 °C after sunset for seven hours. Also, they found that the solar heater with the PCM provides the drying air with a temperature of around 3.5 - 6.5 °C after 02:00 P.M. which is higher than those without the PCM. **El Khadraoui, et al., 2016** conducted a comparative experiment to evaluate the performance of the SAH with and without using the PCM. The results showed that the PCM cavity increases the temperature of outlet air of the SAH using the PCM by differences between 3 °C and 7 °C compared with those of without using the PCM during the night. **Kabeel, et al., 2016**, investigated experimental tests on flat and v-corrugated plate solar air heaters combined with a built-in PCM (heat storage material). The air heater had been integrated with paraffin wax as a PCM. Some performance parameters of the heaters were presented with and without PCM at different values of mass flow rates. The experimental results showed that the outlet temperature of the v-corrugated plate heater with the use of the PCM was more than the ambient temperature by 1.5–7.2 °C through 3.5 hr after sunset when comparing with 1–5.5 °C through 2.5 hr for flat plate heater with 0.062 kg/s mass flow rate. Also, it was seen that the daily thermal efficiency of the v-corrugated air heater with PCM was 12% more than without PCM. The efficiency was also 15% and 21.3% more than the equivalent values as the flat plate was utilized with and without PCM at 0.062 kg/s mass flow rate, respectively.

Most of the previous researches had focused on the research possibility in enhancing the performance of the solar air heater by using thermal energy storage. In the present study, the performance of a double pass solar air heater with integrated storage unit is evaluated. The rectangular cavity filled with paraffin wax is used as a phase change energy storage material.



Charging and discharging experiments had been conducted and the performance results obtained in the solar air heater with PCM and a conventional plate solar air heater without PCM are compared under the same climatic conditions in Baghdad city, Iraq on October 2017.

## 2. EXPERIMENTAL SETUP

In this work, two double pass solar air heaters have been manufactured from mild steel plate of 1 mm thickness, and these two heaters which work as a conventional forced air by a cross-flow cooling fan, as shown in **Figs. 1a, 1b and 2**. The figures show a schematic diagram of a solar air heater with, without using the PCM and a photographic image for the two SAHs (with and without PCM), respectively. The dimensions of the first heater SAH without using PCM were (1.5 m x 0.9 m x 0.2 m). It consists of an absorber plate made from mild steel plate with dimensions (1.3 m x 0.8 m x 0.001 m) and placed between the upper and bottom channels. The height of each channel was (7.5 cm). The upper channel was placed between the transparent glass cover and the absorber plate, while the bottom channel was placed between the absorber plate and the thermal insulator which be down the collector. To increase the absorbed heat from the sun rays, the absorber plate was coated with a black layer to configure an absorbent surface and to convert solar radiation to thermal energy. As well as, an insulator of polyurethane with a thickness of (5 cm) was placed in the bottom and on lateral sides of the solar collector to reduce heat losses to the atmosphere. As for the upper side of the heater, it has been covered with a normal commercial transparent glass with a thickness of (4 mm) to reduce the loss of heat from the upper side of the heater and to ensure the permeability of solar radiation to the absorber plate. A cross-flow cooling fan (12V, 4.8W, 0.057 m<sup>3</sup>/s, and 2200 rpm) was used and installed into the air collector inlet to deliver the air into the collector through the upper channel. The air will rotate back in the opposite direction through the bottom channel. The gate valve can be used to maintain the air flow rate constant.

To improve the performance of the system, a second heater was used with paraffin wax as a phase change material (PCM) to store the excess thermal energy. The second heater, SAH using PCM has dimensions of (1.5 m x 0.9 m x 0.26 m) and consists of transparent glass, insulator and has the same existing properties in the first heater, but here the absorber plate was replaced with a closed cavity with dimensions (1.3 m x 0.8 m x 0.06 m). This cavity was placed at an equal distance of (7.5 cm) between the transparent glass and the back insulator. The upper surface of the cavity was coated with a black layer to increase the absorbed heat from the sun rays. **Fig.3** shows a section view of the solar air heater with PCM channel. The cavity had been filled with paraffin wax by pouring (60 kg) from molten paraffin wax through a channel at the top of the cavity to make sure that the paraffin surface is adjacent with the absorber plate. The paraffin wax has been used as a phase change material to store heat energy for several reasons: cheap and available, chemically stable and has high-density storage compared with some other materials. **Table 1** shows the thermo-physical properties of the paraffin wax.

Thermocouple (k-type) sensors were used and placed in different locations of the heater system and connected to a digital data logger in order to measure the inlet and outlet temperatures, glass temperature, upper and bottom absorber plate temperature and PCM temperature. To measure the intensity of solar radiation, a solar meter has been used. The two heaters (with and SAH without using PCM) were tilted towards the south at an angle of 38° with the horizontal level.

