Flat solar air heater collector with phase change materials for domestic purposes in Iraqi climate

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Abstract. In this study, a solar air heater was built and flat in shape, one with a black plate to gain heat and the other was placed by a tank under this plate containing paraffin wax to increase thermal storage. Energy and exergy for air heater were also analyzed. The performance of heat air heaters was analyzed by measuring various variables such as the intensity of solar radiation, the ambient temperature, the temperature of the air inside and out of the heater, and thermal efficiency. The maximum thermal efficiency of solar heater with PCM is 16.3% compared to normal heater which was 12.4%. The addition of paraffin wax to the air heater caused an increase in the duration of air heating. The maximum exergy effectiveness of a flat solar air heater collector with heat storage materials (PCM) is 0.7%.

1. Introduction:

Global climate change has had severe consequences for people, especially their comfort conditions. Climate change has caused an increase in temperatures in countries that have traditionally been cold countries in general and decrease temperatures in countries that have always been warm countries in general [1]. In the winter, many are accustomed to using wood, coal, and fossil fuels, which are traditional heating systems and have been used for decades in both developed and developing countries. Currently, more advanced technologies are used in heating buildings such as electric heater, heating pipes, and heat pump systems. The electricity used to power these devices comes from fossil fuels, which exacerbates environmental problems such as climate pollution and global warming. Therefore, the shift to the use of renewable energies in the heating of buildings and spaces has become a goal and a target for most countries in the world that suffer from the large environment pollution and global warming effects [2]. Scientists and researchers are currently interested in developing efficient, economical and environmentally friendly energy systems. The tendency to use new renewable energies depends entirely on the geographic location and availability of such energy. For Iraq there is a large scope for the use of solar energy as the location of Iraq adjacent to the solar belt makes it receive a large intensity of solar radiation from 286 W/m2 in winter to 980 W/m2 in summer [3]. Global and local studies have demonstrated the possibility of using solar PV or solar thermal collectors to produce electricity and heat.
The heat absorbed from solar radiation can be used in solar air heating collectors to heat warm and dry crops [4]. There are many designs for solar air heaters, but generally they all consist of four main parts: (1) flat plate absorber to absorb solar energy, (2) transparent cover that allows solar energy to pass through and reduces heat loss from the absorber, (3) transfer fluid (air or water) that flows through the collector to remove heat from the absorber, and (4) a heat-insulating layer [5]. Such heaters suffer from some problems that affect their performance such as low heat transfer coefficient of air, which reduces the heat exchange between the hot plate and air, resulting in a greater heat of the absorption plate an increase in thermal losses across the lids. So, many researchers have worked to improve the heat transfer coefficient of air and raise the performance of the solar air heater [6]. Some have suggested using a double glass cover above the air heater to reduce its thermal losses [7]. Others suggested using a double channel for the heater so that the movement of air was directed upwards and then below the sucker plate [8]. Other researchers have made numerous adjustments, such as the addition of fins to the double corridor of the air heater [9]. References [10, 11] added fins to the absorber plate.

The solar air heaters dependence on solar energy available in the morning makes these heaters after sunset useless. Therefore, many researchers have studied the possibility of using the capabilities of thermal storage materials to increase the heating time of these heaters. Ref. [11] added lauric acid (phase change material) to store solar heat and the study proved that the use of these materials caused the prolongation of the operating time of the heater. The results of this study increased interest in phase change materials (PCM) and their practical use in solar air heaters. The use of PCMs in different solar applications is not unusual. Researchers used them in solar distillation units [12, 13], to cool PVT solar systems [14, 15], and were also used in thermal storage in solar thermal systems [16, 17]. Ref. [18] focused on the importance of charging and discharging heat from the PCM used depending on the heat transfer properties specifications of the PCM used. For this purpose, the researchers used paraffin wax and studied the effect of its addition on the performance of the air heater depending on the weather variables and its effect on the performance of the heaters used. Ref. [19] used PCM to maintain an appropriate thermal response to a single-pass solar air heater and experimentally investigated heat storage and recovery from PCM in the system. The authors added aluminum chip to one part of the heater to increase the exchanging surface area with air and to take advantage from this high thermal conductivity material. The results showed an improvement in the performance of the PCM system and an increase in its efficiency by 38.2%. The researchers analyzed the cost of setting up the system and found a slight margin of added cost when compared to the improved operating time of the system. Ref. [20] examined the thermal performance of a solar air heater by adding nano-SiC to PCM and aluminum chip in Baghdad-Iraq winter climate. The nano-SiC PCM and aluminum chip air heaters performance reduced the charging time by increasing the thermal conductivity of paraffin by 18.2. Adding nano-SiC to paraffin reduced its heat capacity by 4.5% and increased the working time of the solar air heater by 3 hours at night.

