EXPERIMENTAL INVESTIGATION ON THE THERMAL EFFICIENCY OF A FOLDED PLATE SOLAR AIR HEATER

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ABSTRACT

The purpose of this research is to carry out an experimental investigation of folded and flat plate solar air heaters. The current experimental investigation was carried out in Ismailia, Egypt. Ismailia is located at 30.60˚ N latitude, 32.27˚ E longitude, and has an average elevation of 0 m from the sea level. The experimental run began from 8:00 am to 9 pm, with three air mass flow rates of 0.0068 ,0.048 and 0.0021 kg/ s. The parameters affecting the thermal performance of the flat and folded plate solar air heater. These parameters include solar radiation, the temperature difference of air across the heater, instantaneous thermal efficiency, and daily average efficiency. From the experimental results, it was found that the outlet temperature of the folded plate solar air heater was higher than ambient temperature by 19 ˚C during 5 h after sunset compared with 2 ˚C during 1 h after sunset for flat plate solar air heater when the mass flow rate was 0.0021 kg/s. It was also concluded that the daily efficiency of the folded solar heater was 38% higher than the corresponding values when the flat plate when the mass flow rate was 0.0068 kg/s.

Keywords**:** Solar air heater, Energy Storage, Flat Plate, PCM, Folded plate, Experimental study, Thermal performance.

1. INTRODUCTION

Due to increased energy demand and environmental issues brought on by burning fossil fuels, several countries now adopt renewable and sustainable energy sources. Solar energy, the most favorable and economical renewable energy source, has drawn a lot of attention [1,2]. This renewable energy source, however, is not usable at night or on days when it is cloudy or raining. At first, many efforts were made to improve the thermal performance of solar air heaters without any storage medium by increasing the heat transfer area, as well as improving the turbulence in the air duct by adding fins [3-5] or corrugated surfaces with various patterns [6–8]. Flat plate, finned, and v-corrugated air heaters were studied experimentally and conceptually by Karim and Hawlader [9]. In comparison to flat and finned plate collectors, they indicated that the v-corrugated collector is 10-15% and 5-11% more efficient, respectively, when m = 0.04 kg/s. El-Sebaii et al. investigated the double pass flat heater and the double pass v-corrugated [10] and finned plate [11] solar heaters experimentally and conceptually in forced convection mode. They indicated that, when m = 0.02 kg/s, the v-corrugated plate is 9.3-11% and 11-14% more efficient than the flat and finned solar air collectors, respectively.

In this work, the flat and folded plate solar air heaters are tested. The flat and folded plate solar air heaters are also tested at a wide range of mass flow rates (0.0021–0.068 kg/s). The factors influencing the thermal performance of both solar air heaters were investigated, including the temperature difference of air in the heater, the instantaneous thermal efficiency, and the daily efficiency. In this work, the folded plate solar air heaters are tested for the first time.

1.1 Thermal performance parameters

In this section, the governing equations of the thermal performance parameters of the solar air heater are evaluated as below. The useful thermal heat energy of the air across the heater (Q_u) is given by;

$$Q_u = \dot{m} C_p (T_{out} - T_{in}) \quad (1)$$

Where ṁ is flow rate of air (kg/s), C_p is specific heat (J/kg K), Tout is outlet air temperature (°C), Tin is inlet air temperature (°C).

The instantaneous thermal efficiency of the heater (gins) is given by [12];

$$\eta_{ins} = \frac{Qu}{I * Ap} \quad (2)$$

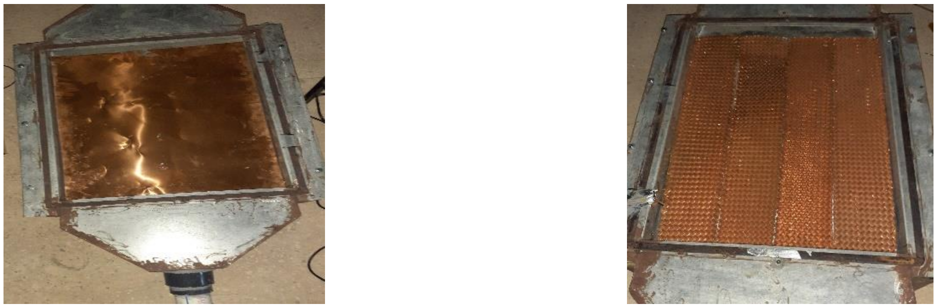
where A_p is the heater projected area (m^2) and I is the total solar radiation incident on the heater (W/m^2). The daily efficiency of the collector. (η_{da}) is defined as the accumulative heat gain by the air to the cumulative input solar heat that incident on the heater surface throughout the day which is given by [12];

