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Experimental Performance Evaluation of a Double Pass Solar Air Heater With and Without Thermal Storage

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ABSTRACT

Although there is excess heat from the solar air heater available during the day to heat the building, but after sunset an auxiliary heat is required. The purpose of this work is to design and test double-pass solar air heater (SAH) without and with thermal energy storage (water) to store the excess solar energy and release it during the sunset. The experimental work was conducted to evaluate the effect of water storage during the day-time performance of a solar air heater at different air mass flow rates and different cold winter days of January 2016. Experimental results show that, the maximum average efficiencies obtained for the double pass with and without were 83% and 65% respectively for a mass flow rate 0.04 kg/s. Also an increase in the air mass flow rate led to an increase in the collector efficiency and decrease in the temperature gain across the collector. With thermal storage (water), the maximum temperature difference between inlet and outlet air flow is 30°C, when the mass flow rate of air is 0.03 kg/s. The study concluded that the presence of the thermal storage medium (water) at the absorber plate gave average outlet air temperature 7.6 °C above the inlet temperature for 3 hours after sunset.

INTRODUCTION

The ongoing and rapid increase in the economic development worldwide is accompanied by a strong demand for an uninterrupted supply of energy. Conventional fossil energy sources are limited and serious uncertainties associated with their stable supply/pricing persist. Moreover, greater use of fossil fuels is linked to emission of harmful gases that in turn are responsible for climate change and environmental pollution,(Towler G.P., et al., 2004) These serious challenges represent the main driving forces behind efforts to utilize various sources of renewable energy more effectively. Solar energy is the one most abundant renewable energy source (Thirugnanasambandam, M., *et al*., 2010). The primary forms of solar energy are heat and light. Sunlight and heat are transformed and absorbed by the environment in a multitude of ways. 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 (Tchinda, R., 2009). Different from other exporters of energy, solar energy active source for air heating system because the warm air is also the final receiver of energy. This energy has a thermal conversion mode which necessitates a simple technology which is suitable to the place and to the particular region for many applications. All these systems are based on the solar air collectors. Solar energy collectors are employed to get useful heat energy from incident solar radiation. They can be concentrating or flat plate type. Solar air heater can be used in a many different of applications, but it is a definite resource. (Turhan, K., 2006).

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Solar energy is intermittent in nature and time dependent energy source. Conversion of solar energy into thermal energy is the easiest and the most widely accepted method. Due to this nature, thermal energy storage system can play an important role in popularization of the solar energy based systems. Thermal energy can be stored as sensible heat, latent heat or chemical energy.

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. Sopian *et al*., (2009) carried theoretical and experimental investigation of double pass solar heater with porous material packed in the lower channel. To increase heat transfer the porous media fabricate in different area density, porosities and the total heat transfer rate. Pressure drop and heat transfer relations developed for air flow through porous media. The exist of porous media in the second channel improved thermal efficiency by increasing the heat transfer coefficient. Aldabbagh *et al*., (2010) have investigated experimentally the thermal performances of single and double pass solar air heaters with steel wire mesh layers are used instead of a flat absorber plate. The mass air flow rate effect on thermal efficiency and the outlet temperature were studied. The results show that the efficiency increases with increasing the mass flow rate for the range of the air flow rate of 0.012 - 0.038 kg/s. For the same range of air flow rate, efficiency of a double pass SAH was 34-45% higher than single pass SAH. In addition, for the flow rate of 0.038 kg/s the maximum efficiency attained in single and double pass SAHs are 45.93% and 83.65%, respectively. The results indicate for the same mass flow rate the air heater temperature differences increased with the increasing solar radiation. Dhiman *et al*., (2011) 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. El-khawajah *et al*., (2011) have investigated experimentally the thermal performance of a double pass solar air heater with fins attached and using wire mesh layers between the fins instead of an absorber plate. The results show that the thermal efficiency increases with increase in mass air flow rate for the range of 0.0121 - 0.042 kg/s. The maximum efficiency was obtained by using 6 fins at the same mass air flow rate. Moreover the maximum efficiency obtained for the 2, 4, 6 fins of solar air heater were 75.0%, 82.1% and 85.9%, respectively for the same mass flow rate of 0.042 kg/s. In addition, the maximum average temperature difference between the inlet and the outlet temperature, for the solar air heater with 6 fins was more than compared to 2 and 4 fins solar air heater for the same mass flow rates. The maximum instantaneous peak and average temperature obtained were 62.1 ◦C and 43.1 ◦C , respectively for the 6 fins solar air heater when the mass flow rate was 0.0121 kg/s.

