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Development of Compound Parabolic Concentrator based on Flat Plate Receiver Solar Air Heater and Phase Change Material

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ABSTRACT

This work involves an experimental investigation of a Compound Parabolic Concentrator (CPC) solar air flat plate collector with adding Phase Change Material (PCM). To explore the best model performance, the structure of CPC has two symmetric giant parabolic mirror reflectors, a concentration ratio of 1.7, similar flat plate receiver with 12 tubes filled with paraffin wax PCM. The tests were performed in April and May 2023 in Mosul City/Iraq under standard conditions for around 11 hours during the day. The outcomes indicated that a rise in air mass flowrate leads to a rise in the receiver performance. The findings confirm the thermal efficiency of 64.3% for 0.0174kg/s. For constant air flowrate, the performance of involute shape by A significant inlet temperature change has been found in CPC. It is demonstrated that phase change material and the position of the receiver have considerable influence on the model performance. The current work provides important information for evaluating the CPC model performance for Mosul/city.

1. Introduction

Solar energy, both thermal and electrical, is a very pure form of energy. Solar collectors vary by country and purpose. The literature review reveals that only the compound parabolic collector (CPC) using an evacuated tube receiver has received serious consideration. According to the study, researchers have yet to investigate how a flat plate receiver would affect CPC functionality. Population growth has increased energy demand. Creating electricity in Iraq uses a lot of fossil fuels, one of Iraq's main exports. The compound parabolic concentrator (CPC) is a promising solar collector design with a wide range of possible uses thanks to its stationary benefit for collecting giant sun rays and producing high thermal efficiency [1].

[2] The team constructed a CPC solar collector and subjected it to the local climate to see how well it would function for residential applications in Kano, Nigeria. The findings show that the collector height decreases as the concentration ratio increases and the acceptance angle increases. [3] analyzed the performance of a stationary solar collector equipped with evacuated glass and a counter-flow tube as the medium using both experimental and numerical methods. Non-imaging reflectors called exterior compound parabolic concentrators (XCPC) have been used to run the system. Optical efficiency at 200 degrees Celsius is greater than 40% when using the proposed model, which is an improvement over previous non-tracking solar systems. [4] Using a concentration ratio of 1.12, we analyzed how well the CPC collector performed between 100 and 250 degrees Celsius. The CPC was able to maintain 170 degrees Celsius for 45 minutes on September 27 with a thermal efficiency of 29%, according to laboratory tests. [5] tested the solar dryer's thermal performance with and without the PCM. The PCM showed that the drying air temperature was 2.5 to 7.5 °C higher than the ambient temperature seven hours after sunset. After 2:00 PM, the solar heater with the PCM provides drying air between 3.5 and 6.5 °C, more than those without the PCM. [6] optimized the reflector design, optical efficiency, and thermal efficiency of a CPC with an evacuated tube for use at different sun azimuths. Comparisons have been made between pressurized water and regular thermal oil. The data demonstrates that pressurized water's features (high conductivity and low dynamic viscosity) make it superior to oil for heat transfer. [7] upgraded the efficiency of the serpentine CPC collector (a hybrid of concentrating and flat plate solar collectors) by developing a new model. Based on the data, we know that the new collector can attain an efficiency of 60.5%. As the results of the experiments and simulations show, the new form of CPC makes it easier to provide low-temperature hot water for space heating in cold climates. [8] evaluated the SAH's efficacy with and without the PCM in a controlled experiment. The results demonstrated that the PCM cavity raises the outlet air temperature of the SAH using the PCM by differences of 3 °C to 7 °C when compared to those without using the PCM during the night. [9] The integrated unit's copper tubes are soldered longitudinally with black-painted copper foil, and high-quality synthetic oil called Therminol-55 is used to conserve sensible heat in these tubes. At mass flow rates of 0.017, 0.02, and 0.028 kg/s, both the revolutionary SAH and a conventional SAH without heat storage were evaluated. Maximum efficiency for the new SAH was 67.7% at 0.028 kg/s before solar radiation dropped at 14:00 h. The sensible heat storage of the absorber plate boosts thermal output. In-built-storage SAHs outperformed those without. [10] A new design method for performance optimization of a complex multi-part parabolic concentrator (M-CPC) based on a comprehensive algorithm is presented. Based on the calculation results of the program, a prototype model was created and the focused beam path of the designed model was examined with a laser. [11] Experimental study of a soil heating system for agriculture in severe cold regions based on solar concentration technology, and a novel compound parabolic concentration photothermal and photoelectricity device an experimental test system was used to investigate the relationship between the air temperature of the inlet and the outlet. The maximum air temperature of the outlet can reach 55.6 °C, the total output power of the solar cells is 474.4 W. and the thermal efficiency of the device is 60.4% during a sunny day.