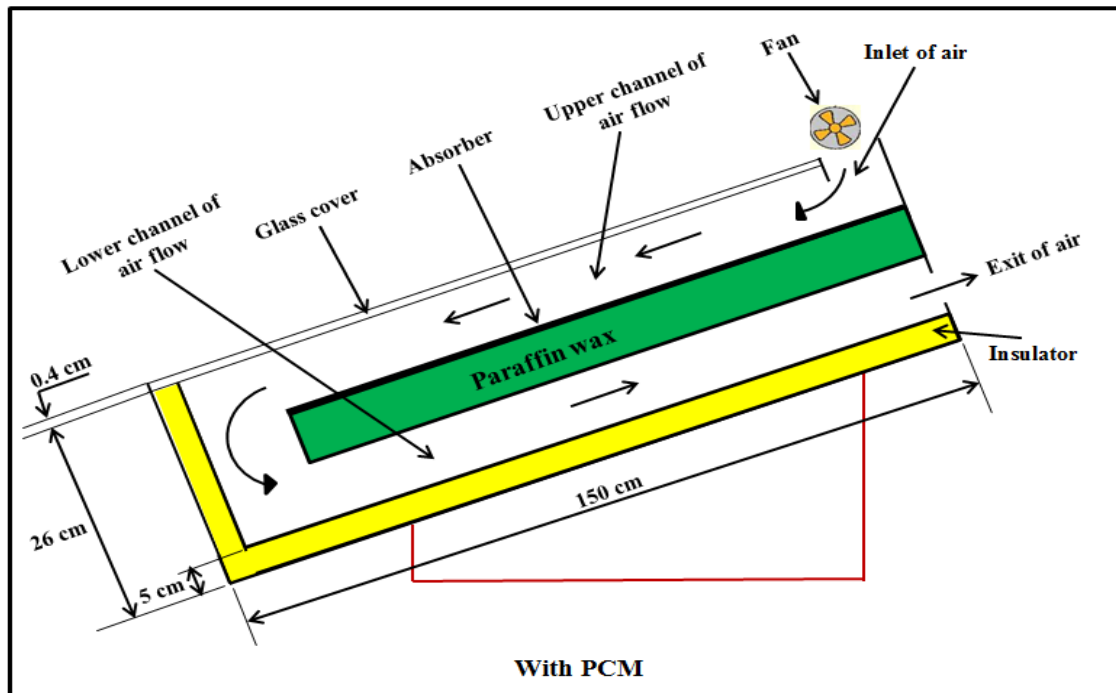


Figure 1a. A schematic diagram of the double pass solar air heater using the PCM.

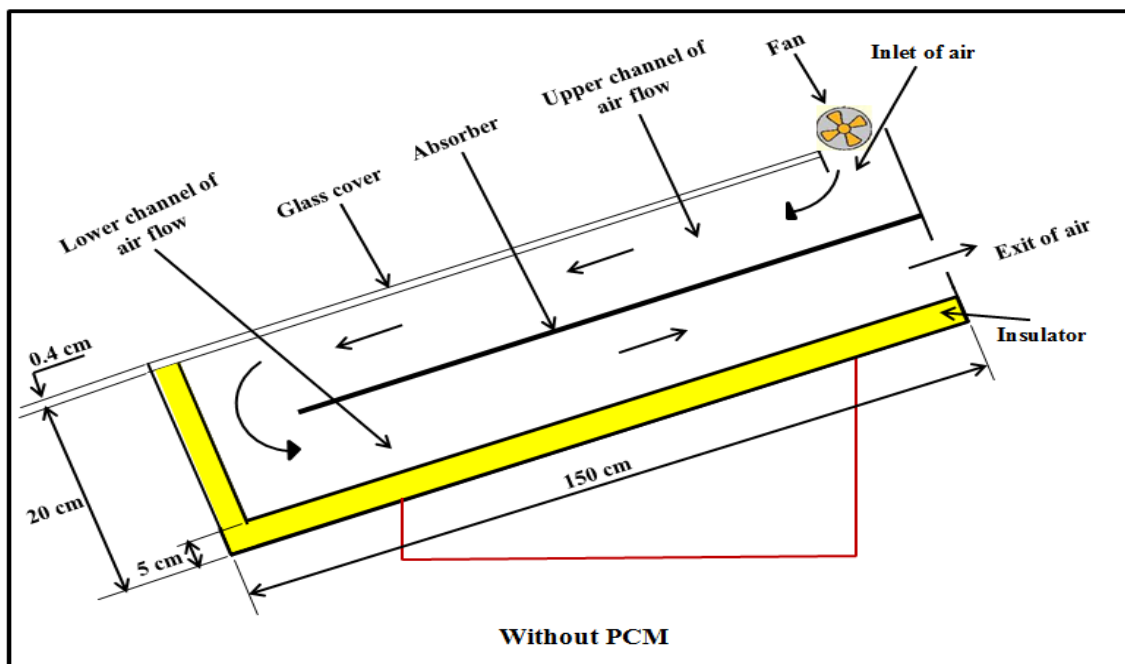


Figure 1b. A schematic diagram of the double pass solar air heater without using the PCM.





Figure 2. A photographic image of the double pass solar air heaters (with and without using PCM).

