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Experimental Study on Solar Air Heating

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Abstract

A new type of solar air heater was designed, fabricated, and tested in Baghdad, Iraq winter conditions. The heater consists of two main parts. The horizontal section was filled with the black colored iron chip while the vertical part has five pipes filled with Iraqi paraffin wax. A fan was fixed at the exit of the air. Two cases were studied: when the air moved by natural convection and when forced convection moved it. The studied air heater has proven its effectiveness as it heated the air passing through it to high temperatures. The results manifest that using little air movement makes the temperatures, stored energies, and efficiencies of the two studied cases converge. The suitable solar intensity of Baghdad city makes the use of solar air heater suitable to reduce the electricity and fossil fuels consumption.

Keywords: *Forced convection, iron chip, PCM, paraffin wax, solar air heater.*

1. Introduction

The demand for energy is increasing with time due to its massive consumption energy to meet the population and development's needs. The today power generation (whether for electricity or transportation) is coming mainly from fossil fuels like coal, oil and natural gas. The burning of these resources caused many environmental problems all over the world as global warming, acid rains, and the ozone hole. Today, the nation's heading towards the renewable and sustainable energies like solar energy to compensate the fossil fuels [1, 2].

Solar energy has many advantages compared to conventional fossil fuels on the environment. This energy is clean, abundant, and available all over the world. It is safe and environmental friendly [3]. The solar collectors for water heating have been used for many years with efficient operation in developed countries like the USA and Europe [4].

Solar air heaters are thermal systems used to convert the incident solar radiation into heat used to warm the air. These air heaters are used today in many applications like space heating for comfort conditions, drying agricultural plants and marine products [5]. The use of air heater reduces the dependence on fossil fuels. The air heater primarily consists of an isolated duct for hot air, a heating panel, a glass cover, and an air blower for moving air. The group has a thermally isolated absorbing plate with black color in general [6]. The glass cover allows the solar radiation to pass through it and prevents its exit. This process causes the greenhouse effect which improves the efficiency of air heater. The glass also works as part of the air duct [7].

However, these systems suffer from many problems like low convection heat transfer coefficient of air which reduces the thermal exchange between the heater and air [8, 9]. The absorber plate, in this case, will become hotter and the thermal losses will be increased through the covers. Many researchers tried to enhance the heat transfer coefficient of air and the air heater performance.

Prasad et al. [10] suggested double glassing cover for the air heater to minimize its thermal losses. Sopin et al., Ozgen et al., and Chaichan et al. [11-13] tested a double pass channel air heater where the air flows from above and then below the absorber plate. Many researchers made many modifications on the air heaters to reduce its thermal losses and increase the air heat transfer coefficient like adding fins for the double pass air heater [14]. Also, References Lertsatitthanakorn et al. [15], Esen [16], Paisaran [17], and Ho et al. [18] studied adding fins to the absorbing plate. Qenawy and Mohamad [19] and Thankur et al. [20] used a porous material to increase the heat exchange inside the air heater. The porous material consisted of wire mesh screen. Ramadan et al. [21] used limestone and gravels as a porous media while El-Sebaii et al. [22] added iron scrap to gravel and limestone.

The solar heater reliance on sunlight as the only energy source makes its use after sunset is useless. Many researchers investigated the abilities to use thermal storage materials to increase the working time of the air heater. Srivastava et al. [23] used a phase change material (lauric acid) as a heat storage material. This study increased the attention on using of phase change materials (PCM) in air heaters as it elongates the working time. The authors fingered the importance of the charging and discharging of the used PCM heat transfer characteristics. Kabeel [24] investigated the effect of adding paraffin wax as a PCM for an air heater performance. The authors presented the weather parameters affecting the performance of their module.

Chaichan et al. [25] used nano-Al_2O_3 with paraffin wax to enhance the charging and discharging process in a heat storage wall (Trombe wall). The authors claimed better thermal conductivity of nano-PCM which made the wall gained higher temperatures up to 29.08% compared to the use of paraffin wax alone. The addition of nano-Al_2O_3 to PCM made the materials stored temperature increased with about 42.68%.