This research aims to develop of new model system consisting of a Compound Parabolic Concentration (CPC) with receiver by using phase change material (PCM). The model is called involute shape CPC. Moreover, the major goal is to perform an experimental investigation to explore the effectiveness and the ability of the proposed model to decrease the electricity consumption employed for household heating air (from April 2023 to the end of May 2023) of Mosul city/Iraq by using paraffin wax PCM. The tests have been carried out. under standard conditions during daylight hours. The sun radiation of Mosul city (longitude of 43.12° E, latitude 36.34° N, and elevation 225 m above sea level) has been recorded to calculate the performance of CPC. Also, the air temperatures of the inlet, outlet, paraffin wax PCM, and air flowrate have been recorded. The current work is significantly useful in solar energy.

2. Mathematical Model

2.1 2.1 Description of Compound Parabolic Collector Model Involute Shape (CPC)

As shown in Figure 1, the reflector consists of numerous mirrors assembled into two mirrored parabolas big (AO and DO). Where AD and BC denote the aperture's width (W) and the absorber surface's width (w), respectively, the reflectors' surface areas have been constructed to be compatible with the receiver area to reflect all the incident sun rays toward the receiver surface. Parabolas 1 and 2 have their axes intersect at an angle, with B as the focus of Parabola 1 and C as the focus of Parabola 2. Points A and D on the parabola have tangents parallel to the CPC axis. In Figure. 2, the flat plate is made of an absorbent plate aluminum with 12 paraffin wax tubes organized in a zigzag shape and does not contain insulation, as all sides are covered with double glass. the distance between the receiver's bottom surface and the reflectors is optimized. To get the best possible concentration ratio A laser ray tracking method has been used to verify the reflectivity of mirrors, guaranteeing that incoming solar radiation is reflected to the receiver

2.2 Concentrating of Collector

The absorber in this research turns solar energy into heat, and the working fluid (air) transfers the heat. while most conventional collectors use either a flat plate receiver or a tubular receiver covered in black. An acceptance angle of 2θc is obtained by crossing the tangential lines that extend from the receiver to the two sides of the aperture [3].

showed Previous research that the limits of acceptance half angle (θc) have been identified between 5° and 36° [13,14].

Therefore, the formula for the highest possible theoretical concentration ratio is as follows: [13,14]:

$$C_{max} = \frac{1}{\sin \theta c} \quad \dots \dots \dots (1)$$

2.3 Collector Thermal Daily Efficiency

In most solar thermal systems, heat is extracted from the sun's rays by an absorber surface, and then transferred to the load via a heat exchange process involving the working fluid. This allows us to calculate the useful energy in the following way [14]:

$$Qu = \dot{m}_{air}\, Cp_{air}\, \Delta Ta_{ir} = \dot{m}_{air}\, Cp_{air}\, (T_{out} - T_{in}) \quad \dots (2)$$

The mass flow rate of the air ($\dot{m}$) through the heater can be calculated by using Eq. (3):

$$\dot{m}_{air} = \rho_{air}\, A_t\, V_{air} \quad \dots \dots \dots (3)$$

collector's thermal Daily efficiency (η_{da}) is the ratio of the amount of energy that is used to the amount of energy that is incident on the aperture area [3].