Chii *et al*., (2013) 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 this 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. Prashant and Satyender, (2015) have proposed analytical models to indicate the thermal and thermo hydraulic efficiencies of two different designs of double pass packed bed solar air heater with external recycle. Two different models of the double pass packed bed type of solar air heaters for the thermal performance improvement under external recycle are considered. For Model A the maximum thermal efficiency is found to be 80.8%, which is 13% more than that of Model B at the same mass flow rate of 0.025 kg/s, the channel depth ratio of 3 and the recycle ratio of 1 respectively. The thermal performance of the collectors is proportional increasing recycle ratio, air mass flow rate and channel depth ratio. It is concluded that the performance of the solar air heaters with single air pass effect by the varying channel depth ratio. The optimum value of the mass flow rate, the recycle ratio and the channel depth ratio for Model A is 0.025 kg/s, 1.0 and 3, respectively, whereas it is 0.025 kg/s, 1.5 and 3 for Model B, respectively.

A literature review reveals that although thermal energy can be stored in a various forms packed bed , phase changing materials and endothermic chemical reaction, water is still the most widely used medium. Consequently, not only does water have the ability to serve as an excellent storage medium but also to simultaneously serve as a collector of solar energy. As a result, water is able to convert intermittent solar radiation directly into a steady source of thermal energy (Kreider, J.F., *et al*., 1989).

The objective of this work is to fabricate and test a double pass solar air heater integrated with energy storage system. Water in cylindrical copper pipes is used as energy storing material. Experiments were conducted and performances were compared for different mass flow rate and with system without thermal storage.

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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, $2\ m^3/s$, 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 (α=0.92 , ε=0.28) to increase the absorptivity of the solar radiation and reduces the heat losses between the inside and outside surfaces (Rhett Noseck, 2013). 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 (Duffie, J.A., W.A. Beckman, 2013). 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 water (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).

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

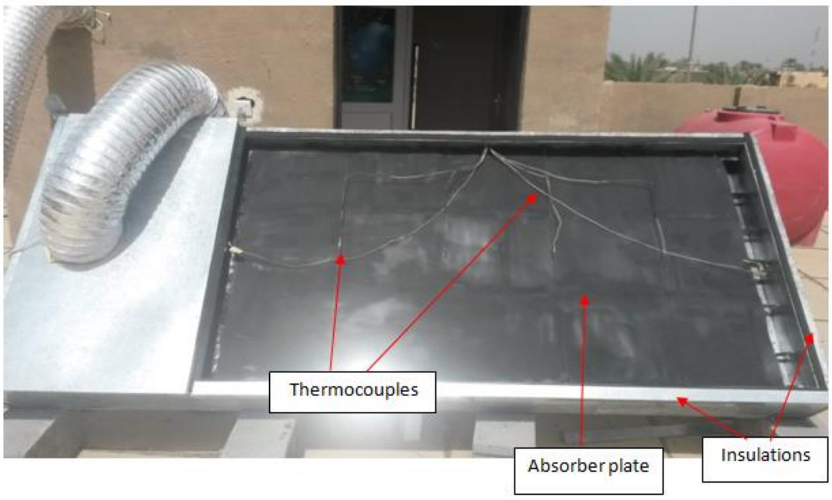

Plate 1: Double pass flat plate SAH without thermal storage.