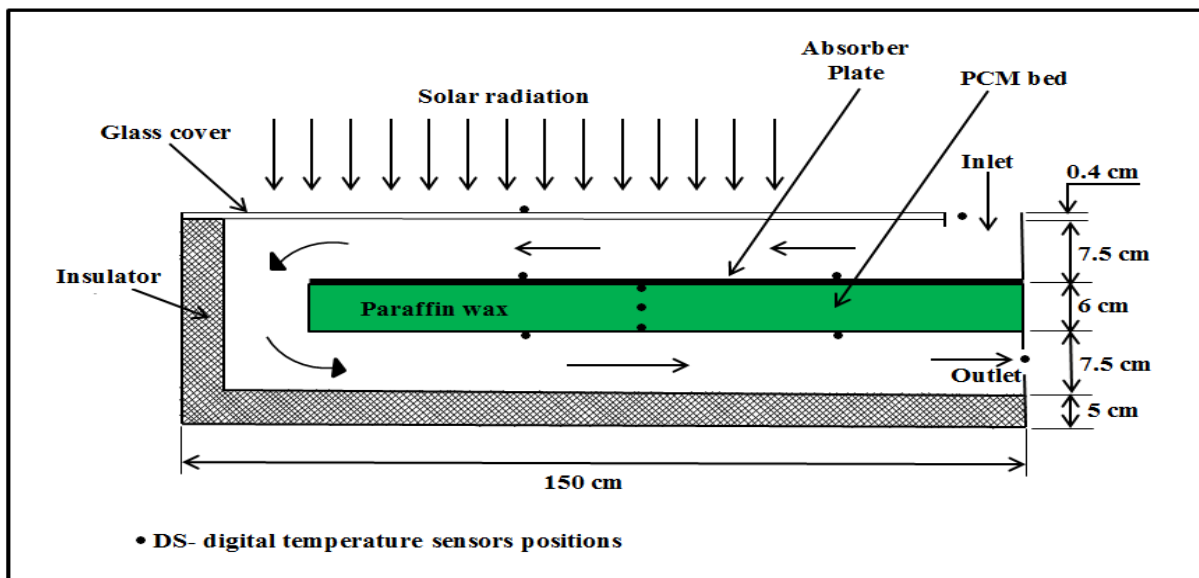


Figure 3. Section view of the double pass SAH with PCM channel.

**Table 1.** Thermo physical properties of paraffin wax, **Zalba, et al., 2003.**

Property	Value
Melting temperature	54 °C
Thermal conductivity (solid)	0.23 W/m.°C
Thermal conductivity (liquid)	0.21 W/m.°C
Latent heat of fusion	190 kJ/kg
Specific heat (solid)	2.0 kJ/kg. °C
Specific heat (liquid)	2.15 kJ/kg. °C
Solid density	876 kg/m <sup>3</sup>
Liquid density	795 kg/m <sup>3</sup>

### 3. EXPERIMENTAL PROCEDURE

Charging and discharging experiments were conducted to evaluate the performance of two types of solar air heaters with and without using PCM. Before starting the experiments, it should be sure that there is no leakage in all links and joints of the SAH and the paraffin wax cavity. Also, make sure that the thermocouples are placed in the proper places and all devices are working properly. The tests were conducted in Baghdad city, Iraq (Latitude 33.333° and longitude 44.433°) in the days with a clear sky on the 21<sup>st</sup> of Oct. 2017.

Charging and discharging experiments had been conducted for the solar air heater with PCM starting from sunrise around 7:00 AM until sunset at about the 5:00 PM. After decreasing the solar radiation, i.e. when the paraffin wax temperature becomes higher than the absorber surface temperature, the charging process will be ended with staying the discharging process continuous. This is because of the thermal energy stored in the PCM as well as the heat transfer from the wax to the absorber surface and then to the air directly. The discharge process time has been obtained until 10:00 P.M., approximately, for 5 hr after sunset.

The intensity of solar radiation was measured by using a Lutron (SPM - 1116SD) solar meter device. A cross-flow cooling fan was used to deliver the air inside the heater. Its airspeed was measured by using wind speed (Anemometer). The air exit speed was measured in six locations of the exit air throat of the heater to obtain the average value of airspeed. The average speed could be used in determining the air density and cross section area of the exit air throat and the air mass flow rate.

The PCM temperature was measured by using three thermocouples (k-type) sensors to obtain the average temperature of the PCM placed inside the PCM cavity as shown in **Fig.2** The upper and bottom absorber plate temperature was measured by using two temperature sensors (k-type). Another sensor was placed on the glass to measure the glass temperature for the SAH with and without using the PCM. All (Thermocouple) sensors are connected with a digital data logger type (Lutron TM - 903A) to measure the temperature every 60 minutes. The ambient, inlet and outlet air temperatures of the solar air heater with and without the PCM were measured by using three temperature sensors and read through a digital data logger type (Lutron HT – 3007 SD). All the accuracies of measuring instruments are listed in **Table 2**.



All readings were recorded every one hour (60 min), except the readings during the phase change period (12:00 to 02:00 P.M.), was taken every half hour (30 min.).

**Table 2.** The accuracies of measuring instruments.

Instrument	Accuracy	Range
(SPM – 1116 SD) Solar irradiation meter	± 5 %	0 to 2000 W/m <sup>2</sup>
Lutron (TM – 903 A), 4 channels temperature data logger	± (0.5 % + 1 °C)	- 100 °C to 1300 °C
Lutron (HT – 3007 SD), temperature data logger	± (0.4 % + 0.5 °C)	- 50 °C to 1300 °C
K – type thermocouple	± 0.4 %	- 100 °C to 1100 °C
Air flow meter	1 %	0.2 to 40 m/sec

#### 4. EVALUATION OF THERMAL PERFORMANCE

In this section, the governing equations of performance parameters of the SAH are evaluated by the following equations:

##### 4.1 Useful Heat Energy (Q<sub>u</sub>):

Eq. (1) was used to calculate the useful heat energy (Q<sub>u</sub>) for the air passing through the heater:

$$Q_u = \dot{m}_{air} C_{p_{air}} \Delta T_{air} = \dot{m}_{air} C_{p_{air}} (T_{out} - T_{in}) \tag{1}$$

Where:

- $\dot{m}_{air}$  is the mass flow rate of air across the heater in (kg/sec).
- $C_{p_{air}}$  is the specific heat of air in (kJ/kg. °C).
- $\Delta T_{air}$  is the difference of air temperature across the heater in (C °).
- $T_{out}$  is the outlet air temperature (°C).
- $T_{in}$  is the inlet air temperature (°C).