$$\eta_{da} = \frac{\Sigma Q_u}{\Sigma(I_T * A_{ap})} \quad \dots \dots \dots (4) \quad \text{Where } A_{ap} = AD * L$$

3. Experimental Setup and Procedures

3.1 Experiment Setup

Concentrating solar collectors, such as the one depicted in Figure 3, consist of two main parts: the reflector, the double parabolic concentrating surface,

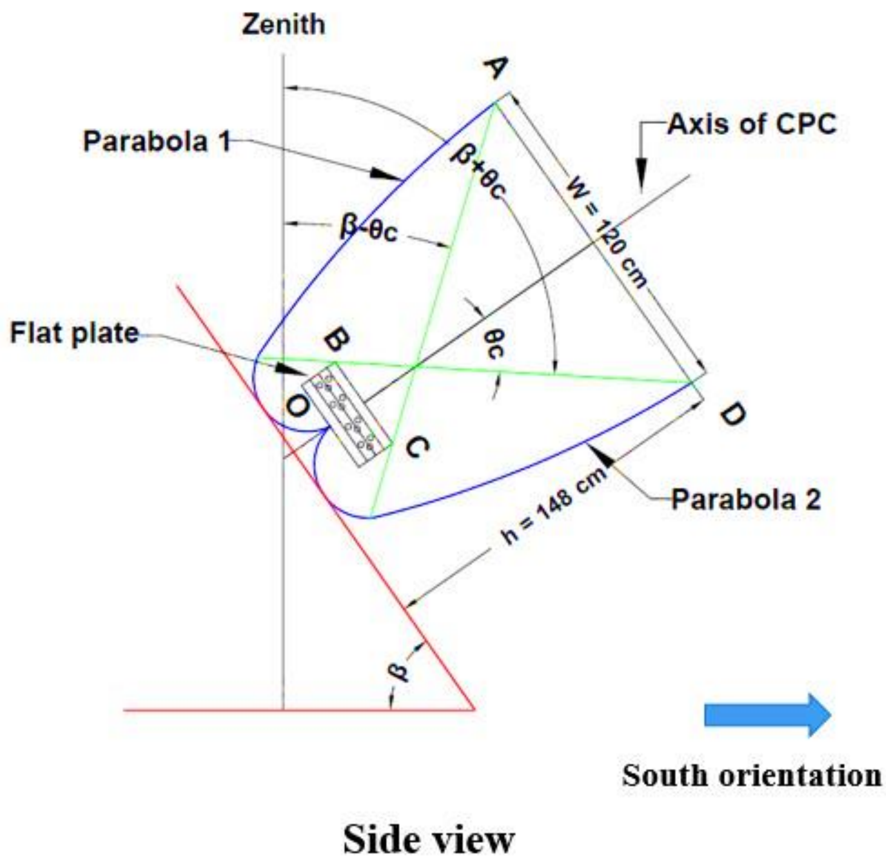

Figure 1 Schematic diagram of CPC acceptance angles

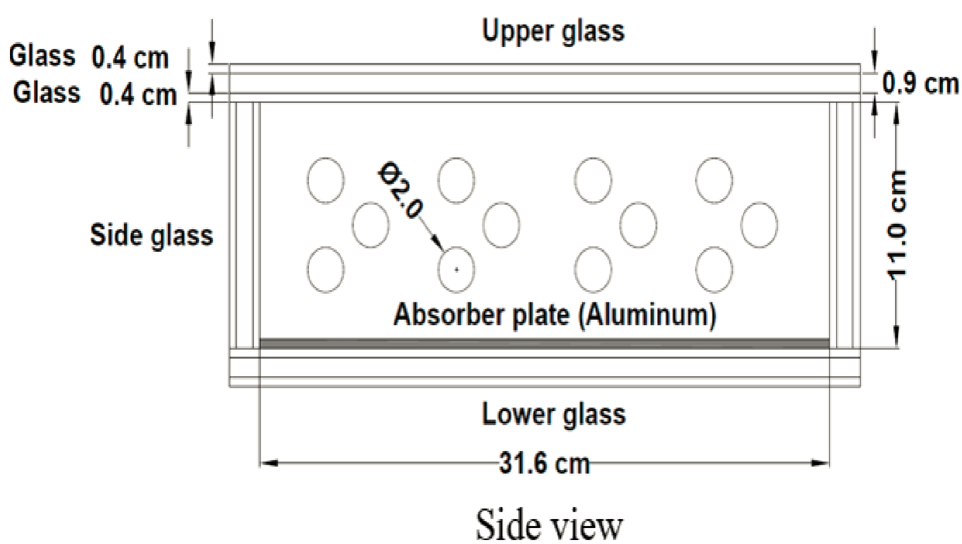

Figure 2 Schematic representation of flat plate receiver for CPC

and the parabolic iron frame. The reflector has a concentration ratio of C_{max} =1.7 due to the many mirrors that make up the concentrating surface. The second part is a flat plate identified as the absorber in Figure 2. Conductive heat loss has been minimized by enclosing the absorber with double glass on all sides. The CPC shown in Figures 1 and 2 has a flat plate receiver, the size and geometric parameters are listed in Table 1. To keep the mass flow rate of air into the absorber constant, the air has been used as the working fluid. An air AC regulator has been set up to control the airflow into the collector.

Table 2 summarizes the thermos-physical characteristics of thermal storage. The system performance was enhanced by combining a CPC collector with a flat plate (solar air heater) with the thermal storage system, i.e., phase change material. The surplus heat was stored in paraffin waxes in twelve copper tubes (each 2 cm in diameter and 135 cm in length). The absorber plate and tubes are black so that they may soak up as much sunlight as possible, and the tubes are set up in a zigzag pattern. the presence of baffles has helped to improve the heat transfer between the air and the absorbent plat and wax tube.

Laser ray tracking was used to analyze the mirror's surface and confirm that the beam from the sun was being focused onto the receiver (flat plate).

Figure 3 Test-rig experimental model