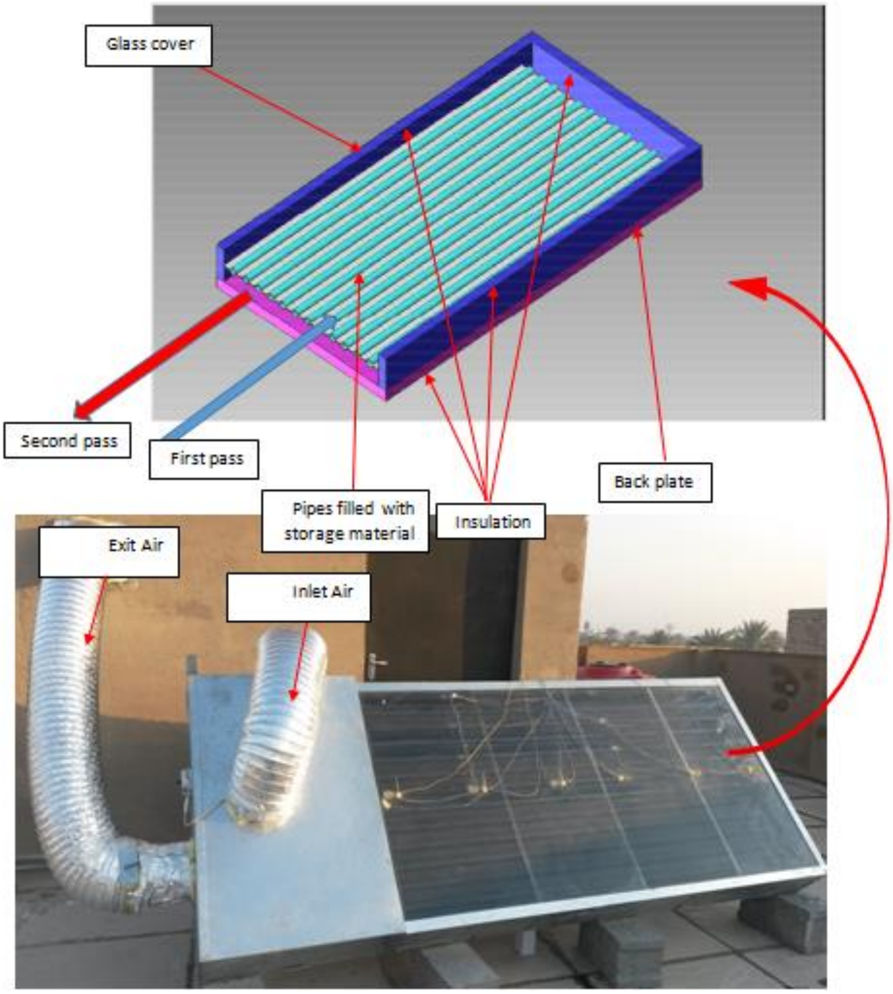

Plate 2: Double pass SAH with thermal storage.

2.2. Experimental trials:

The charging and discharging experiments are conducted to evaluate the performance of the system without and 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 (0.03, 0.035 ,0.04 , 0.45and 0.05 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:

*Fr*om the results in Fig. 1 show the variation of the solar insolation during the experiments conducted in the month of January - 2016 . It is seen from the figure, that the solar insolation increases from 200 W/m^2 at 8.00 A.M to about 725 W/m^2 around 12.00 P.M. Beyond this time, the solar insolation reduces to the end of day time at 5.00 P.M.

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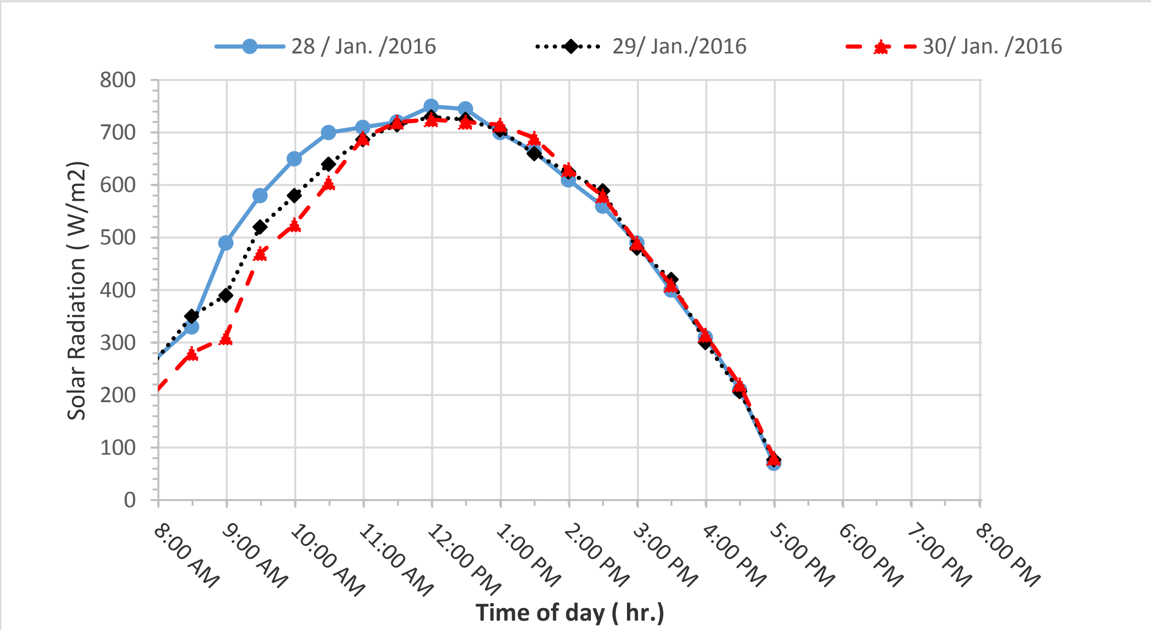

Fig. 1: Variation of solar insolation of SAH.

