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Experimental Performance of a Double Pass Solar Air Heater with Thermal Storage

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ABSTRACT

Solar air heater is a heating device produced hot air for many engineering applications such as heating of buildings .The purpose of this work is to fabricate and test double-pass solar air heater (SAH) with thermal energy storage system under the climatic conditions of Iraq-Baghdad to store the excess solar energy and release it during the night. The experimental work was conducted to evaluate the charging and discharging characteristics of the new system and performed at different air mass flow rates; varying from 0.025 kg/s to 0.06kg/s, for different cold winter days of January , February, and March 2016. The results show that, the maximum average efficiencies obtained for the double pass SAHWS and SAHWOS were 90% and 61% respectively for a mass flow rate 0.04 kg/s. With paraffin wax, the maximum temperature difference between inlet and outlet air flow is 41.4 °C, when the mass flow rate of air is 0.025 kg/s. For the same flow rate the average efficiency of the double pass SAH with thermal storage is found to be higher than the double pass SAH without thermal storage by 20- 36%. The study concluded that the presence of the thermal storage medium at the absorber plate gave average outlet air temperature 8.2 °C above the inlet temperature for 4.5 hours after sunset. Low mass flow rate is able to utilize the maximum capacity of the storage system and to supply heat for a longer duration. Also the recommended range of air mass flow rate which gives an appropriate efficiency and useful heat gain is 0.03 - 0.04 kg/s.

KEYWORDS: Thermal storage , Solar air heater (SAH) , Double-pass , PCM.

INTRODUCTION

On the past 50-100 years the rapid increase in energy usage characteristic cannot continue indefinitely as limit energy resources of earth are terminated [1]. Therefore, there is a need to looking for the renewable energy sources to accept the energy demand in present state[2]. Solar energy is the one most ample renewable energy source and emits energy at a rate of 3.8×10^{23} kW, of which, approximately 1.8×10^{14} kW is intercepted by the earth [3]. The primary forms of solar energy are light and heat. Sunlight and heat are absorbed and transformed by the environment in many ways [4]. The supply of hot air is one of the most applications of solar energy for the drying of agricultural, textile and marine products, and heating of buildings to obtain a comfortable environment in the winter season and re-generating dehumidify agent [5]. Solar energy is intermittent in nature and time dependent energy source. The easiest and the most widely accepted method is conversion of solar energy into thermal energy. Due to this property, thermal energy storage system can play an important role in popularization of the solar energy based systems. Thermal energy can be stored in different way such as sensible heat, latent heat or chemical energy. Latent heat storage systems using phase change material (PCM) is a particularly attractive technique, since it provides a high energy storage density and has the capacity to store heat as latent heat of fusion at a constant temperature [6].

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Number of researches is going on to enhance the performance of the solar air heater by integrating flat plate collector with packing material and energy storage systems. Mittal and Varshney ,2006 [7] investigated the performance of the solar air heater with wire mesh as packed bed and found that the thermal gain was relatively more than the smooth collectors. El-Sebaii et al.,2007 [8] investigated the double pass solar collector with iron packed bed and found that the thermal efficiency of the system was (22–27)% more than the system without packed bed. Aldabbagh et al.,2010 [9] investigated that the single and double pass solar air heaters with wire mesh as packed bed. The efficiency for single pass solar air heater and double pass solar air heater were 45.93% and 83.65% respectively. Omojaro and Aldabbagh ,2010 [10] investigated the single and double pass solar air heaters with wire mesh as packed bed and show that as air mass flow rate increases, the efficiency increasing. The efficiency of the double pass was (7–19.4)% more than the single pass for the same flow rate. Dhiman et al., 2011 [11] carried out an experimental study of the double pass solar air heater with packing material on the upper channel. The analytical model was developed which describes the different temperatures and heat transfer characteristics of parallel flow packed bed solar air heater to study the effects of mass air flow rate and varying porosities of packed bed material on its thermal performance. The thermal efficiency of parallel flow packed bed solar air heater was 10–20% more than the double pass SAH system without packing material. Chii et al. , 2013 [12] have investigated experimentally and theoretically the performance of wire mesh packed double-pass solar air heaters with attaching wire mesh with external recycle. The enhancement of system performance of wire mesh packed solar air heaters with various flow patterns is expressed graphically and compared, for different configuration including the single-pass, recycle flat-plate double-pass and double-pass with recycle and wire mesh packing material. The wire mesh packed double-pass device introduced in the study was proposed for aiming to strengthen the convective heat transfer coefficient for air flowing through the wire mesh packed bed, and to determine the optimal design on an economic consideration in terms of both heat transfer efficiency improvement and power consumption increment. Chii et al., 2015 [13] have investigated experimentally and theoretically the device performance of a solar air heater with recycling and wire mesh packed. Comparisons were made among various designs including the single-pass, flat plate double pass, and recycling wire mesh packed double-pass operations. The SAH efficiency of the recycling wire mesh packed double pass system is more than the other configurations with different recycle ratios and mass flow rates.