Table 1 Geometric parameters of the collector of CPC

Parameter	Symbol	Dimensions
Collectors tilt angle	β	32-24
Collectors azimuth angle	γ	0°
Collectors Disposition	--	East – West
Acceptance half angle	θ_c	35°
Absorber Area	A_c	0.5 m^2
Aperture area of the reflector	A_{ap}	1.62 m^2
Concentration ratio	C_{max}	1.7
Height of concentrator	h	148 cm
Aperture width	W	120 cm
Receiver width	w	35 cm
Receiver length	l	135 cm
Aperture length	L	135 cm
Paraffin wax tubes diameter	d_{out},d_{in}	2.0 cm, 1.8 cm
Glass thickness	τ	0.4 cm
Glass transitivity	τ_a	0.92
Absorber absorptivity	α_r	0.9
Number of paraffin wax tubes per flat plate	No.	12

Table 2 The thermo-physical properties of paraffin wax [12].

Property	Values
Melting temperature (Tm) [°C]	54-57
Specific heat (C_{ps}) [kJ/kg.K]	2
Specific heat (C_{pl}) [kJ/kg.K]	2.15
Thermal conductivity (k_s) [W/m.K]	0.22
Thermal conductivity (k_l) [W/m.K]	0.24
Density ($\boldsymbol{\rho}_s$) [kg/m3]	910
Density ($\boldsymbol{\rho}_l$) [kg/m3]	790
Latent heat of fusion [kJ/kg]	170
Volume expansion (solid/liquid phase change)	16%
Total weight of paraffin wax PCM per flat plate [kg]	1.920

3.2 Experimental Procedures

Figure 3 shows the CPC experimental method employing the flat plate receiver. This study investigated the collector's thermal performance in Mosul, Iraq, under clear skies in April and May. The ASHRAE set the collector angle at 32^o in April and 24^o in May [15] with the East-West orientation pointing south ($\gamma = 0^o$). The collector is put outdoors without blocking the sun's rays, and air flows well. All tests had a consistent flow rate by adjusting the air volume with an AC Regulator. Between 9 a.m. and 7 p.m., air flow rate, ambient air temperature, inlet and exit air temperatures, and sun radiation were measured. All readings were taken under a clear sky. Datalogging Solar Power Meters are solar irradiance meters. At the entrance and exit, a Thermometer Data Logger. To monitor airflow, an anemometer was utilized.