Iraq is characterized by bright sun of most days of the year, with an average of 335 days, and relatively high solar radiation intensity ranging from 245 W/m^2 in winter to 980 W/m^2 at summer [26]. These conditions make Iraq a suitable location for using air heaters in all its applications that reduce the demand on electricity which the country is suffering from its lack [27].

The aim of this study is to design, fabricate and test a new type of air heater. The objective is to find a suitable, cheap, and easy to construct the system. The proposed method is useful in reducing energy and fuel consumption, which means better environment and less pollution.

2. Experimental Technique

The new designed and made solar air heater consists of a horizontal passage and a vertical passage connected. The heater has a cubic form cross section with a rib length of 20 cm. Two sides of the heater are from isolated wood covered by a copper plate painted with black, while the other two sides are from the glass with 3 mm thickness. The wood is covered with a glass wool insulator with a 1.5 cm thickness to confirm the system thermal insulation. Glass has been installed on the wood in the gaps paved in wood, and area in contact between the glass and wood was filled with silicon to ensure no leakage of hot air from the system can be exist. Fig 1 shows a schematic diagram of the studied solar air heater with its dimensions.

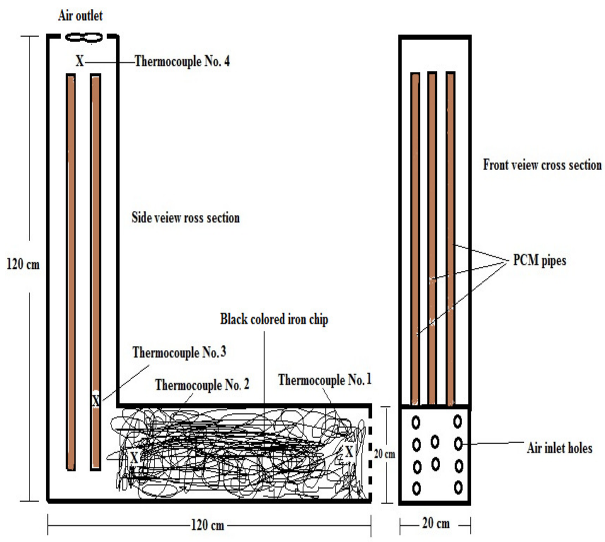

Fig. 1. a schematic diagram of the designed, fabricated, and studied solar air heater.

The horizontal part of the air heater was filled with 3 kg of iron chip colored in non- shiny black to increase the absorbed radiation. In the vertical part of the heater, five black pipes were fixed on the plate. The 5 cm diameter pipes were filled with Iraqi paraffin wax which its specification are listed in Table 1. The used paraffin wax was 10 kg. The horizontal part of the heater was closed by a piece of wood has 10 holes having diameter of 1.0 cm each. The vertical part was mounted with a wood cover with an air fan has a diameter of 7.5 cm and power of (4 watt) to force air movement from the heater to the conditioned space. Fig. 2 shows a photo of the tested air heater.

Four thermocouple type K were used to measure the temperature of the air heater parts. One thermocouple was fixed in the front of the entrance inside the chip. The second one was set at the end of the chip while the third was attached on one of the PCM pipes. The last thermocouple was fixed at the exit part of the heater before the fan. The air temperature was measured in the shadow by a thermometer.

Fig. 2. a photo of the tested air heater

Table 1,
The specifications of the paraffin wax used

Melting temperature (°C)	40
Latent heat of fusion (kJ/kg)	190
Solid specific heat (kJ/kg °C)	2.384
Liquid specific heat (kJ/kg °C)	2.49

The temperatures were tiled as the following:
T_a- the ambient air temperature.
T_1- the chip temperature at the center, near the air entrance.
T_2- the chip temperature at the center of the horizontal part of the heater.
T_3- The temperature of the middle paraffin wax pipe, in the vertical part of the heater.
T_4- The air temperature at exist of the heater.
The following equations were used to calculate the heat storage values for the air heater and its components.
The storage energy inside the air heater

$$Q_s = mc_p(T_{t+1} - T_t) \quad \text{(kJ)} \quad \dots(1)$$

The whole day storage energy

$$Q_{total} = Q_{7-8} + Q_{8-9} + \cdots + Q_{3-4} \quad \text{(kJ)} \quad \dots(2)$$