Iraq is one of the richest countries in oil and natural gas, and this is why it has fallen behind in the use of solar energy to rely on these two cheap sources for the country. But, this excessive burning of these fossil materials has caused high environmental pollution. The current study aims to use a solar energy application and provide a reliable model. The study evaluates the performance of a solar air heater that works by adding a specific amount of paraffin wax as a variable phase under the heating plate, which is commonly used in such heaters. The study was conducted in the winter of Baghdad for the period from 15/12/2019 to 15/1/2020.

2. Experimental setup

To study the effectiveness of the use of a two-way solar air heater in the weather conditions of the city of Baghdad, two separate systems of this type of heater were built. The first system uses a copper stained plate in black while the second system adds a paraffin tank to the bottom of this plate. Figure 1 shows a diagram of the second system composition that contains paraffin wax. Figure 2 shows a photograph of the two systems erected next to each other with the same angle of inclination (30 degrees) and facing south. A solar air heater consists of three main parts, the absorption plate, which is
usually a piece of copper and is painted in black to increase the absorbed thermal energy. The glass cover is preferably of a small thickness until the amount of heat it absorbs decreases to the most possible, a box containing the previous two parts. It is insulated to prevent hot air from leaking out. In this study, absorption boards with dimensions of $1m \times 0.9m$ were used. In an air heater containing paraffin, a box of $1$ cm depth was added to fill with this material under the absorption plate for use as a heat storage for energy absorbed from the sun. The box was made of insulated wooden pieces with glass wool to reduce thermal losses. The used glass plate is $3$mm thick. The experiments were done on the two manufactured systems when working with natural load and used a conical air outlet to increase the power due to air control in addition to increasing its speed.

The experiments were conducted at the University of Technology in Baghdad, Iraq during the winter (January). Baghdad is located at $33.34^\circ$ north latitude, $44.4^\circ$ east longitude, and $41$ meters above sea level. The pools are oriented south at $43^\circ$ (for winter load, the slope (latitude + $10^\circ$) must be for year-round use, the latitude of the slope is equal). These experiments were conducted from 10:00 AM to 5:00 PM for clear days. Solar radiation intensity, temperature, and air velocity are measured and recorded within one-time period. Solar radiation intensity meter was used to measure the solar irradiance that has an uncertainty of $1.01\%$. The temperature was measured using a K-type thermocouple and its uncertainty was $0.9\%$. Using the hot air intensity meter with uncertainty of $0.87\%$ was used to measure air velocity at heater exit. Ten thermocouples were used to measure temperature at different locations.

### Table 1. Details of air heaters double flow solar thermal collector with and without (PCM)

| No | Material                        | Thickness | Dimensions |
|----|---------------------------------|-----------|------------|
| 1  | Glass Plate: Normal Window Glass| 3 mm      | $1m \times 1m$ |
|    | Transmissivity = 0.9            |           |            |
|    | Absorptivity: 0.85              |           |            |
| 2  | Absorber material (Aluminum Black Coated) | 0.8mm | $1m \times 0.9m$ |
| 3  | Properties of the paraffin wax: |           |            |
|    | Melting point                   | 45.04 °C  |            |
|    | Specific heat                   | 2.05 kJ/kg °C |         |
|    | Latent heat of fusion           | 183.1kJ/kg |            |
|    | Density at 70°C                 | 0.769 kg/m³ |           |
| 4  | Insulation: Glass wool          | 3 cm      | $1.2 m \times 1.2 m$ |

**Figure 1.** Photographic image of the experimental set up (the flat plate collectors with and without PCM).

**Figure 2.** Photographic image of the experimental set up (paraffin wax)
3. Energy Analysis:

The first law of thermodynamics was used to analyze energy and calculate system efficiency. There is an upper limit for any solar system in which it can convert sunlight into heat and it is this convertibility that gives any solar application its efficiency. This conversion efficiency depends on the type and intensity of the solar spectrum that is connected to the application. The energy reaching the surface of the solar heater is calculated by the formula:

\[ Q_c = I_s \times A_c \]  

Where: \( Q_c \)- Energy falling on the heater; \( A_c \)- is the surface area of the heater exposed to sunlight; and \( I_s \)- is the irradiance.

The useful energy acquired by the working fluid (air) is calculated by:

\[ Q_f = \dot{m}C_p(T_o - T_i) \]  

Where: \( Q_f \)- is the absorbed energy by air, \( C_p \)- the air specific heat, \( T_o \) and \( T_i \)- are the outlet and inlet temperature, and \( \dot{m} \)- is the air mass flow rate.