In this study, the airflow rate was fixed at 0.0174kg/s each month on 7/4/2023 and 15/5/2023.

4. Results and Discussion

This study aims to determine the feasibility of using a CPC-type involute Shape with a flat plate receiver to reduce the cost of air-heating electricity in homes during the winter, as well as for industrial uses and drying some agricultural products. The was operated on for at least one hour to warm the collectors before tests, in April and May of 2023, when the weather was clear, from 9 a.m. to 7 p.m., we recorded experimental observations of solar radiation, air mass flow rate ambient temperature, and air temperature at the entrance and outlet of the absorber.

Figure 4 below shows how solar radiation varies during the day as a function of daylight hours throughout both of these months. Select two days April 7, and May 15. Maximum solar radiation has been recorded in May, as shown in Fig. 4. This is because this month, the sun is higher in the sky above Mosul than in April, Furthermore, solar radiation values are slightly different between these two months. Radiation from the sun ranges from 0 W/m2 (at night) to a peak of 1200-1500 W/m2 during the day. The maximum solar radiation was measured at 1002 W/m2 on April 7th, and 1086 W/m2 on May 15th.l, it is clear that the value of solar radiation in May is more than in April during the tests' beginning (at 9 AM) and ending (at 7 PM).

Figure 5 shows the inlet and outlet air temperature for the collector CPC using the PCM versus time. The figure shows that the outlet air temperature increases with the increase of solar radiation and reaches its maximum value at 12 P.M., and 1 P.M. when the solar radiation becomes at its highest value. It was found that the maximum temperature of the outlet air was 60 °C, the temperature of paraffin wax was 71.3 °C on 7 April and temperature of the outlet air was 93.5 °C, temperature of paraffin wax was 95 °C on 15 May. The temperature difference is the increase in solar radiation in May compared to April while the inlet temperature was 24 °C, and 32 °C respectively.

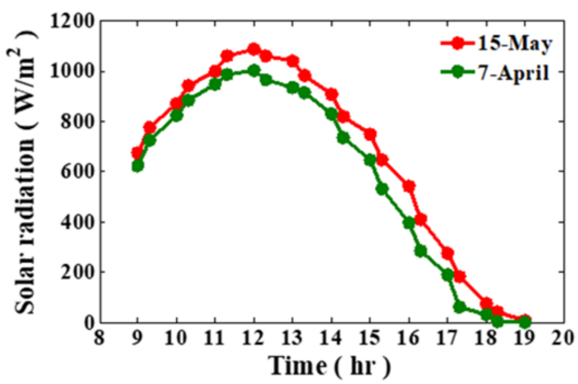

Figure 4 Variations of solar radiation as a function of daylight hours on 7 April, and 15 May.

Due to the discharge process of heat stored in paraffin wax. It was found that after sunset, the temperature of the outlet air was higher than the ambient temperature by 3 –15 °C for one hour.

For CPC, see Figure 6. The difference in air temperatures follows the same pattern as the solar radiation profile. On the other hand, paraffin wax (PCM), which acts as a thermal storage medium and allows the system to function without significant solar input until thermal equilibrium is reached, is the cause of the higher temperature after sunshine hours [9]. During the discharging process (After 03:30 P.M.), when the solar radiation decreases, the energy stored in the wax is recovered when the PCM temperature is higher than the absorber plate temperature, therefore, the air temperature difference will continue even after sunset, and then slowly decreases until be close to zero at the end of the discharge process. An intriguing important component in assessing the system's performance is the air mass flow rate.