The energy drawn by fan

$$Q_u = \dot{m}_a c_{p_a}(T_{air\ out} - T_{air\ in}) \quad \text{(kW)} \quad \dots(3)$$

The total drawn energy

$$Q_{u_{total}} = Q_{u_{10-11}} + Q_{u_{11-12}} + \cdots + Q_{u_{3-4}} \quad \text{(kW)} \quad \dots(4)$$

The air flow rate

$$\dot{m}_a = AV_a\rho_a \quad \text{(kg/s)} \quad \dots(5)$$

The system efficiency

$$\eta = \frac{Q_{air}}{I \times A} \quad (\%) \quad \dots(6)$$

Error Analysis

Error analysis is used to determine the accuracy of the measurements and depends on the accuracy of readings from all the devices used in the experiments. In this study, the first measuring devices were used to measure the temperature and the second to measure the air speed. The two devices were calibrated by comparing their measurements with a standard device. Table 2 gives information about the devices used and the rate of deviation in the readings.

Table 2,
The used measuring devices in the present study.

Measuring parameter	Device name	Company	Range	Error rate
Temperature	Digital thermometer	Comark (UK)	-25 to 70°C	1.02
Air speed	Anemometer	Lutron YK-80AM	0-15 m/s	1.32

The results of the calibration showed that the error rate is calculated according to equation [28]:

$$e_R = \left[\left(\frac{\partial R}{\partial V_1}e_1\right)^2 + \left(\frac{\partial R}{\partial V_2}e_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial V_n}e_n\right)^2\right]^{0.5} \quad \ldots(7)$$

$$e_R = [(1.02)^2 + (1.32)^2]^{0.5} = 1.668$$

The error rate was less than 5% making the readings acceptable geometrically.

Experimental Procedure

The tests on the solar air heater were conducted in Baghdad city-Iraq in last two weeks of Dec-2016 and the beginning two weeks of January-2017. This month was selected due to its low ambient temperature as it has the lowest solar intensity compared to the other months. The system was fixed facing the south, and the variable temperatures were measured for two cases:

1-When the air was flow by natural convection.

2- When the air was flow by forced convection using the fan.

The tests were repeated more than three times, and the average values were taken to ensure the repeatability and to reduce the impact of uncertainty variables.

3. Results and Discussion

The solar air heater starts its work with the sun rise in the first morning, as the sunlight heats the chip in spite of its low radiation intensity values. For this reason, the temperature T_1 (35.3°C) starts higher than air temperature (2°C), as Figures 3 &4 show.

The iron chip gains heat from the sun easier and faster that the PCM for the period from 8 AM to 2 PM. After this hour, the chip temperature starts to decline rapidly whenever the sun goes down. The ambient air temperature in Baghdad climate is small in winter. However, the suggested air heater proved its effectiveness as the exit air temperatures were very high starting from 10 AM (45°C) till it reached its maximal at 2 PM (65°C).

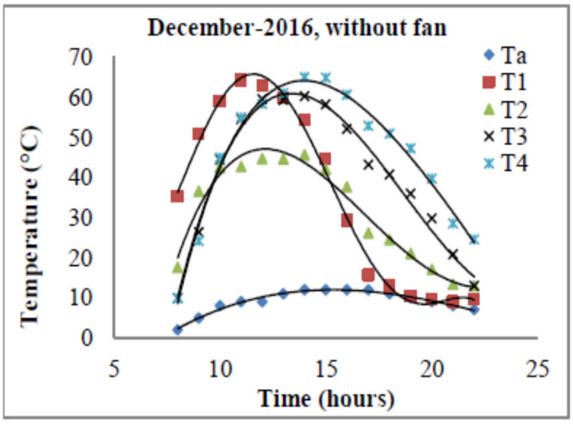

Fig. 3. The distribution of the system variable parts temperatures with time without fan

The paraffin wax starts to gain heat with a time lag compared to the iron chip. The thermal conductivity of the wax is small compared to the chip which causes this heat gain delay. The PCM temperatures increased till it reached its melting point, at which the increase in the wax temperature pause until all the wax is melted, then temperature continued to rise.