The recent researches focused on the phase change materials based air heating systems, because it has high energy storage density compared to sensible heat storage and suitability for optimum thermal performance of solar air heater. Enibe ,2003 [14] constructed and studies a natural convection solar air heater with phase change material energy storage and used the paraffin wax as a PCM under natural environmental condition involving ambient temperature variation in the range 19-41°C and daily global irradiation in the range 4.9-19.92 MJ/m^2. Peak temperature rise of the heated air was about 15°C , while peak cumulative useful efficiency was about 50%, the maximum air flow rate was 0.01 kg/s. Jain and Jain,2004 [15] analyzed the inclined multi pass solar air heater with in-built thermal storage on deep-bed for drying application and found that the bed moisture content decreases with the time of the day and also the drying rate increases with the increase in the depth of drying bed. Mahmud et al. 2011 [16] studied the solar air collectors with thermal storage units and found that the PCM with high latent heat were required for optimum thermal performance of solar air heater. Krishnananth and Murugavel, 2013 [17] have fabricated a double pass solar air heater and tested with energy storage system to evaluate the performance of the double pass solar air heater with various configurations . Paraffin wax with alaminium capsules was used as phase changing energy storing material. Experiments were conducted to study the performance of the air heater with and without energy storage materials. In each configuration, the paraffin capsules were placed in different locations. From the experimental results, it was observed that, the solar air heater with paraffin wax as energy storage material delivers comparatively high temperature air throughout the day. The efficiency is also higher during evening hours. The double pass solar air heater with capsules placed on the absorber plate is the efficient one.

In the present work, a double pass solar air heater was fabricated and tested integrated with energy storage system. Paraffin wax in cylindrical copper pipes is used as phase change energy storing material. Experiments were conducted and performances were compared for different mass flow rate .

2. Experimental set-up and equipment:

2.1. Experimental set-up:

The photographic view of the experimental setup constructed for this study are shown in plate (1) and plate(2) . An electrical centrifugal blower (0.75 kW, $2\ \mathrm{m}^3/\mathrm{s}$, 1500 rpm) is used to deliver air with a constant flow rate to the air heater. Ambient air which is sucked by the electrical centrifugal blower, flows through an intermediate tunnel to enter the SAH. The tunnel has internal guide vanes to ensure uniform distribution of the air over the width of the air heater. SAH has (2 × 1 × 0.15) m^3 inner dimensions. The top of the SAH is covered with a single transparent glass cover; (3 mm) thickness.. The gap spacing between the absorber plate and the glass cover is about 7.5 cm. Also the gap spacing between the absorber plate and the back plate is about 7.5 cm . The air heater frame is constructed from mild steel plate of 1.5 mm thickness. The upper surface of absorber plate; which is made of copper plate having 1.93 m length, 1 m width and 0.5mm thickness, is painted with selective coating black layer ($\alpha=0.92$, $\varepsilon=0.28$) to increase the absorptivity of the solar radiation and reduces the heat losses between the inside and outside surfaces [18]. The air is heated first while passing between the transparent glass cover and absorber plate. The air then reverses direction in the lower channel . Addition heating for the air while passing between the absorber plate and the rear plate. The system is insulated from all sides and bottom by a 0.05 m thickness glass wool to reduce the heat losses to ambient air. The whole solar air heater is oriented due south and tilted 47º with respect to the horizontal to maximize the solar radiation incident on the air heater [19] .The photograph for the double pass flat plate solar air heater experimentation setup without thermal storage was shown in the plate (1).

To improve the system performance, the conventional absorber flat plate is replaced by a twelve copper pipes filled with PCM (4 cm diameter each ,193 cm length and 0.1 cm thickness) were used to store the excess thermal energy. The spaces between the pipes are joined by copper plates . Each plate has (193 × 4 × 0.05) cm^3 dimensions. The copper plates and copper pipes are painted with selective coating to absorb maximum solar radiation and emits low energy . Blower is connected to the inlet of the air heater through a gate valve. Gate valve is used to control the mass flow rate of air and air flow meter is used to measure the mass flow rate. To measure the inlet and exit air temperatures, absorber plate temperature, glass temperature and back plate temperature, K type thermocouples were placed at different locations and connected to the digital data logger . Solar meter is used to measure the solar radiation intensity. The specification of the measurement devices are shown in table-1. The photograph for the double pass solar air heater experimentation setup with thermal storage medium was shown in the plate (2). The cylindrical copper pipes filled with PCM (paraffin wax). The thermo-physical properties of the PCM are given in table-2. [20].