##### 4.2 Mass Flow Rate (ṁ):

The mass flow rate of the air (ṁ) through the heater can be calculated by using Eq. (2):

$$\dot{m}_{air} = \rho_{air} A_t V_{air} \tag{2}$$

Where:

- $\rho_{air}$  is the air density = 1.2 kg/m<sup>3</sup>.
- $A_t$  is the cross section area of exit air throat of the heater in (m<sup>2</sup>).
- $V_{air}$  is the airspeed at the heater exit throat in (m/sec).





### 4.3 Instantaneous Thermal Efficiency ( $\eta_{ins}$ ):

The instantaneous thermal efficiency of the heater ( $\eta_{ins}$ ) was calculated by Eq. (3):

$$\eta_{ins} = \frac{Q_u}{I A_p} \tag{3}$$

Where:

$I$  is the solar radiation incident on the heater in ( $W/m^2$ ).

$A_p$  is the heater projected area in ( $m^2$ ).

### 4.4 Daily Efficiency ( $\eta_{da}$ ):

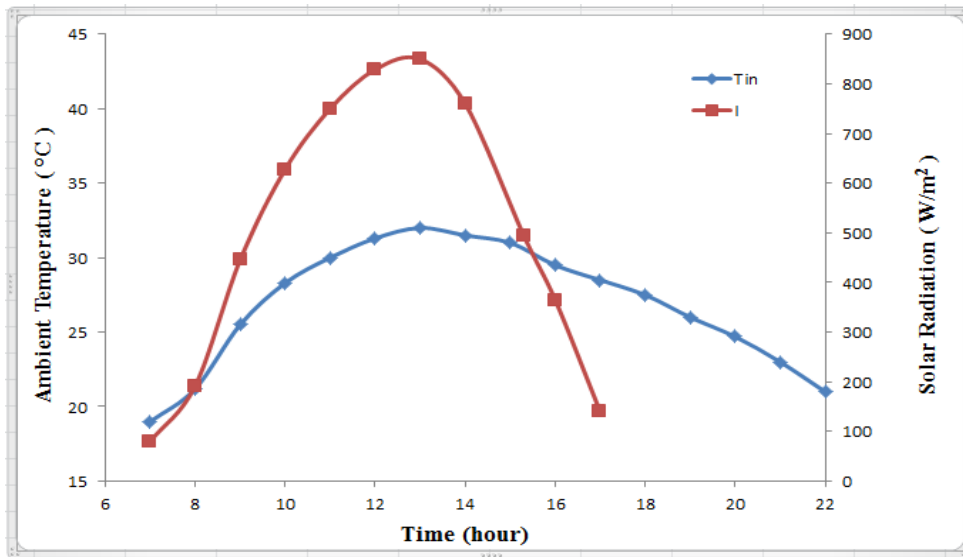
The daily efficiency of the collector ( $\eta_{da}$ ) was calculated by Eq. (4):

$$\eta_{da} = \frac{\sum Q_u}{\sum I A_p} \tag{4}$$

## 5. RESULTS AND DISCUSSION

An experimental investigation was conducted to evaluate the thermal performance of the double pass solar air heater with and without using thermal storage. All tests were carried out at a constant air flow rate of (0.0375 kg/sec.) in the clear sky days on the 21<sup>st</sup> of Oct. 2017 in Baghdad city, Iraq.

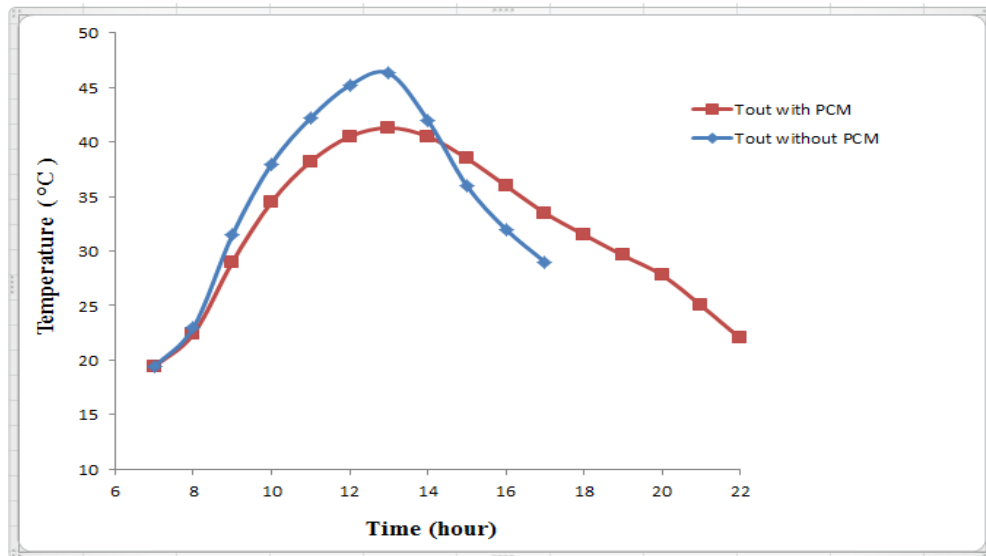
**Fig.4** shows the variation of both the intensity of solar radiation and ambient temperature versus time. From the figure, it has been seen that the solar radiation increases from 80  $W/m^2$  at 07:00 A.M. and continues to increase with time until it reaches maximum value 850  $W/m^2$  at 01:00 P.M., and then gradually decreases to the lowest level at sunset (05:00 P.M.). Also, it can be shown that the ambient temperature, from morning till the evening, ranges between 19 and 32  $^{\circ}C$ .