$$\eta_{da} = \frac{\sum Qu}{\sum I * A} \quad (3)$$

2. EXPERIMENTAL ANALYSIS

2.1. Experimental setup for modified SAH & Conventional flat SAH

The photographic view of the experimental setup constructed for a conventional flat plate SAH and another modified SAH, as shown in Fig. 1(a) and (b). The experimental setup, essentially for each SAH, consists of a centrifugal blower, PVC connection pipe, solar air heater. The centrifugal blower was attached to an air collector inlet with a PVC connection pipe inserted with a gate valve used to control the air mass flow rate. each of the solar air heater was designed and fabricated using an available locally material according to the guidelines of ASHRAE recommendations 93–77 [13]. Both consist of a copper plate as an absorber plate. The top of each collector was covered with commercial glass plate that was coated with black mat paint to increase the absorbed heat. It was installed 5 cm above the absorber plate. The glass plate protected the hot absorber plate from the ambient environment and reduced the convective heat. The lower box of air heater were insulated with a 5 cm height foam layer.



(a) (b)

Fig. 1. Photograph for the solar air heater system (a) A conventional flat plate SAH, (b) modified SAH

2.2. Experimental setup sensors

The experimental setup was equipped with several sensors to detect and track the dynamic thermal response SAHs. Input air temperature, output air temperature, ambient air temperature, airflow velocity, and sun irradiation were all measured variables [14]. The temperatures of the moving air and the absorber surface were measured using calibrated DS-digital temperature sensors (temperature range from 10 to 125 °C and accuracy 0.5 °C). At the intake (T_{in}) and outlet, the temperatures of the air flow are measured (T_{out}). T_1, T_2, and T_3 are the surface temperatures of the absorber along its centerline, respectively. To gauge the temperatures of the glass coverings, DS-digital temperature sensors were fitted to their upper surfaces [15-19]. Additionally, a thermometer with a temperature range of 0 to 100 ˚C and an accuracy of 1 ˚C was used to measure the ambient temperature. The solar intensity was measured using the Pyranometer (TM-207) Solar Meter.

2.3. Test conditions

The current experimental investigation was carried out in Ismailia, Egypt. Ismailia is located at 30.60˚ N latitude, 32.27˚ E longitude, and has an average elevation of 0 m from the sea level. The experimental runs began from 8 am to 9 pm, from 28th June11th and 12th July 2022. The pyranometer and digital temperature sensors related to a microcontroller (ARDUINO) board coupled to a PC-Lap to observe and record the solar radiation and the different temperatures at the same time every minute automatically and accurately [20]. After that, the recorded values from ARDUINO board they were imported to the Excel sheet and saved for any predetermined data sampling rate [21-24]. A two-phase induction motor was used to blow the air through the solar air heater. The air flow rate was measured by the mean of a calibrated anemometer, with of range 0.2–10 m/s and accuracy of ±0.2 m/s, which measures the air exit velocity at ten positions of the exit pipe diameter, then the average velocity was determined to get the mass flow rate by knowing the cross section exit area and air density. The mass flow rate was (0.0068,0.0048,0.0021) kg/s.

2.4. Uncertainty analysis

Uncertainties often occur due to the errors, methodology, experimental conditions, and instrumentation during an experimental run. Hence the uncertainty analysis offers the chance to assess the errors in the measured and calculated parameters in an experimental test [25-28]. The uncertainties in the experimental results were affected by the errors in the primary measurements [29]. Experimental error analysis was checked according to Holman [30-31]. Let the result R is a given function of the independent variables.