Fig.2 illustrate the variation of the temperatures of the exits air , upper surface, lower surface and water (T_e, T_u, T_l *and* T_w) 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_w 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_w and lead warm the water.

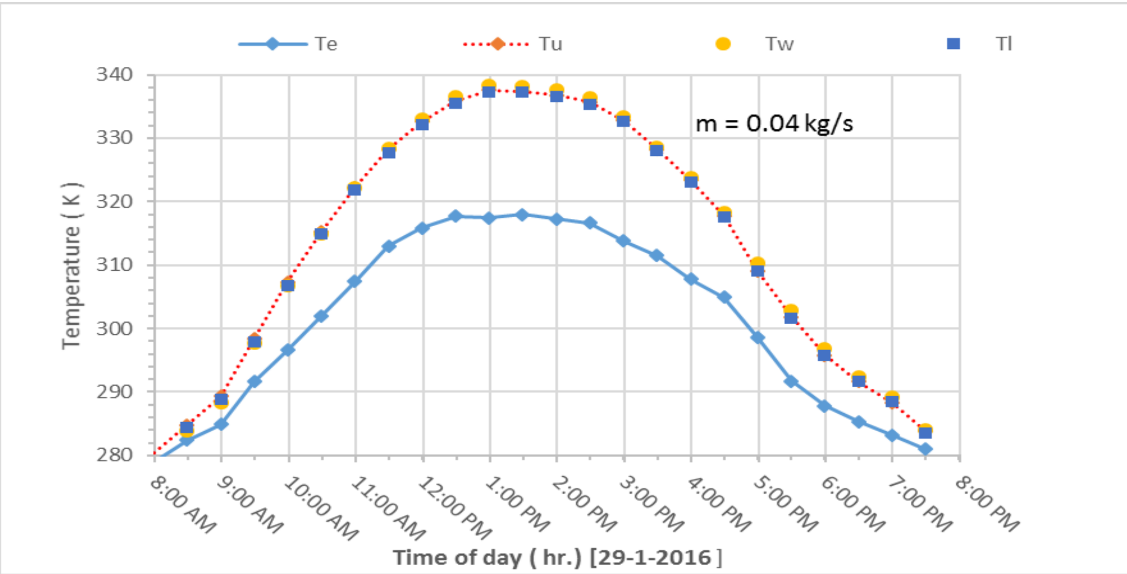

Fig. 2: Variation of the temperature of SAHWS during the day.

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. 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

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their maximum values at 12.00 P.M. The observed maximum difference air temperature ranged between 19 °C and 30°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 water and the time of discharging depend on the mass flow rate.

By using water storage, the maximum value of the outlet temperature of the flowing air was obtained as 30°C greater than the inlet temperature at noon when the mass flow rate of air is 0.03 kg/s. The average outlet air temperature was maintained at 7.6°C above the inlet temperature for 3 hours after sunset.