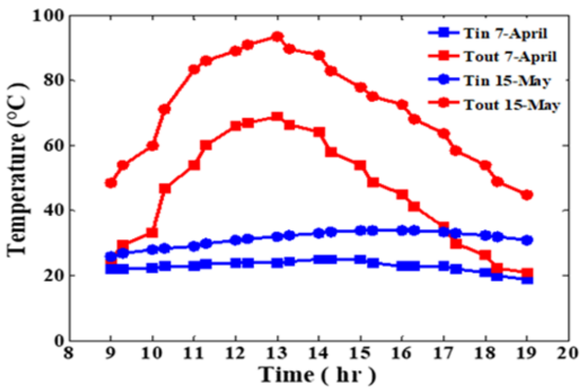

Figure 5 Variations of inlet temperature, (°C), outlet temperature, (°C), as a function of daylight hours on 7 April, and 15 May for ṁ = 0.0174 kg/s.

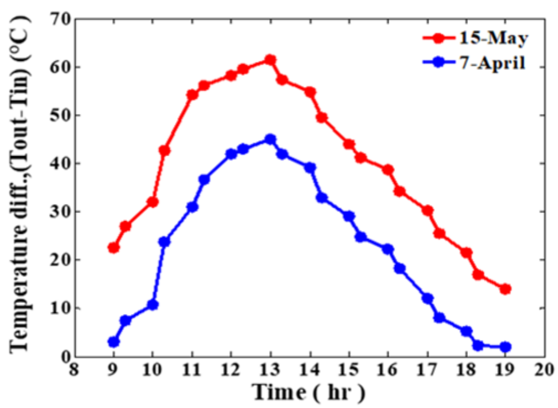

Figure 6 Variations of temperature difference, (°C), as a function of daylight hours on 7 April, and 15 May for ṁ = 0.0174 kg/s.

Figure 7 Variations of useful energy, (W) as a function of daylight hours on 7 April and 15 May for ṁ = 0.0174 kg/s. 7 The variations of useful energy along with daylight hours on two days measured at 806.8 (W) on April 7th, and 1057.6 (W) on May 15th for CPC. Similarly, to Fig. 4, the peak value of heat gained occurred between 12 PM and 1 PM due to the significant temperature difference between the outlet and the inlet temperatures of the absorber. the heat gain of CPC with the PCM will be higher, this is because the thermal energy stored in the paraffin wax will be released which leads to an increase in the outlet air temperature energy stored in the wax is recovered when the PCM temperature is higher, the outlet temperature then slowly decreases until be close to zero at the end of the discharge process (8:00 P.M.). The heat gained is enhanced as the air mass flow rate increases due to the rise in the heat exchange rate between the absorber, PCM, and air (see Eq. (3).).

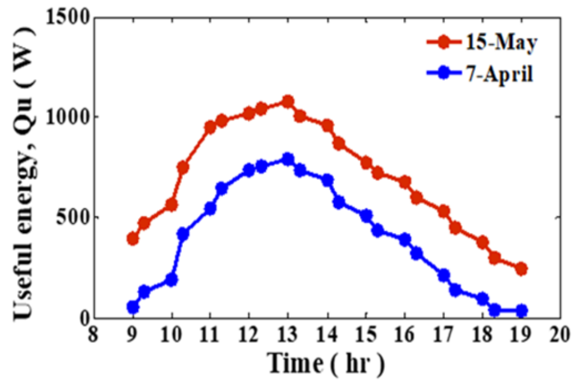

Figure 7 Variations of useful energy, (W) as a function of daylight hours on 7 April and 15 May for ṁ = 0.0174 kg/s.