$X_1, X_2, X_3, ..., X_n$.

$R = R\,(X_1; X_2; X_3; \dots ; X_n)$

Let W_R be the uncertainty in the result and W_1, W_2, W_3,.., W_n be the uncertainties in the independent variables X1, X2, X3,..., Xn, respectively. WR can be calculated from the following equation [14,27]

$$W_R = [(W_1 \partial R/\partial X_1)^2 + (W_2 \partial R/\partial X_2)^2 + \ldots + (W_n \partial R/\partial X_n)^2]^{0.5} \quad (4)$$

The uncertainties and relative errors in measurements of solar adiation intensity, air temperature difference across the heater, mass flow rate, useful heat gain by air and the thermal efficiency of the solar air heater are summarized in Table1.

Table 1

The uncertainties and relative errors in measurements are shown in Table 1 below.

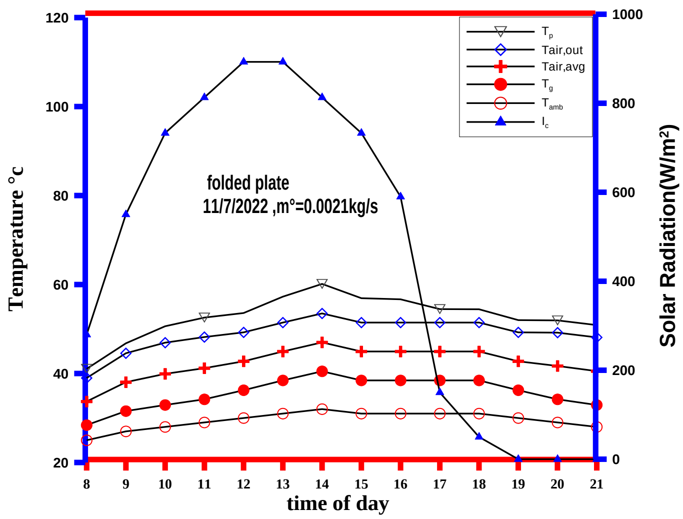
S. No.	Parameter	Uncertainty	Relative error (%)
1	Solar radiation (W/m^2)	±6	0.63
2	Temperature difference across the heater (˚C)	±0.1414	0.58
3	Mass flow rate (kg/s)	$\pm 1.039 / 10^{-3}$	1.675
4	Useful heat gain by the air (W)	±8.8106	1.2855
5	Thermal efficiency (%)	±0.01	0.0143

3. RESULTS AND DISCUSSION

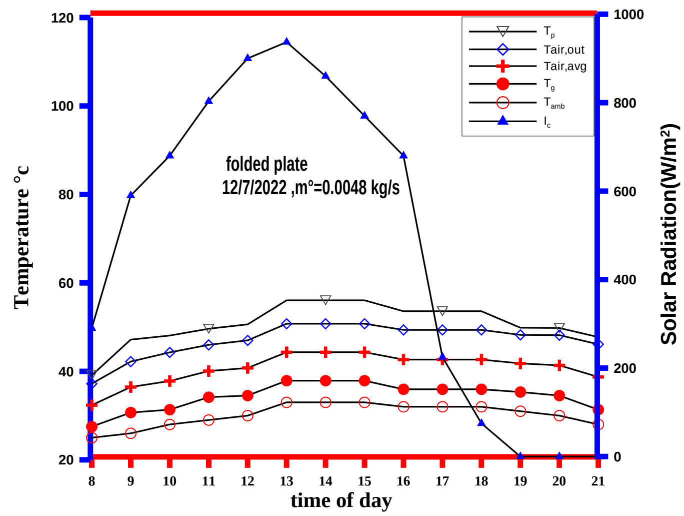
3.1 The Folded Plate Effect on Solar Air Heater

The thermal performance of the folded plate solar air heater is investigated on a wide range of mass flow rates (0.0021 -0,0048- 0.0068 kg/s). the air heater is tested with the folded plate on consecutives clear sky days of 11th of July 2022 when m˚= 0.0021kg/s, 12th of July 2022 when m˚= 0.0048 kg/s and 28th of June 2022 when m˚=0.0068 kg/s, respectively. The results are plotted in Fig. 2 (a), (b) and(c), shows measured temperatures of the different elements of the folded plate solar air heater, vs. time.