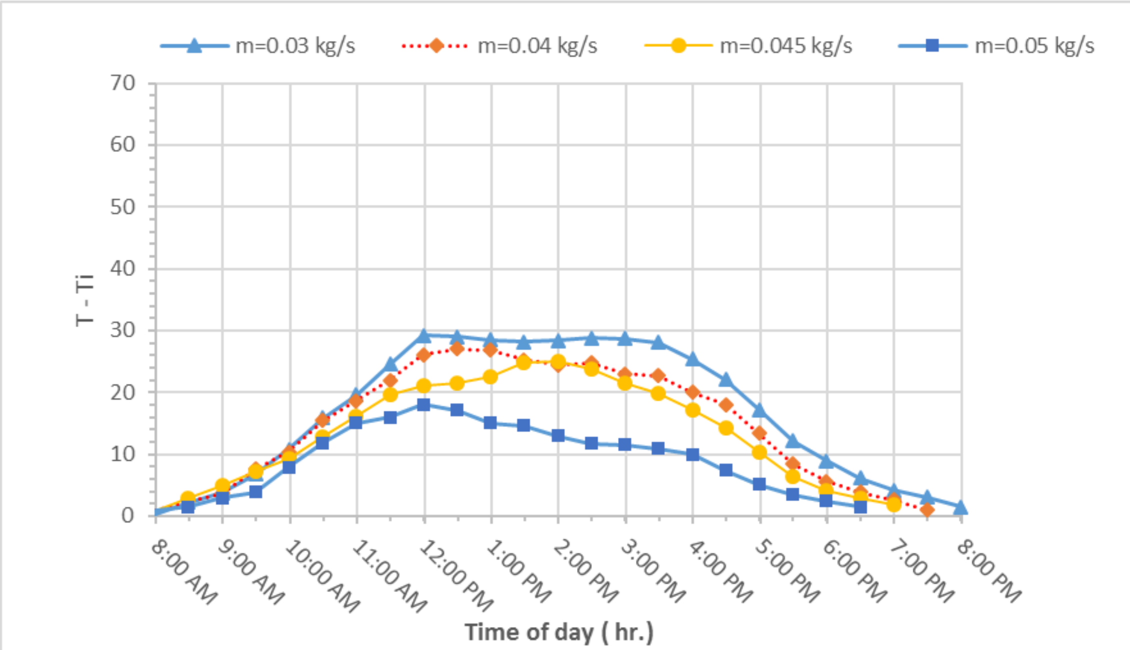

Fig. 3: Air temperature difference versus standard local time of the day at different mass flow rates for double-pass SAHWS.

Based on Duffie and Beckman (2013), the useful heat gain from SAH is :

$$Q_u = m\, C_p (T_e - T_i) \quad (1)$$

Fig.4 illustrate variation of useful energy for different values of mass flow rate . It may be concluded from Fig.4 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 decreases the useful energy . It is seen from the figure that the discharging of heat is possible for duration of 3 h, 2.5 h and 2 h when the mass flow rate is 0.03 kg/s , 0.04 kg/s , 0.045 kg/s and 0.05 kg/s respectively

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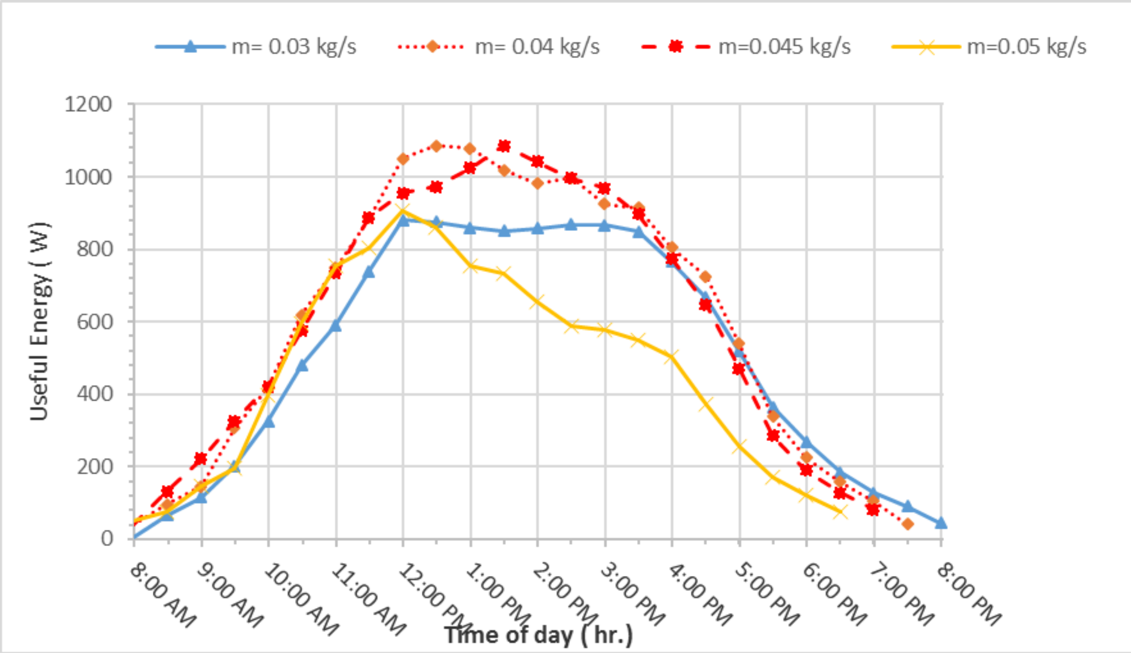

Fig. 4: Variation of useful heat gain for different values of mass flow rate.

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.