**Figure 4.** Variation of the intensity of solar radiation ( $I$ ) and ambient temperature ( $T_{in}$ ) versus time.



**Fig.5** shows the outlet air temperature for the double pass solar air heater with and without using the PCM versus time. The figure shows that the outlet air temperature increases with the increase of solar radiation and reaches its maximum value at 01:00 P.M. when the solar radiation becomes at the highest value of  $850 \text{ W/m}^2$ . It was also observed that the temperature of outlet air for the SAH without PCM is higher than those with PCM during the charging process due to the presence of thermal storage. It was found that the maximum temperature of the outlet air is  $46.3 \text{ }^\circ\text{C}$  and  $41.3 \text{ }^\circ\text{C}$  at 01:00 P.M. for the SAH without and with using the PCM, respectively. After this time, the outlet air temperature begins gradually to decrease. But, after 02:30 P.M. (discharge process), the temperature of outlet air for the SAH with PCM becomes higher than without PCM, due to the discharge process of heat stored in paraffin wax. It was found that after sunset, the temperature of the outlet air for SAH with using PCM was higher than the ambient temperature by  $1.5 - 6.5 \text{ }^\circ\text{C}$  for 5 hours.



**Figure 5.** The outlet air temperature ( $T_{out}$ ) of the double pass SAH with and without PCM versus time.

**Fig.6a** shows the change of temperatures of the upper, bottom absorber plate and outlet air ( $T_u$ ,  $T_b$  and  $T_{out}$ ), respectively for the SAH without using PCM versus time. Upper absorber plate temperature is considered higher compared to other temperatures because it is the hottest part in the air heater. So, it is observed that the upper and bottom absorber plate temperature increases with time due to the increase in the solar radiation intensity, and it reaches its maximum value at noon (01:00 P.M.). After that, they begin to decrease until it reaches lower values at sunset (05:00 P.M.). Also, the outlet air temperature increases because of the convection heat transfer from the upper and bottom absorber plate to the air and this increase will be less as compared with the absorber plate temperature. The maximum temperatures of the upper, bottom absorber and outlet air was found to be  $73 \text{ }^\circ\text{C}$ ,  $68 \text{ }^\circ\text{C}$  and  $46.3 \text{ }^\circ\text{C}$ , respectively at 01:00 P.M.

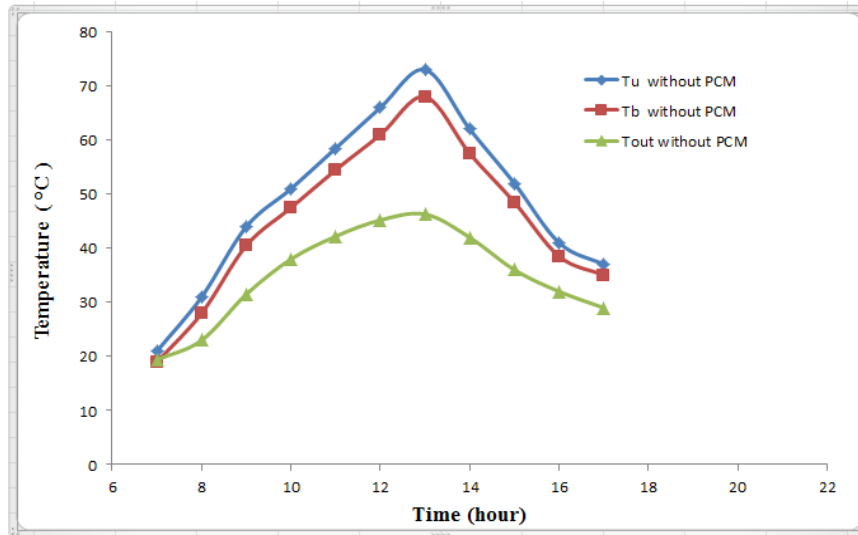


Figure 6a. The temperatures of the upper, bottom absorber plate and outlet air ( $T_u$ ,  $T_b$ , and  $T_{out}$ ), respectively of the double pass SAH without using the PCM versus time.

Fig.6b shows the variation for each of the temperatures of the upper, bottom absorber plate, PCM (paraffin wax) and outlet air ( $T_u$ ,  $T_b$ ,  $T_{PCM}$ , and  $T_{out}$ ), respectively for the SAH with using the PCM versus time. From this figure, it is observed that the upper absorber temperature ( $T_u$ ) from 08:00 A.M. until 02:30 P.M. (charging process) was the highest compared with other temperature. After this time, the PCM temperature becomes the highest until the end of the discharge process at (10:00 P.M.), this is because of the thermal energy stored in the paraffin wax. It is clear that the paraffin wax begins to melting at (12:15 P.M.) and needs time around (1:75 hr) to change its phase completely into liquid at the temperature of 54 °C and then benefit from this energy stored in paraffin wax after (02:30 P.M.), when the solar radiation is low. The maximum temperatures of the upper, bottom absorber, PCM (paraffin wax) and outlet air was found to be 61.5 °C, 49 °C, 57 °C and 41.3 °C respectively at 01:00 P.M.