The results show that the temperatures of the various elements increase with time as the solar radiation increases but decreases by increasing in air flow rates. The maximum measured values of T_p, $T_{air,ou}$t, $T_{a,avg}$ are found for all mass flow rates occurs at 14:00 pm. As shown in Fig.2(a). The maximum measured values of Tp, $T_{air,out}$, $T_{a,avg}$ are found to be 60.00 , 53.37, 47.00 ˚C, respectively. It is also found that maximum measured solar intensity is 893 W/m^2 at 13.00 am and the ambient temperature varies between 25 and 32˚C. For Fig.2(b). The maximum measured values of T_p, $T_{air,out}$, $T_{a,avg}$ are found to be 56.06,50.77, 44.33˚C, respectively. It is also found that maximum measured solar intensity is 937 W/m^2 at 13.00 pm the ambient temperature varies between 25 and 33˚C. For Fig.2(c). The maximum measured values of T_p, $T_{air,out}$, $T_{a,avg}$ are found to be 53.45,49.88,42.83˚C, respectively. It is also found that maximum measured solar intensity is 937 W/m^2 at 13.00 pm the ambient temperature varies between 24 and 33 ˚C. Table 2 is summary for The maximum measured values of T_p, $T_{air,out}$, $T_{a,avg}$.



(a)



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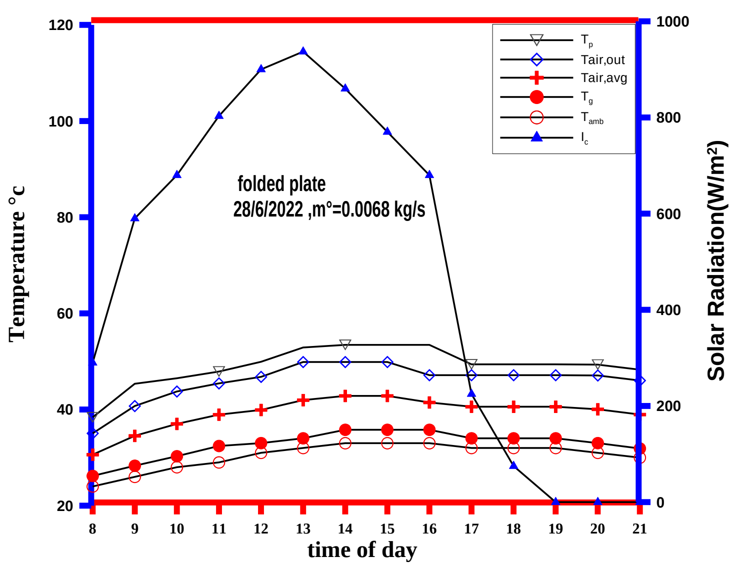


(c)

Fig.2 Measured temperatures of the different elements of the folded plate solar air heater, vs. time, when (a) m˚= 0.0021kg/s, (b) m˚= 0.0048kg/s and(c) m˚= 0.0068kg/s.

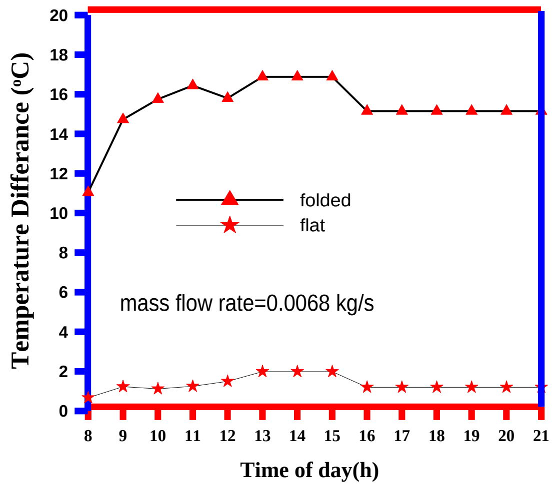
Table 2

The summary for the maximum measured values for folded plate.