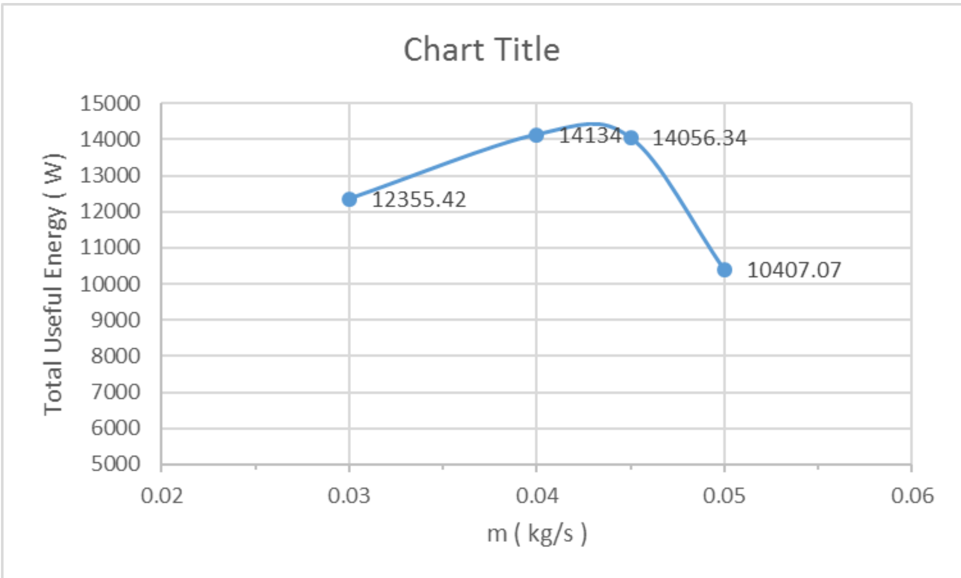

Fig. 5: Variation of total useful energy for different values of mass flow rate.

The advantage of thermal storage can be attributed to discharge the useful energy during the night as shown in Fig. 6**.**

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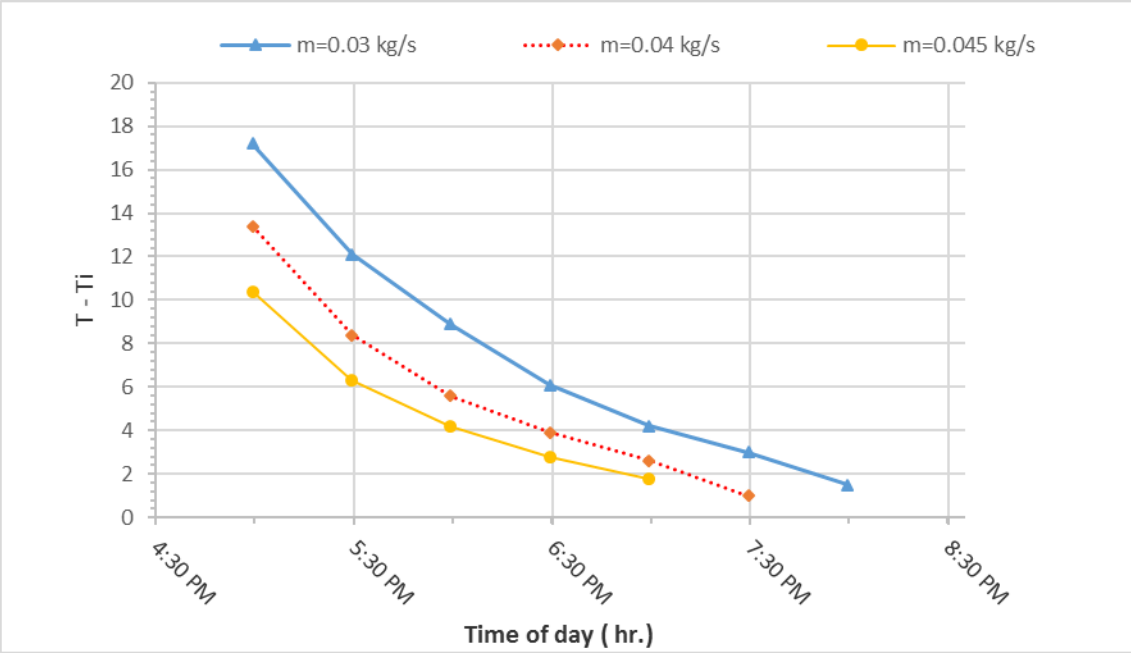

Fig. 6: Air temperature difference versus standard local time of the day during discharge period.

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

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

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). 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 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 the storage (water).