Table 1: Accuracies and errors for various measuring instruments

Instrument	Accuracy	Range
K-type thermocouple	0.2 %	$-100°C \sim 1300°C$
AT45xxMulti-channel Temperature Meter	0.2% + 1°C	$-200°C \sim 1800°C$
Solar power meter	5%	$0 \sim 2000\ W/m^2$
Air flow meter	1.0%	0.2 - 40.0 m / s

Table 2: Thermo-physical properties of PCM. [20]

Property	Value
Melting temperature	62 °C
Liquid density	770 (kg/m^3)
Solid density	850 (kg/m^3)
Latent heat	176 (kJ / kg)
Specific heat-liquid	2.871 (kJ / /kg .K)
Dynamic viscosity	0.03499 (kg / /m .s)

Plate 1: Double pass flat plate SAH without thermal storage .

Plate 2: Double pass SAH with thermal storage.

2.2. Experimental trials:

The charging and discharging experiments are conducted to evaluate the performance of the conventional and the new design of SAH with PCM thermal storage unit under different air mass flow rates. The temperatures of the air entering and leaving the solar collector and radiation intensity are measured at intervals of 10 minutes during the day. Charging and discharging experiments are conducted by supplying ambient air at the inlet. Five different mass flow rates of (0.025, 0.03 ,0.04 , 0.05 and 0.06 kg/s) are used. Several experiments are conducted to check the repeatability of the readings.

RESULTS AND DISCUSSION

3-1 the system performance with thermal storage:

*F*rom the results in Fig. 1 show the variation of the solar insolation during the experiments conducted in the month of February - 2016 . It is seen from the figure, that the solar insolation increases from 150 W/m^2 at 8.00 A.M to about 720 W/m^2 around 12.30 P.M. Beyond this time, the solar insolation reduces to the end of day time at 5.00 P.M.

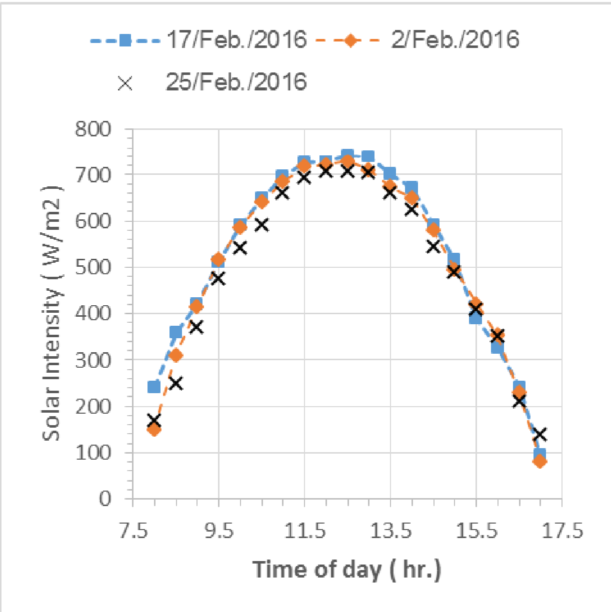

Fig. 1: Variation of solar insolation of SAH.

Fig.2 illustrate the variation of the temperatures of the exits air , upper surface, lower surface and PCM (paraffi88n wax) (T_e, T_u, T_l and T_{PCM}) respectively, during the day. Measured data illustrated that the maximum temperatures are obtained in the interval from 12:00P.M. to 2:00 P.M where solar radiation at maximum, with peak value are nearly at 1:00 P.M. In all results, it was observed that the pipe surface temperature (T_u, T_l) exhibited the highest temperature until 11.30A.M after this time T_{PCM} will be the highest . It may be concluded from Figs.2 that the temperatures in general increase with the increase of solar radiation. This can be explained as follows: For a certain value of mass flow rate an increase in the incident radiation flux increases the temperature level of the pipe surface that has an effect on T_{PCM} and lead to melt the paraffin wax. It is observed from the present experimental results that the heating rate of PCM during the solid sensible heating is slow and increases at a higher rate beyond 330 °K. Hence, it is concluded that the PCM has changed its phase completely into liquid.