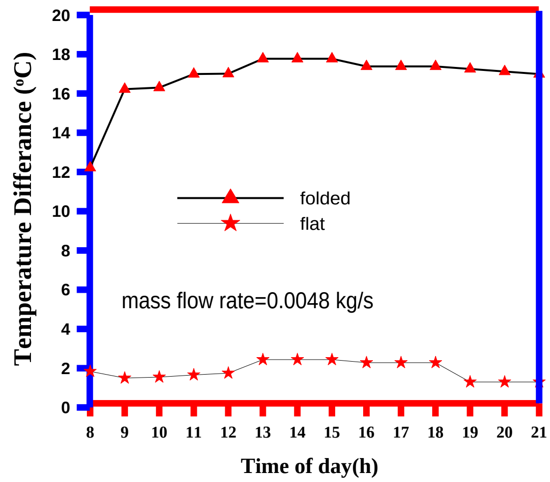
DATE	Flow rate kg/s	time for max temperature's	T_p	$Tair,_{out}$	Ta_{avg}
11/7/2022	0.0021	14 pm	60.13	53.50	47.00
12/7/2022	0.0048	14 pm	56.06	50.77	44.33
28/6/2022	0.0068	14pm	53.45	49.88	42.83

The thermal performance of the flat and folded plates arrangement solar air heater is investigated on a wide range of mass flow rates (0.0068, 0.0048 and 0.0021 kg/s). As seen in Fig. 3, the air heater is tested for the flat and folded plates when the mass flow rates are 0.0068, 0.0048and 0.0021 kg/s on consecutives clear sky days of July 2022, from 8 am to 21pm for 13 h As seen in Fig. 3(a),(b) and (c). A comparison of the temperature difference of air across solar air heaters when the mass flow rates are (0.0068 ,0.048 and 0.0021 kg/ s) is presented in Fig. 3(a),(b) and (c). According to the results obtained from Fig. 3(a),(b) and (c) and based on the temperature difference of air across the heater, it is concluded that the folded plate is more efficient than flat plate. The later result is due to the increment of heat transfer area of the folded plate compared with flat plate. Besides the folded plate increases the turbulence inside the air channel which enhances the convective heat transfer coefficient between the absorber plate and the flowing air.

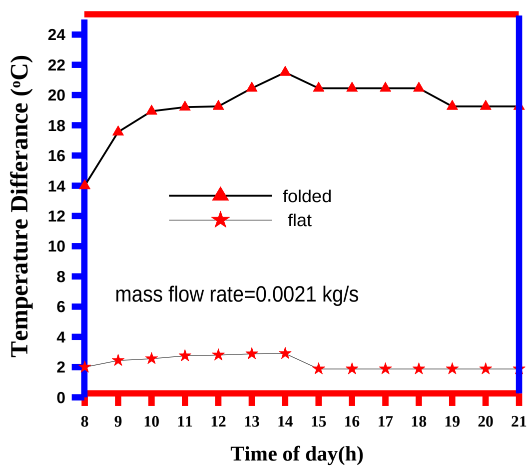
The temperature differences across the heaters increases when the mass flow rate decreases as seen in Fig. 3. (a), (b) and (c). The peak values of temperature differences across the solar heater for different types of absorber plates individually named folded and flat plate) after sunset are found to be 19and 2 °C, respectively m°=0.0021 kg/s. It is also found that the temperature differences across the solar heater go down to be zero after sunset by 5 and 1h, respectively.



(a)



(b)



(c)

Fig. 3. A comparison of the measured temperature difference of the air between folded and flat plate solar air heater when (a) m. = 0.068 kg/s, (b) m. = 0.048 kg/s and (c) m. = 0.021 kg/

3.2 Accumulated heat gains evaluation

The accumulated heat gains were calculated based on equation. (1) The total accumulated heat gains are shown in Table 3. Making an objective assessment of the dynamic thermal response and efficiency at various points during the trial run is made easier by contrasting the solar energy that was collected with the heat gains produced by the SAHs.

Table 3

Accumulated heat gains for SAHs demonstrated in Table 3 below.