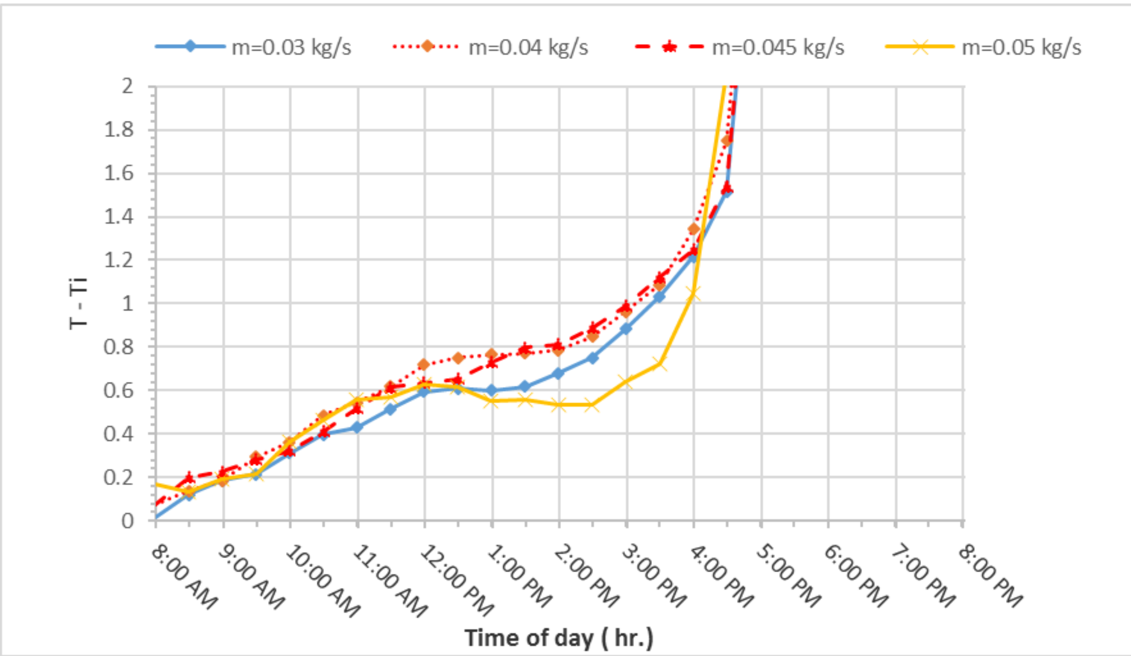

Fig. 7: Variation of the thermal efficiency for different values of mass flow rate.

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). As shown in Figs.8 for mass flow rate 0.04 kg/s the maximum air temperatures difference ($T_e - T_i$) are 28 and 24 for double pass SAHWS and SAHWOS respectively. While the maximum absorber temperatures difference ($T_b - T_i$) are 47 and 51 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.