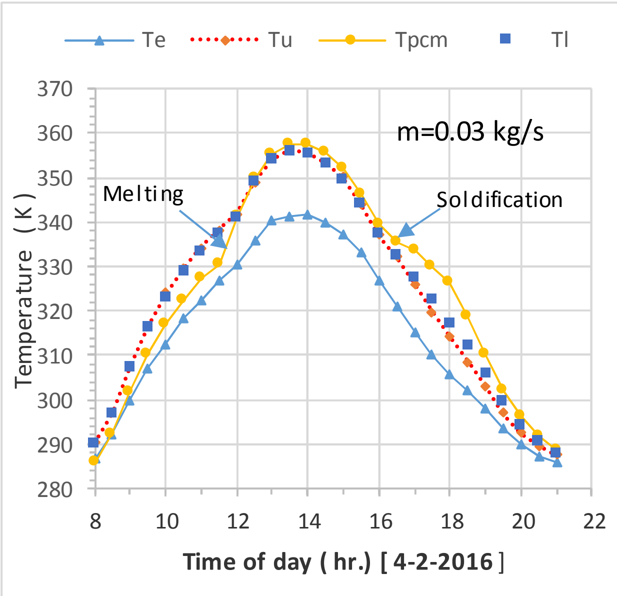

Fig. 2: Variation of the temperature of SAHWS during the day.

Fig.3 illustrates the variation of air temperature difference during the charging and discharging processes for various mass flow rates. The SAH air temperature difference is an important parameter for the heating of buildings and many engineering applications. It may be observed from Fig.3 that the air temperature difference decreases with increasing air mass flow rate until mass flow rate equals 0.04 kg/s. With further increase of mass flow rate, average air temperature difference decreases with higher rate. This is due to the fact that when the air flow rate increases, the amount of air to be heated with the same quantity of solar energy increases. Also it may be observed from Fig.-3 that the difference of air temperature exhibit the same behavior as the solar radiation. However, they achieve their maximum values at 1.30 P.M. The observed maximum difference air temperature ranged between 19.3 °C and 41.4 °C during the period of experimentation depending on the mass flow rate. It is seen from the Fig-3 that the difference temperature continue beyond the sunshine time due to discharging from the PCM and the time of discharging depend on the mass flow rate.

By using paraffin wax, the maximum value of the outlet temperature of the flowing air was obtained as 41.4°C greater than the inlet temperature at noon when the mass flow rate of air is 0.025 kg/s. The average outlet air temperature was maintained at 8.2°C above the inlet temperature for 5 hours after sunset.

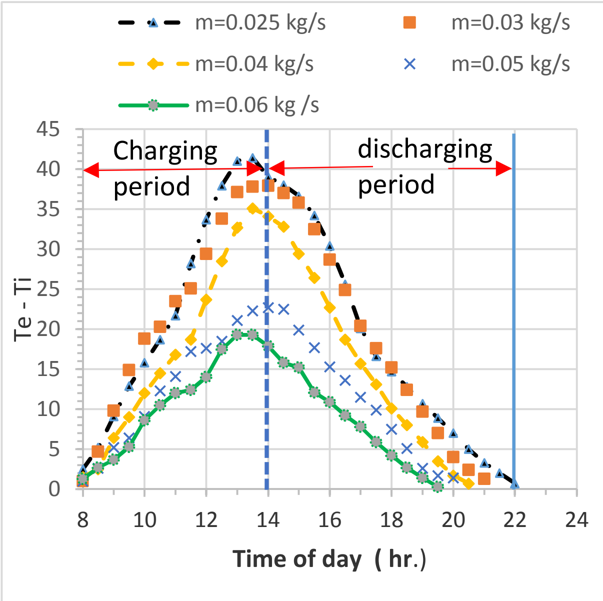

Fig. 3: Air temperature difference versus standard local time of the day at different mass flow rates for double-pass SAHWS.

Based on Duffie and Beckman [19], the useful heat gain from SAH is :

$$Q_u = m\, C_p (T_e - T_i) \tag{1}$$

Fig.4 illustrate variation of useful energy for different values of mass flow rate .It can be remarked that the maximum value of heat gain occurs at m=0.04kg/s. Further, it may be concluded from Fig.(4.a) that the useful energy decreases by decreasing the mass flow rate. Decreases of mass flow rate leads to increase the temperature of the absorber plate and to the increase of the near wall air temperature, and consequently, to the increase of the air viscosity. This increase in air viscosity affects the wall shear stress and decreases the local R_e as well which causes an increase in thermal boundary layer thickness, and results in decreasing the convective heat transfer coefficient .Moreover that will increase the temperature difference with ambient which cause the increase the heat losses. With further increase of mass flow rate as shown in Fig.(4.b) decreases the useful energy . It is seen from the figure that the discharging of heat is possible for duration of 5 h, 4 h, 3.5 h, 3 h and 2.5 h, when the mass flow rate is 0.025 kg/s , 0.03 kg/s , 0.04 kg/s, 0.05 kg/s and 0.06 kg/s respectively