The efficiency of the solar air heater system is calculated by:

\[ \eta_{th} = \frac{Q_u}{Q_c} \]  

Where: \( \eta_{th} \)- is the solar air heater thermal efficiency.

Exergy Analysis:

The exergy expresses the energy that has been converted into a beneficial form. The useful exergy for the solar heater has been calculated using the equation [20]

\[ E_x = Q_c(1 - \frac{T_a}{T_s}) \]  

Where \( T_a \)- is the ambient temperature and \( T_s \)- is assumed to be 4350 K as suggested by Ref. [21].

The flowing air exergy in the studied solar air heater is

\[ E_{xf} = \dot{m}[(h_o - h_i) - T_a(S_o - S_i)] = \dot{m}C_p[(T_o - T_i) - T_a \ln \frac{T_o}{T_i}] \]  

The exergy efficiency of the studied solar air collector is

\[ \eta_{Ex} = \frac{E_{xf}}{E_x}, \quad \eta_{E_x} = \frac{E_{xf}}{E_{xc}} \]  

4. Results and Discussion

In this study, the thermal performance of a two-pass flat solar air heater containing heat storage material (PCM) was evaluated. The PCM used is Iraqi paraffin wax; it was selected from many PCMs because of its availability, low cost and safe handling. The performance of this heater was compared to another one, which was manufactured without adding PCM to it. The experiments were conducted in the winter of Baghdad from 12/15/2019 to 15/1/2020 and this period is considered the coldest period in Iraqi winter season.

Figure 3 shows the average hourly solar radiation intensity changes for the study period from 10 AM to 5 PM. The average maximum intensity of solar radiation for the city of Baghdad during the period of practical measurements reached 503 W/m², and this density is between 12 AM to 1 PM which represents the peak period.
Figure 3. The variation of solar irradiance with time.

Figure 4 shows the variations in the outgoing air temperature of the studied heaters. Both heaters cause a significant increase in the temperature of the air passing through them, for example, the temperature of the air leaving the normal heater reached its maximum (60.1°C) at 12 AM. As for the PCM heater, its maximum temperature reached (52.2°C) at 1 PM. The air temperatures coming out of the normal heater are greater than the condition of the PCM heater during the first operating hours until around 1 PM. This is because the paraffin in the heater absorbs an important part of the heat that the plate acquires. Paraffin absorbs and stores it as latent and sensible heat. The plate achievement of temperatures higher than the melting point temperature of paraffin means that the wax in the container will completely change its phase, and therefore the benefit from it will be great. This is evident in the evening hours after 2 PM, as the usual heater air temperature drops very quickly unlike the paraffin heater, which maintains an important part of its thermal energy to heat the air during this period.

The use of paraffin in the solar air heater caused the thermal efficiency of the heater to increase to its maximum value of 16.3% at 5 PM, as shown in Figure 5. As for the maximum efficiency of the ordinary heater, it reached 12.4% at 11 AM.

Figure 6 shows the average hourly variations of the plate temperature in the normal heater, the plate temperature in the PCM heater, and the paraffin temperature. The normal heater plate temperature reached (93.7°C) at 12 AM. This degree is very high, but the high intensity of solar radiation in Baghdad has made it possible to reach it. The maximum temperature of the PCM heater plate reached (91°C) at 1 PM while the maximum temperature of paraffin reached 80°C. The temperatures reached highlight the importance of exploiting solar applications in Iraq to reduce dependence on fossil fuels.
Figure 7 shows the energy and exergy efficiencies of the PCM flat solar air heater. Exergy efficiency is lower than energy efficiency and this is caused by the loss of a major part of exergy from heat absorbed by the various parts of the heater. The maximum efficiency of a flat solar air heater with heat storage materials (PCM) was 16.3%, and its exergy was 0.7%.

5. Calculation
In this study, the performance of solar air heater in the winter season of Baghdad-Iraq was evaluated in practice. One of the two heaters (the traditional one) contains a heating plate and two air passages. The second heater is similar to it, but a phase change material (paraffin) has been added in the heater underneath the plate to increase the thermal storage. The traditional plate heater heats up more than the paraffin heater in the early morning hours, and the air temperature outside it reaches its peak (60.1°C) at 12 AM. While, the paraffin heater exit air reaches its maximum temperature at 1 PM and is less than the traditional heater condition (52.2°C). Also, the maximum thermal efficiency reached by the PCM was 16.3%, while the traditional one was 12.4%. When comparing between the thermal and exergy efficiencies of the PCM heater, it was found that the efficiency of exergy was much lower due to the loss of exergy across many components of the collector.

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