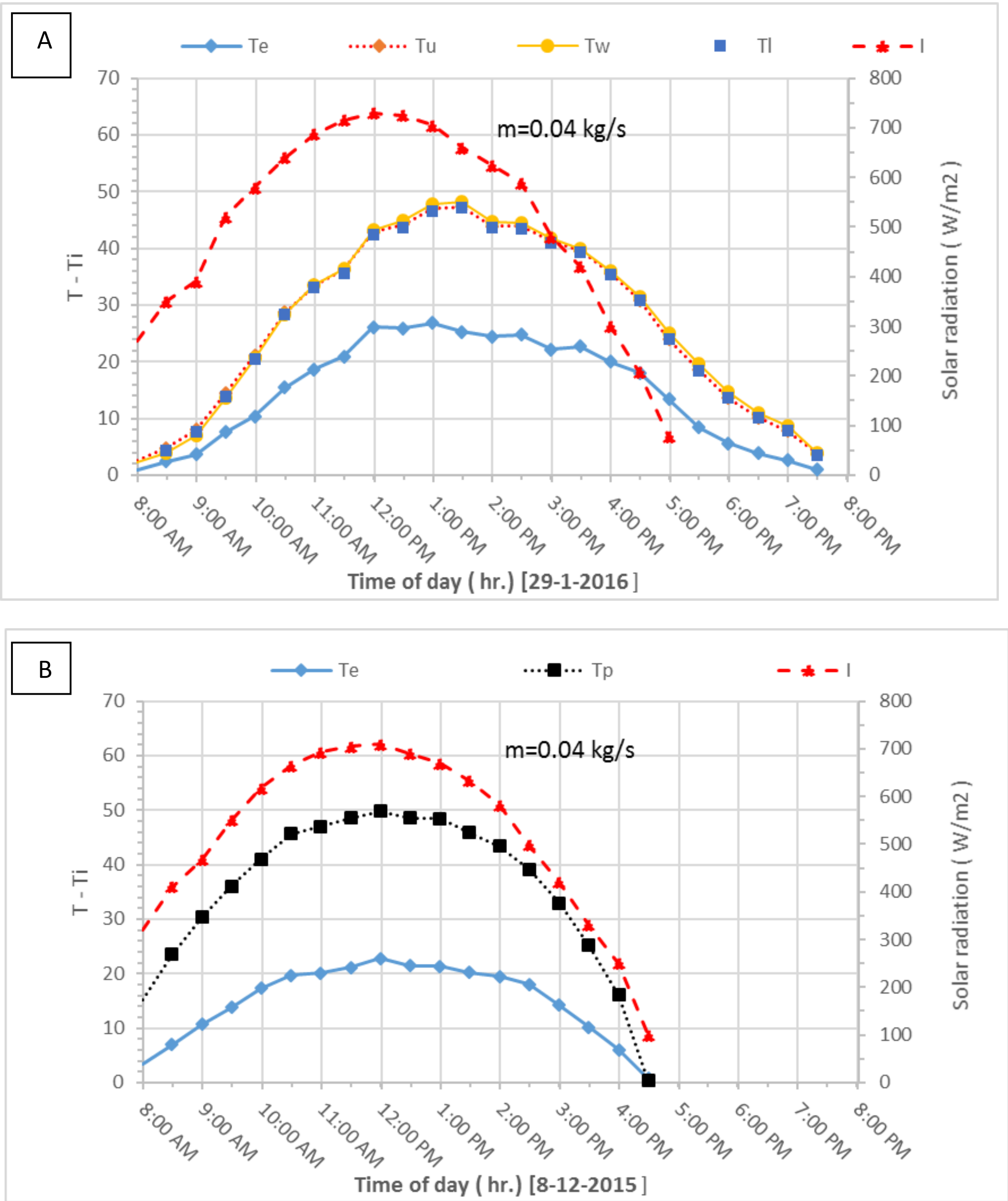

Fig. 8: Exit air, absorber temperatures difference and solar radiation versus standard local time of the day at different mass flow rates for(a)- double-pass SAHWOS and (b) - double-pass SAHWS.

Fig.9 compares the average thermal efficiency for the two configurations at various air rates. The efficiencies increased to maximum at 0.045 kg/s. The efficiency of the double pass with storage is higher than that of the single pass collector by 15-25% depending on the air mass flow rate. The maximum average

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efficiencies obtained for the double pass SAHWS and SAHWOS were 83% and 65% 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.

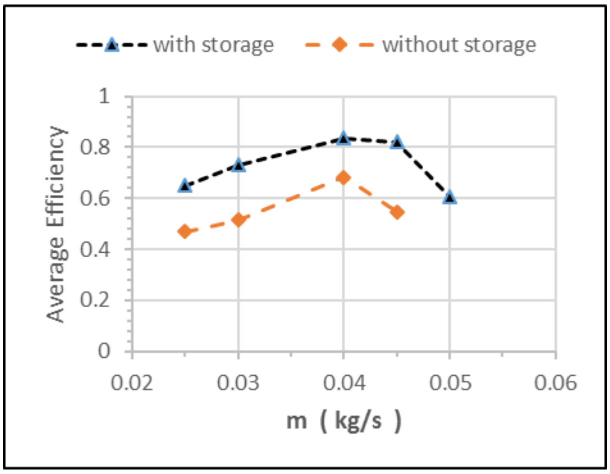

Fig. 9: Variation of the average thermal efficiency for different values of mass flow rat.

Conclusions:

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

- The thermal efficiency exceed 100% due to excess energy discharge to the air flow from water storage during discharge period.
- The average efficiency of the double pass SAH with thermal storage is higher than the double pass SAH without thermal storage for the same flow rate.
- 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 temperature difference between the outlet and the inlet decrease with increasing the air mass flow rate.
- The maximum value of the outlet temperature of the flowing air was obtained as 30°C greater than the inlet temperature.
- The hot air outlet average temperature was 7.6 °C above the inlet temperature extended for 3 hours beyond sunset time.

Nomenclature

Letter	Description
A	Collector area (m^2)
C_p	Specific heat at constant pressure
I	Solar radiation (W/m^2)
m	Mass flow rate (kg/s)
Q	Useful heat gain without storage (W)
Q_u	Useful heat gain (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
Tw	Temperature of water
α	Absorptivity
H	Thermal efficiency
ε	Emissivity

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