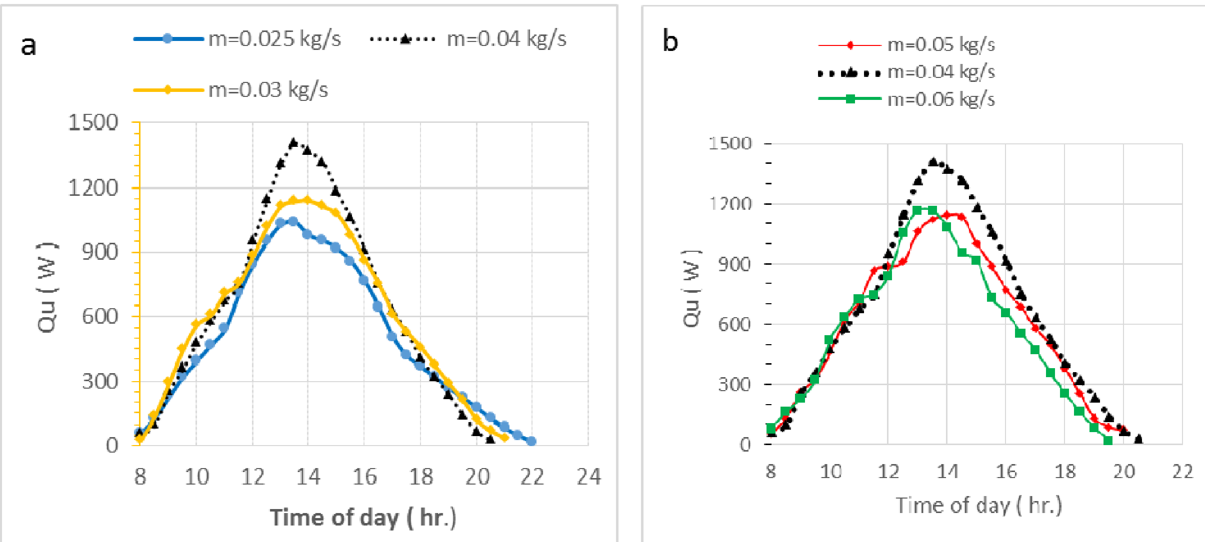

Fig. 4: Variation of useful heat gain for different values of mass flow rate.

Fig.5 show the variation of total useful energy for different values of mass flow rate. It may be remarked that the maximum value of total useful energy occurs at m=0.04kg/s.

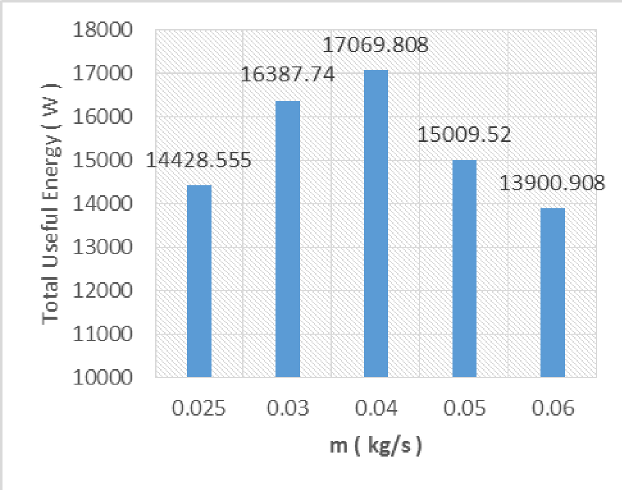

Fig. 5: Variation of total useful energy for different values of mass flow rate.

The thermal performance advantage of thermal storage can be attributed to the useful energy enhancement of about 53% at m=0.04 kg/s as shown in Fig. 6

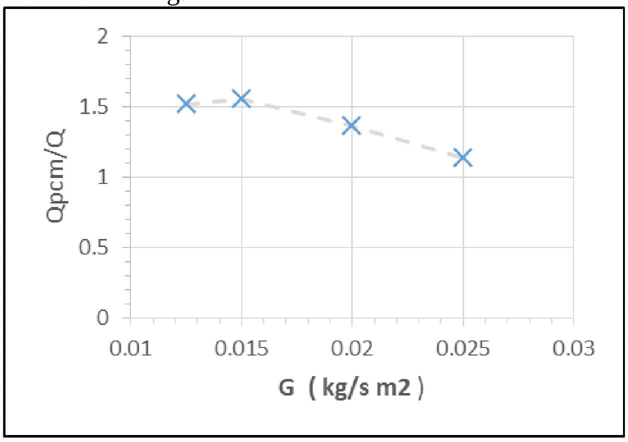

Fig. 6: Heat transfer enhancement versus the mass flow rate per unit area .