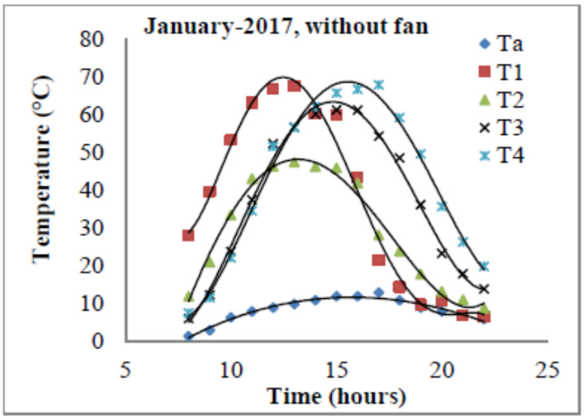

Fig. 4. The distribution of the system variable parts temperatures with time without fan

The wax temperature all the charging period (the heating time from 8 AM to 2 PM) was lower than the chip temperature. At the discharging time (from 2 PM till night) the PCM temperature was higher than the chip ones. The PCM stored more thermal energy than the chip which benefits after sunset as the exit air temperature was 24.5°C at 10 PM. The resulted temperature confirm the success of the established system as it gathers the rapid gain of heat by the chip and the high stored energy quantity by the PCM.

Figures 5 & 6 represents the measured temperature of the system variable parts with time when the air was forced to move using a fan. The used of the fan is crucial in this kind of systems to control the air mass flow rate as desired. In this case, the system was left to warm up till 10 AM; then the fan was operated. The results indicate high temperatures of the systems' parts that have tiny lower quantities compared to the free convection operation of the scheme.

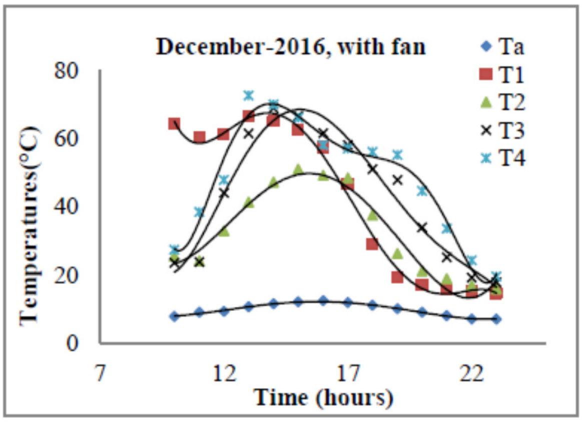

Fig. 5. The distribution of the system variable parts temperatures with time with fan

In the case of employing a fan, the chip temperatures decline rapidly in the discharging period due to the reduction in the heat supply from the sun. Here, the use of PCM as a heating source was wise as it preserved the high air temperatures. The clear sky and high solar intensity of the Iraqi winter made these temperatures possible, which means that the use of such air heaters in homes and buildings can reduce the relay on grid electricity that it is generated from fossil fuels.

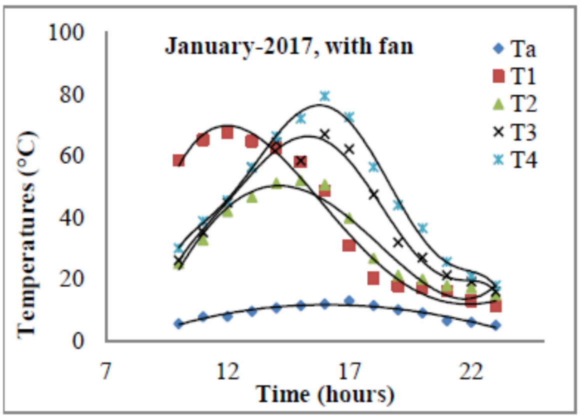

Fig. 6. The distribution of the system variable parts temperatures with time with fan

Figures 7 and 8 show the stored thermal energy variation with time. The stored energy of the chip was little compared with the paraffin wax. The maximum storing energy gained by the wax at the phase change period. The benefit of this stored energy appeared in elongating the air warming period for several hours after the heating source (the sun was set).