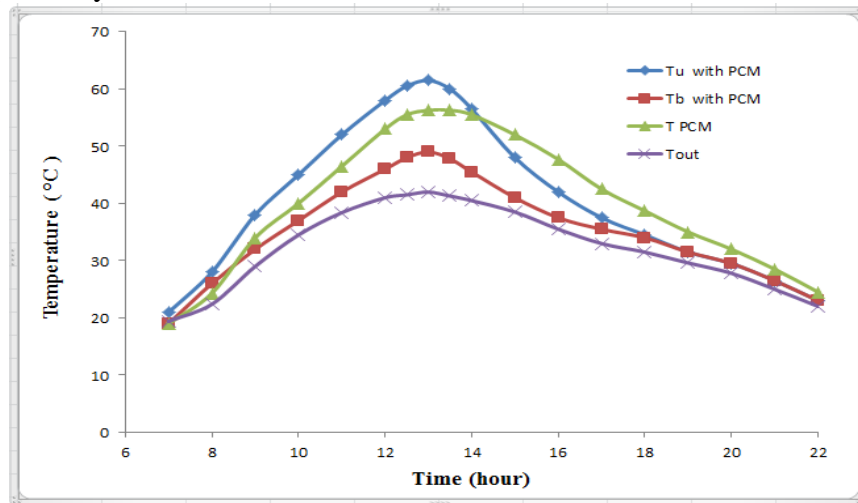


Figure 6b. The temperatures of the upper, bottom absorber plate, PCM (paraffin wax) and outlet air ( $T_u$ ,  $T_b$ ,  $T_{PCM}$ , and  $T_{out}$ ), respectively of the double pass SAH with using the PCM versus time.

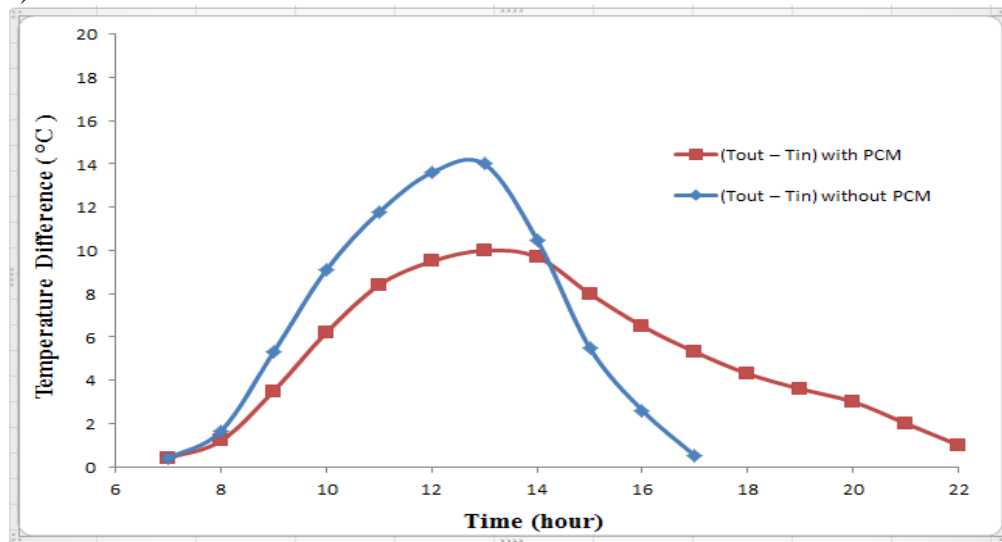


From the curves shown in **Figs. 6a and 6b**, it is observed that the temperature difference between the upper and bottom absorber plates for the SAH without using PCM is 5 °C, while in the case of using PCM the temperature difference of 12.5 °C that means an increase by 60 % at 01:00 P.M. This is due to heat transfer by conduction from the upper absorber plate to the wax material and then to the bottom absorber plate. Therefore, the wax will acquire the part of the heat transferred between the two plates. Also, it is noticed that the outlet air temperature of the SAH at 01:00 P.M using PCM will decrease by 11 % as compared with that when without using the PCM.

**Fig.7** shows the difference in air temperature ( $T_{out} - T_{in}$ ) during the charging and discharging process for the SAHs (with and without using the PCM) versus time. From the figure, it is observed that the difference in air temperature takes the same behavior as solar radiation, increases with time and reaches its maximum value at 01:00 P.M. After this time, it begins gradually to decrease. The maximum value of the air temperature difference was found, at 01:00 P.M., to be 10 °C and 14.2 °C for the SAHs with and without using PCM, respectively.

From the obtained results, it was observed that the difference in temperature for the SAH with using PCM from 07:00 A.M. till 02:30 P.M. is less compared with the SAH without using the PCM, this is because, the amount of thermal energy absorbed during the charging process is stored inside the wax, which leads to reducing the heat gain of the air flowing.

During the discharging process (After 02:30 P.M.), when the solar radiation decreases, the energy stored in the wax is recovered when the PCM temperature is higher than the absorber plate temperature, therefore, the air temperature difference for the SAH with the PCM will be higher (until sunset) and then slowly decreases until be close to zero at the end of the discharge process (10:00 P.M.).