The thermal efficiency of SAH is determined from the following equation :

$$\eta = \frac{m\, C_p (T_o - T_i)}{I\, A} \tag{2}$$

The efficiency from equation - 2 is a function of I and ΔT, considering C_p and A as constants.

Fig.7 show the variation of the thermal efficiency of SAH for different values of mass flow rate. The thermal efficiency increases with increasing mass flow rate until a value of 0.04 kg/s as shown in Fig.(7.a). This is due to the reduction in the heat losses associated with the decrease of the average temperature of the collector and to the increase in the value of the heat transfer coefficient at a higher mass flow rate. Beyond that mass flow rate, the efficiency decrease with increasing of the mass flow rate as shown in Fig.(7 .b) due to decrease of heat transfer. Also it can be see from these figures the thermal efficiency exceed 100% due to excess energy discharge to the air flow from PCM.

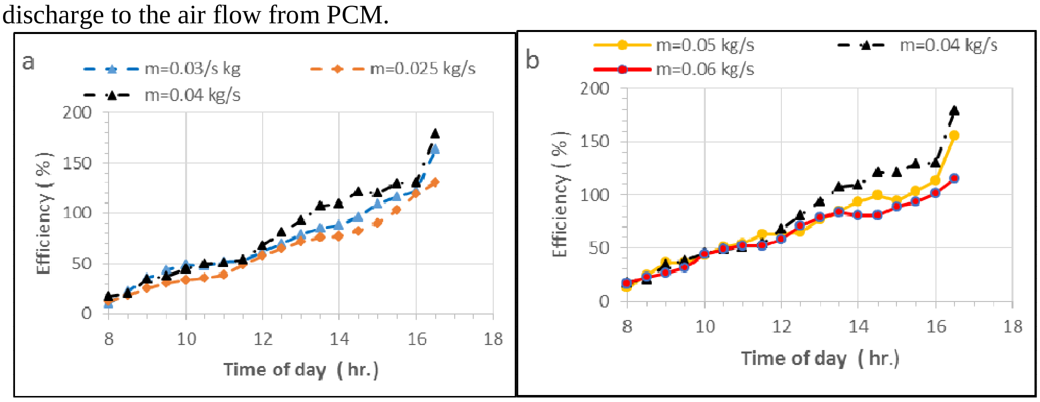

Fig. 7: Variation of the thermal efficiency for different values of mass flow rate.

3-2 Comparisons between the system performances with and without thermal storage:

The performance of the double pass solar air heater with storage (SAHWS) was compared with a conventional double pass solar air heater without storage (SAHWOS). The outlet air temperature and absorber temperature difference are analyzed and compared for the two systems (Fig.8-a and fig.8-b). The average thermal efficiency for double pass SAHWS and SAWOS is shown in Fig.9 .As shown in Figs.8 for mass flow rate 0.03 kg/s the maximum air temperatures difference ($T_e - T_i$) are 39 and 29 for double pass SAHWS and SAHWOS respectively. While the maximum absorber temperatures difference ($T_b - T_i$) are 52 and 59 for double pass SAHWS and SAHWOS respectively. We concluded that the double pass SAHWS could maintain outlet air temperature greater than The SAHWOS due to lower absorber temperature rise of the SAHWS compared to the SAHWOS which lead to low losses from the SAH**.**