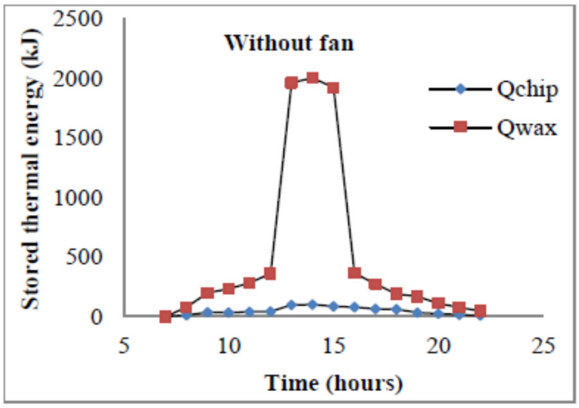

Fig. 7. Stored thermal energy variation with time.

Fig. 9 manifests the system's stored thermal energy variation with time for the two cases. The results indicate clear convergence for the two cases. The air flow rate with the fan was weak which manage the system parts to gain heat without fast cooling. The figure results support the previous conclusion about the system success in Iraqi winter weathers.

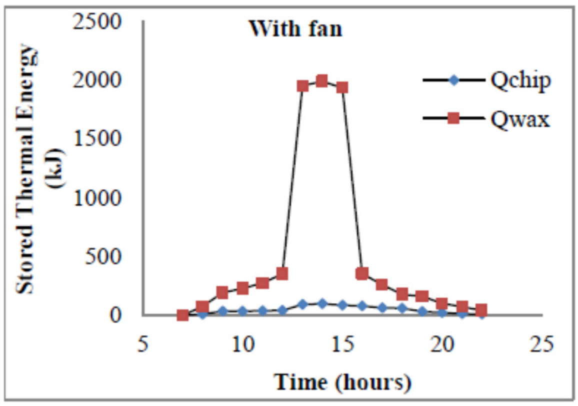

Fig. 8. Stored thermal energy variation with time.

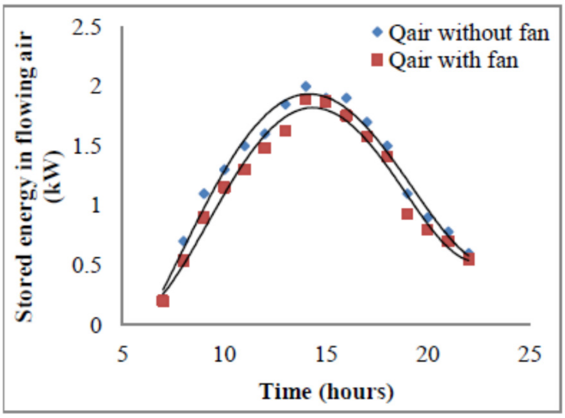

Fig. 9. The flowing air stored energy with time distribution for the studied cases.

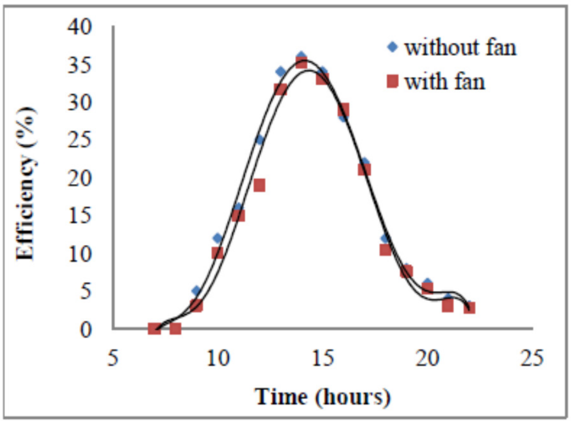

Fig. 10. The system efficiency variation with time for the studied cases.