Figure 8 shows the hourly variations in the thermal efficiency of CPC for the mass flow rate of 0.0174 kg/s. The thermal efficiency increased as time increased, peaking around noon; on the other hand, the system's efficiency reached its first peak around noon and the second peak towards the evening hours as the solar intensity decreased steeply. The thermal efficiency of CPC with using the PCM becomes higher due to the immense heat supplied by the PCM during the discharge process. As well as, after 04:30 P.M., the efficiency of the CPC with the PCM increases sharply and exceeds 100% after sunset. This is because of the thermal input supplied by the storage unit [9]. Also, from the results obtained, the daily efficiency was calculated. It was found that when using the energy storage system, the day-to-day efficiency of the CPC was (64.3 %) on 15 May and (41.2%) on 7 April; (see Eq. (4).). this is because of the accumulative proper heat gained by air for several hours.

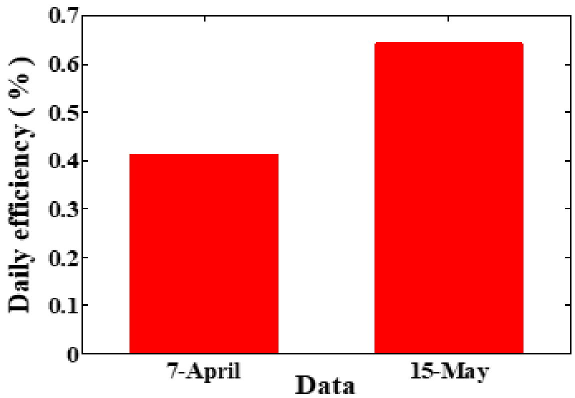

Figure 8 Variation of CPC efficiency (%) as a function of daylight hours on 7 April, and 15 May for ṁ = 0.0174 kg/s.

Conclusions and Final Remarks

This investigation focuses on the performance of the new model Compound Parabolic Concentration (CPC) solar air flat plate collectors using Phase Change Material (PCM), where the concentration ratio is equal to $Cmax$ =1.7. The tests were done under standard weather conditions in Mosul /Iraq from 9 AM to 7 PM. From this investigation, the major observations are set as follows:

1. There is a change in solar radiation from April to May. During May, solar radiation was the most powerful.
2. Experiments show that at midday the outlet air temperature is maximum. on the other hand, the temperature of the air outlet decreases as the mass flow rate increases.
3. Because of the large disparity in air temperature of the absorber, the greatest useful energy occurred at 12 PM and 1 PM.
4. The temperature of inlet air and the ambient air temperature gradually rise over the day as a result of the increased solar radiation.
5. Compound Parabolic Concentration (CPC) solar air flat plate collectors with Phase Change Material (PCM) can be used to make the most of this resource, providing a viable alternative and long-term solution for applications like household air in Mosul, industrial uses, and the drying of some agricultural products in light of the electricity problems in Iraq.

The experimental new collector was tested, and its performance was analyzed. The experiments were conducted at a mass flow rate of 0.0174 kg/s, and it was found that the performance of a solar air heater depends on the amount of solar radiation available and the geometry of the CPC.

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Nomenclature

A_{ap}	Aperture area, m^2
A_c	Receiver area, m^2
C_{max}	Maximum theoretical concentration ratio
Cp	Specific energy kJ/kg K
h	Height of truncated concentrator, m
W	Aperture width of a reflector, m
L	Aperture length of a reflector, m
w	Receiver width, m
l	Receiver length, m
Q_u	Useful energy, W
T	Temperature, °C
τ	Glass thickness, m
I_T	Total solar irradiance, W/m2
$\dot{m}$	Mass flow rate, kg/s
d	Pipe diameter, m
ρ_{air}	air density, kg/m^3
A_t	cross-section area of the exit air throat of the heater, m^2
V_{air}	airspeed at the heater exit throat, m/sec

Greek Symbols

η_{da}	Daily efficiency
θ_c	Acceptance half angle, degree
θ	Solar zenith angle, degree
β	Tilted angle, degree
γ	Collectors azimuth angle, degree
γ_s	Solar azimuth angle, degree
α_r	Absorber absorptivity
τ_a	Glass transmissivity

Subscripts

SAH	solar air heater
PCM	phase change material
amb	Ambient
in	Inlet
out	Outlet