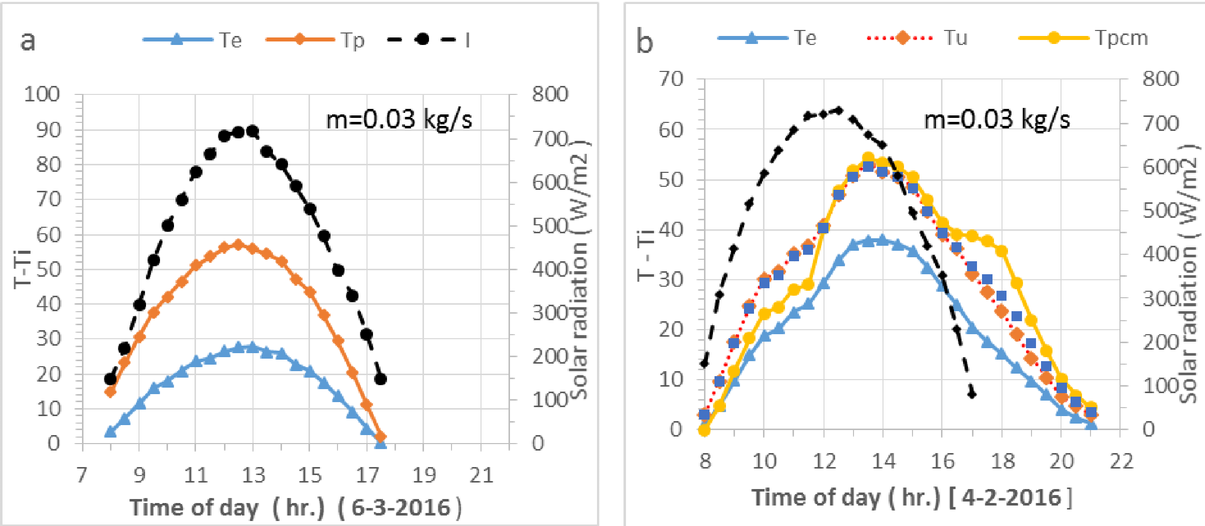

Fig. 8: Exit air, absorber temperatures difference and solar radiation versus standard local time of the day at different mass flow rates for(a)- double-pass SAHWOS and (b) - double-pass SAHWS.

Fig.9 compares the average thermal efficiency for the two configurations at various air rates. The efficiencies increased to maximum at 0.04 kg/s. The efficiency of the double pass with storage is higher than that of the single pass collector by 19-36% depending on the air mass flow rate. The maximum average efficiencies obtained for the double pass SAHWS and SAHWOS were 90% and 61% respectively. The increase in the average efficiency for the double pass SAHWS is due to the reduction in the heat losses from the top cover and the excess energy storage on the paraffin wax.

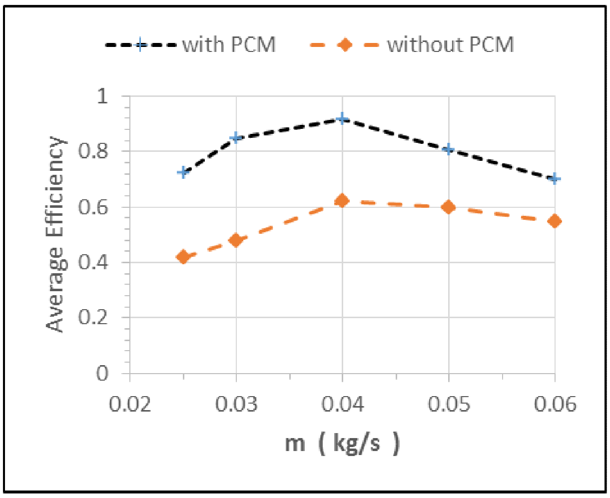

Fig. 9: Variation of the average thermal efficiency for different values of mass flow rat.

Conclusions:

The main finding of the present experimental studies are summarized as follows :-

- The efficiency increase with increasing air mass flow rate up to 0.04 kg/s and then thermal efficiency decreases by increasing the mass flow rate.
- The thermal efficiency exceed 100% due to excess energy discharge to the air flow from PCM during discharge period.
- For the same flow rate, the average efficiency of the double pass SAH with thermal storage is higher than the double pass SAH without thermal storage.
- The hot air outlet average temperature was 8°C above the inlet temperature extended for 4.5 hours beyond sunset time.
- The temperature difference between the outlet and the inlet increases with decreasing the air mass flow rate.
- The maximum value of the outlet temperature of the flowing air was obtained as 41.4°C greater than the inlet temperature.
- The above mentioned observations indicate that the recommended range of air mass flow rate which gives an appropriate efficiency and useful heat gain is 0.03-0.04 kg/s.
- The thermal performance advantage of thermal storage can be attributed to the useful energy enhancement of about 53%

Nomenclature

Letter	Description
A	Collector area (m^2)
C_p	Specific heat at constant pressure
G	Mass flow rate per unit area (W/ kg.m^2)
I	Solar radiation (W/m^2)
m	Mass flow rate (kg/s)
PCM	Phase change material
Q	Useful heat gain without storage (W)
Q_u	Useful heat gain (W)
Q_{PCM}	Useful heat gain with PCM (W)
R_e	Reynolds number
SAH	Solar air heater
SAHWS	Solar air heater with storage
SAHWOS	Solar air heater without storage
T_i	Inlet air temperature (°C)
T_e	Exit air temperature (°C)
T_u	Upper surface temperature (°C)
T_l	Lower surface temperature
T_{PCM}	Temperature of Phase change material
α	Absorptivity
η	Thermal efficiency
ε	Emissivity