Type of SAH	Air Mass Flow Rate kg/ s		
	0.0068	0.048	0.0021
Folded plate SAH	2964 KJ	2485 KJ	1303 KJ
Flat plate SAH	165 KJ	131 KJ	115 KJ

3.3. Thermal Performance Evaluation

An insightful method for evaluating energy systems with varied designs and features is energy analysis. Equation (3) was used to compute the thermal performance, which is shown in Fig. 4 . Using the specified equivalent thermal ratio, as shown in Fig. 4. With respect to the air mass flow rate, Fig. 4 compares the daily average efficiency of flat and folded plate solar air heaters. It has been found that the folded plate solar air heater has a greater daily efficiency than the flat plate solar air heater. Due to the high useful heat acquisition by air and the lower heat losses by the heater at high flow rates, all heaters become more efficient everyday as m. grows. the daily efficiency of the folded solar heater was 38% ,32% and 16% higher than the corresponding values when the flat plate when the mass flow rate was 0.0068 ,0.0048 and 0.0021kg/s , respectively.

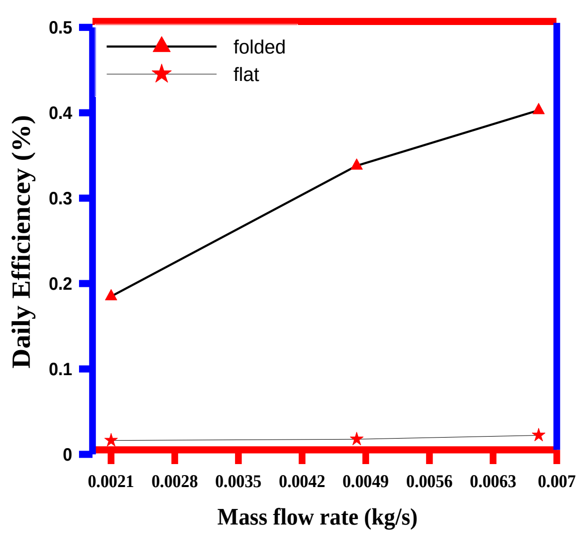


Fig. 4. A comparison of daily efficiency of flat and folded plate solar air heaters

4. CONCLUSION

Experimental research on the solar air heater was conducted for two absorber plate designs, flat and folded. On a wide variety of air mass flow rates and operating conditions, the thermal performance parameters of the folded heater are typically significantly greater than those of the flat heater. The following inferences are taken from the experimentally obtained results.

- The folded plate is more efficient than flat plate. The later result is due to the increment of heat transfer area of the folded plate compared with flat plate. Besides the folded plate increases the turbulence inside the air channel which enhances the convective heat transfer coefficient between the absorber plate and the flowing air.
- The outlet temperature of the folded plate solar air heater was higher than ambient temperature by 19 ˚C during 5 h after sunset compared with 2 ˚C during 1 h after sunset for flat plate solar air heater when the mass flow rate was 0.0021 kg/s.
- The daily efficiency of the folded solar air heater using PCM is 41% higher than the corresponding values when flat plate is used with PCM, when the mass flow rate is 0.0068 kg/s.

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APPENDIX 1

Nomenclature		Greek symbols	
p	projected cross section area of the plate (m^2)		
s	total surface area of the plate (m^2)	*ins*	instantaneous thermal efficiency of the heater
p	specific heat of the flowing air (kJ/kg ˚C)	*da*	daily average efficiency of the heater
	the total solar radiation on horizontal surface (W/m^2)	**Subscripts**	
°	mass flow rate of air (kg/s)	v	average
u	useful thermal heat energy of the air across the heater (kJ)	mb	ambient
amb	ambient temperature (˚C)		absorber
a; out	outlet temperature of air from the heater (˚C)	a	daily
am	average temperature of air inside the heater (˚C)	ns	instantaneous
p	absorber plate temperature (˚C)		inlet
pm	average value of the absorber plate temperatures (˚C)		outlet
pcm	average value of the PCM temperatures (˚C)	**Abbreviations**	
g	glass cover temperature (˚C)	CM	phase change material