**Figure 7.** The difference in air temperature of the double pass SAHs with and without the PCM versus time.

**Fig.8** shows the variation of the heat gain versus time. It was found that from 08:00 A.M. to 02:30 P.M., the heat gain for SAH without the PCM is higher than that with the PCM. This is because part of the absorbed heat from the sun's rays is transferred into the air flow and the rest is stored in the



paraffin wax. It is shown that the maximum values of the heat gain for the SAH without and with using PCM at 01:00 P.M. are equal to 527 W and 377 W, respectively. After 02:30 P.M., the heat gain of SAH with the PCM will be higher compared with those of without PCM, this is because the thermal energy stored in the paraffin wax will be released which leads to increase in the outlet air temperature for the SAH with the PCM and thus obtaining a uniform discharge process for a longer time.

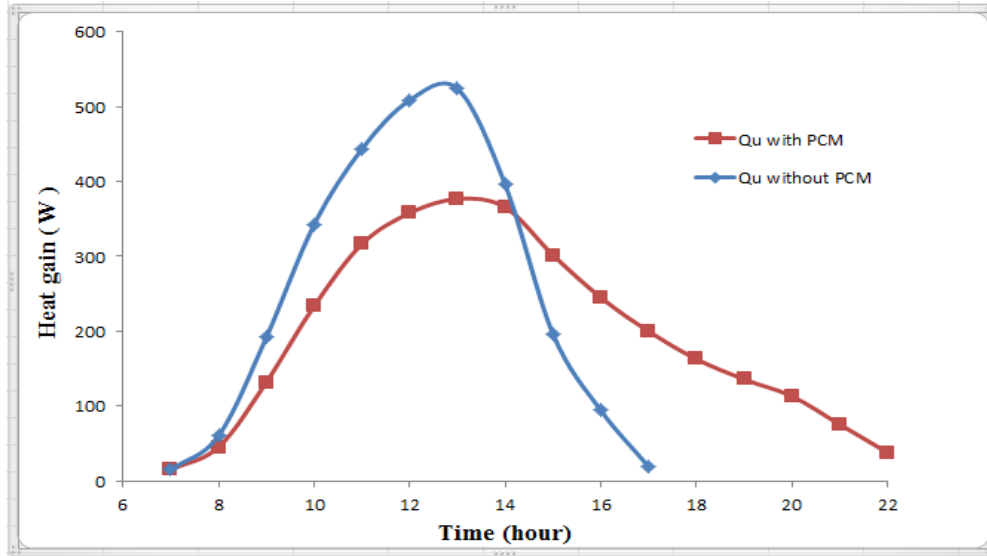


Figure 8. The heat gains of the double pass SAHs with and without PCM versus time.

Fig.9 shows the comparison of the instantaneous thermal efficiency of the double pass SAHs with and without the PCM versus time. The figure shows that the thermal efficiency of the SAH without PCM increases with the time because it depends on the solar energy intensity and reaches its maximum value at 01:00 P.M. and then slowly decreases at sunset. Also, it is shown that the efficiency during the charging process from 08:00 A.M. till 02:30 P.M. for the SAH without PCM will be higher than those with using the PCM. During the discharging process (after 02:30 P.M.), the thermal efficiency of SAH with using the PCM becomes higher compared with those without using PCM, this is due to the large heat supplied from the PCM during the discharge process. As well as, after 04:30 P.M., the efficiency of the SAH with the PCM increases sharply and exceeds 100% after sunset.

Also, from the results obtained, the daily efficiency of the double pass solar air heater had been calculated. It was found that when using the energy storage system, the daily efficiency of the SAH was (56 %), while it was (47%) with no using of the energy storage system case. This is because of the accumulative useful heat gains by air for several hours after sunset in the absence of solar radiation.



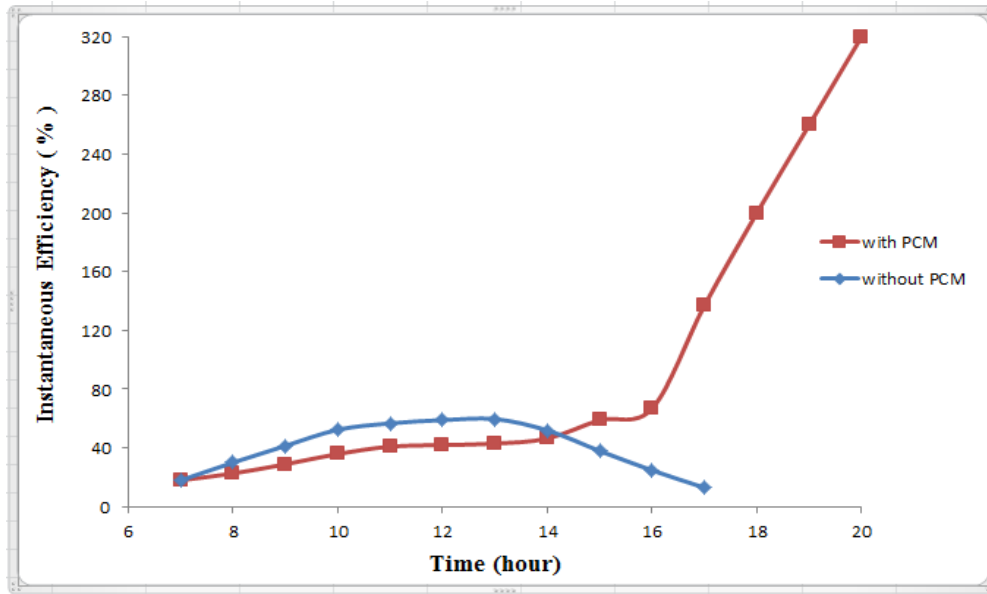


Figure 9. The instantaneous thermal efficiency of the double pass SAHs with and without PCM versus time.