REFERENCES

1. Bhushan B, Singh R.,2010. A review on Methodology of Artificial Roughness used in Duct of Solar Air Heaters, Energy, 35:202–212.
2. Towler GP, Oroskar AR, Smith SE., 2004. Development of a Sustainable Liquid Fuels Infrastructure based on Biomass. Environmental Progress , 23(4):334–341.
3. Thirugnanasambandam M, Iniyan S, Goic R., 2010. A review of Solar Thermal Technologies, Renewable and Sustainable Energy Reviews, 14:312–22.
4. Panwar NL, Kaushik SC, Kothari S., 2011. Role of Renewable Energy Sources in Environmental Protection: A review. Renewable and Sustainable Energy Reviews, 15:1513–1524.
5. Tchinda R., 2009. A review of The Mathematical Models for Predicting Solar Air Heaters Systems. Renewable and Sustainable Energy Reviews, 13:1734–1759.

6. Atul Sharma, Tyagi VV, Chen CR, Buddhi D., 2009. Review on Thermal Energy Storage with Phase Change Materials and Applications. Renewable and Sustainable Energy Reviews, 13:318–345.
7. Mittal, M.K., Varshney, L., 2006. Optimal Thermohydraulic Performance of a Wire Mesh Packed Solar Air Heater. Solar Energy, 80: 1112– 1120.
8. El-Sebaii, A.A., Aboul-Enein, S., Ramadan, M.R.I., El-Bialy, E., 2007. Year Round Performance of Double Pass Solar Air Heater with Packed Bed. Energy Convers. Manage. 48, 990–1003.
9. Aldabbagh, L.B.Y., Egelioglu, F., Ilkan, M., 2010. Single and Double Pass Solar Air Heaters with Wire Mesh as packing Bed, Energy, 35, 3783–3787.
10. Omojaro, A.P., Aldabbagh, L.B.Y., 2010. Experimental Performance of Single and Double Pass Solar Air Heater with Fins and Steel Wire Mesh as Absorber, Applied Energy, 87: 3759–3765.
11. Prashant Dhiman, Thakur NS, Anoop Kumar, Satyender Singh, 2011. An Analytical Model to Predict the Thermal Performance of a Novel Parallel Flow Packed Bed Solar Air Heater, Applied Energy, 88:2157–2167.
12. Chii-Dong Ho, Chun-Sheng Lin, Yu-Chuan Chuang, Chun-Chieh Chao, 2013. Performance Improvement of Wire Mesh Packed Double-Pass Solar Air Heaters with External Recycle, Renewable Energy, 57: 479-489.
13. Chii-Dong Ho, Hsuan Chang, Chun-Sheng Lin, Chun-Chieh Chao and Yi-En Tien, 2015. Analytical and Experimental Studies of Wire Mesh Packed Double-Pass Solar Air Heaters under Recycling Operation, Energy Procedia, 75: 403 – 409.
14. Enibe, S.O., 2003. Thermal Analysis of a Natural Circulation Solar Air Heater with Phase Change Material Energy Storage, Renewable Energy, 28: 2269–2299.
15. Jain, Dilip., Jain, Rajeev.Kumar., 2004. Performance Evaluation of an Inclined Multi Pass Solar Air Heater with in-built Thermal Storage on Deep-Bed Drying Application, J. Food Eng., 65: 497–509.
16. Mahmud, M., Alkilani, Sopian, K., Alghoul, M.A., Sohif, M., Ruslan, M.H., 2011. Review of Solar Air Collectors with Thermal Storage Units. Renewable Sustainable Energy Rev., 15:1476-1483.
17. S. S. Krishnananth and K. K. Murugavel, 2013. Experimental Study on Double Pass Solar Air Heater with Thermal Energy Storage, Journal of King Saud University, 25(2): 135–140.
18. Rhett Noseck, 2013. The Water Wall-a Passive Solar Collector and Thermal Storage Device for Supplementary Radiant Heating, Master thesis, University of Nevada, Las Vegas.
19. Duffie JA, Beckman WA., 2013. Solar Engineering of Thermal processes, Fourth Edition, New York, USA: John Wiley and Sons.
20. Ali Shokor Golam, 2014. Investigation of Heat Transfer Process During Melting and Solidification of Various PCM Configurations, Master thesis, University of Al-Mustansiriya , Baghdad, Iraq.