For validation and ascertaining the quality and efficiency of the designed air heaters, it has been compared with many other devices that were tested in Iraq and other countries weathers. Table 3 lists this comparison. The table indicates that for Iraq the new solar air heater achieved the highest maximum temperature and stored energy and efficiency due to the use of the chip in addition to the PCM. For Ref. [30] the authors used in addition to PCM solar radiation concentrators to increase the incident radiation. However, the paper results converge with the recent study results. Ref [31] used square steel wire mesh with forced convection (air moving by a fan). The authors' designed system operated till 3 PM while the recent study system continued heating till 10 PM.

Table 3,
A comparison between the present study and other published researches.

Reference	Location	System type	Max. Temp. achieved	Max. stored energy achieved	Max. eff. achieved
Present study	Iraq	Chip and PCM	74°C	2100 kJ	36%
Chaichan et al. [25]	Iraq	PCM only	60°C	1300 kJ	-
Chaichan et al. [29]	Iraq	Water	48°C	-	-
Chaichan et al. [13]	Iraq	Aluminum plate	50°C	1000 kJ	-
El-Khadraui et al [29]	Tunisia	PCM	90°C	1900 kJ	32.85%
Roy et al. [30]	Bangladesh	Square wire mesh	52°C	6465 kJ	54%

4. Conclusions

In this study, a new design of solar air heater was fabricated and designed in Iraqi winter weathers. In this design iron chip and PCM were used to gain heat from the solar rays. Two cases were tested when the air passed through the air heater in natural convection and forced convection.

The resulted air temperatures explicit an increase after passing through the heater. The chip was useful in increasing the air temperature due to its high surface area of contact. The paraffin wax was a good choice as it increased the system warming time for more than four hours after sunset.

The results reveal that using a fan with low flow rate reduces the gained temperatures and stored energy but in a limited amount. The produced efficiencies in the two tested cases were convergence. The suggested system in spite of it was a prototype it confirmed its ability to warm Iraqi houses and building for a period that can exceed 14 hours/day. The use of such solar air heaters will reduce the amount of electricity and fuel consumption in winter.

Nomenclature

A	The heater area
Cp_{wax}	wax specific heat (kJ/kg. h)
$\frac{\partial R}{\partial V_1}$	The partial derivative
e_R	Uncertainty in the results
$\dot{m}_{air}$	air drawn (kg/s)
m_{wax}	wax mass (kg)
Qs_1	energy stored in the chip (kJ)
Qu	the drawn energy from the heater (kJ)
$Tair_{out}$	the delivered air temperature (K)
ρ_a	air density (kg/m^3)
Cp_{chip}	chip specific heat (kJ/kg. h)
Cp_a	air specific heat (kJ/kg. h)
e_i	Uncertainty interval in the nth variable.
I	Solar intensity (W/m^2)
m_{chip}	chip mass (kg)
Qs	Storage energy inside the air heater
Qs_2	energy stored in wax (kJ)
Q_{air}	Energy drawn by the air (kJ)
$Tair_{in}$	entering air temperature (K)
V_a	Air speed (m/s)

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الخلاصة

تم تصميم وتصنيع وفحص عمل نوع جديد من مسخنات الهواء الشمسية في اجواء مدينة بغداد- العراق. يتكون مسخن الهواء من جزئين رئيسين. الجزء الافقي ملأ برايش الحديد سوداء اللون بينما ثبتت خمسة انابيب مملوءة بمادة الشمع البرافينيي متغيرة الطور في الجزء العمودي. ثبتت مروحة عند فتحة خروج الهواء. تمت دراسة حالتين: عندما يتحرك الهواء بفعل الحمل الطبيعي والحالة الثانية عندما يتحرك بفعل الحمل القسري.اثبت مسخن الهواء المدروس كفاءته اذ انه سخن الهواء المار خلاله الى درجات حرارة عالية. بينت النتائج ان تحريك الهواء بسرع منخفضة يجعل درجات الحرارة والطاقات المخزونة و الكفاءات للحالتين المدروستين تتقارب. ان شدة الاشعاع الشمسي لمدينة بغداد مناسبه جدا لاستخدام مسخنات الهواء الشمسية والتي من شأنها ان تقلل استهلاك الكهرباء والوقود الاحفوري.