### 5.1 Comparison with the Previous Work

Fig.10 shows the thermal efficiency comparison between the present solar air heater combined with a rectangular cavity with some previous works such as those executed by **Krishnananth**, and **Murugavel, 2013** and **Kabeel, et al., 2016**. From the figure, it can be seen that the thermal efficiency of the double pass solar air heater with energy storage and rectangular cavity implemented in the present work is better throughout evening hours than the two works previously mentioned.

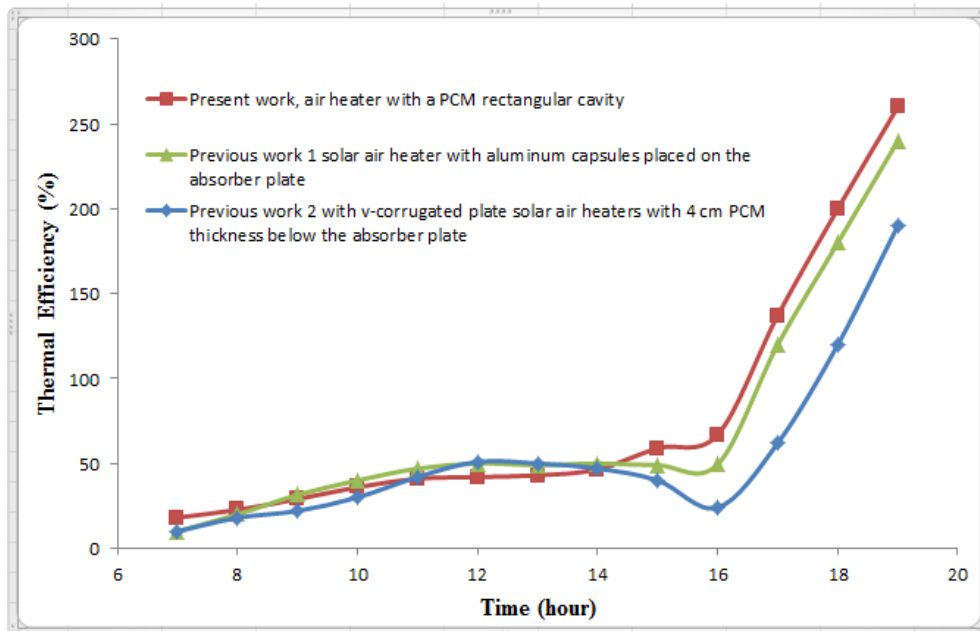


Figure 10. Comparison with the previous work.



## 6. CONCLUSIONS

An experimental study was conducted to evaluate the performance of a double-pass solar air heater with and without using the thermal energy storage. The rectangular cavity filled with paraffin wax was used as a phase change energy storage material. From the results, some conclusions can be extracted as follows:

- 1- The outlet air temperature of the solar air heater with the use of PCM can be maintained for a longer period because the lower absorber plate temperature rises compared with the SAH without PCM which leads to reducing the losses in the SAH.
- 2- The outlet air temperature is significantly affected when using the PCM after sunset, therefore, during the discharging process, the PCM cavity will increase the temperature of outlet air for the SAH with PCM and be higher than the ambient temperature by 1.5 - 6.5 °C for 5 hours.
- 3- The temperature difference of the upper and bottom absorber plate of the SAH without using the PCM is lower than that with PCM because the wax acquires the part of heat transferred between the two plates.
- 4- The instantaneous thermal efficiency during the charging process for the SAH without storage was higher than of the SAH with storage, but after 02:30 P.M., the efficiency of the SAH with storage becomes higher than that without storage.
- 5- The instantaneous thermal efficiency exceeds 100% due to the large heat supplied from the PCM during the discharge process.
- 6- The daily efficiency of the double pass SAH with the PCM is higher than those without PCM.
- 7- Finally, using the PCM in the SAHs is considered as an effective way to improve the thermal performance. Therefore, it can be concluded that the double-pass solar heater with the PCM is an effective design and useful in the drying applications and the heating in buildings compared to that without using PCM.

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### NOMENCLATURE

$A_p$	the heater projected area, $m^2$ .
$A_t$	cross section area of the exit air throat of the heater, $m^2$ .
$C_p$	specific heat at constant pressure, $kJ/kg.k$ .
HTF	heat transfer fluid.
$I$	solar radiation, $W/m^2$ .
LHS	latent heat storage.
$m$	mass flow rate, $kg/sec$ .
PCM	phase change material.
$Q_u$	useful heat gain, $W$ .
SAH	solar air heater.
TES	thermal energy storage.
$T_{amb}$	ambient temperature, $^{\circ}C$ .
$T_b$	the temperature of the bottom absorber plate, $^{\circ}C$ .
$T_g$	glass cover temperature, $^{\circ}C$ .
$T_{in}$	inlet air temperature, $^{\circ}C$ .
$T_{out}$	outlet air temperature, $^{\circ}C$ .
$T_{PCM}$	the temperature of the phase change material, $^{\circ}C$ .
$T_u$	temperature of upper absorber plate, $^{\circ}C$ .
$v$	air speed, $m/sec$ .
$\eta_{da}$	the daily efficiency of the collector.
$\eta_{ins}$	the instantaneous thermal efficiency of the heater.
$\Delta T$	difference in air temperature, $^{\circ}C$ .
$\rho$	air density, $kg/m^3$ .