Experimental Study of the Solar Air Heater Performance with Evacuated Tubes Connected in Series and Involving Nano-Copper Oxide / Paraffin Wax as Thermal Storage Enhancer

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Experimental study of the solar air heater performance with evacuated tubes connected in series and involving Nano-copper oxide / paraffin wax as thermal storage enhancer

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Abstract

The investment of solar energy in life applications has become mandatory in order to maintain a clean environment and reduce the use of fossil fuel. In this work, the performance of solar air heater is aimed to be improved with the help of evacuated tube solar collectors. To achieve this purpose, a system consisting of 5 linked collecting panels was designed, fabricated, and experimentally tested. Each panel included a glass-evacuated tube with two concentric aluminum tube installed inside. The system was reinforced by adding paraffin wax as a PCM and boosting its thermal conductivity by incorporating it with copper oxide nanoparticles CuO. The performance was investigated with and without Nano enhancer phase change material NE-PCM at five mass flow rates (0.006-0.008-0.01-0.03-0.05 kg/s). Experimental results reevaluated that the highest temperature was recorded as 116 °C at a mass flow rate of 0.006 kg/s. The maximum thermal efficiency with storage material was 38% at 0.05 kg/s, and the pressure drop was about 2.2kPa.

Keywords:

Evacuated tube collector; Solar air heater; Nanoparticles; Paraffin wax; Thermal efficiency; Air flow rates.

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29 *Nomenclature*

30	Ap	aperture area solar collector (m ²)
31	Cp	specific heat of air (J/kg K)
32	Do	outer diameter of tube (m)
33	k	thermal conductivity (W/m K)
34	m [·]	mass flow rate of air (kg/s)
35	m	mass of the PCM (kg)
36	N	total number of tubes
37	Pm	pumping work (W)
38	Qu	useful heat gain (W)
39	Qa	actual heat absorbed to collector (W)
40	R	insolation of solar radiation (W/m ²)
41	Ta	Ambient temperature (K)
42	ΔT	change in temperature (K)
43	ΔP	pressure drop (N/m ²)
44	H	Humidity (%)
45	Ws	Wind speed (m/s)

46

47 *Abbreviations*

48	CPC	compound parabolic collector
49	FPSC	flat plate collector
50	ETSC	Evacuated tube solar collector
51	PCM	phase change material
52	Ne-PCM	Nano-enhanced PCM
53	HTF	heat transfer fluid
54	SAH	solar air heater

55 *1 Introduction*

56 In light of high-energy costs and strict emission standards, and increasing demand for energy, natural
57 resources and renewable energy must be exploited, which is characterized by economic savings and environmental
58 cleanliness. Solar energy is the most important natural resource because has outstanding advantages, such as vast
59 availability, inexhaustibility, environmental friendliness, extensive distribution and provides various energy as
60 benefit by transform to photovoltaic, thermal, and electric energy. ([Khan et al., 2018](#); [P. Singh & Gaur, 2021](#)).Solar

collector is a well-known solar thermal energy conversion device that absorbs solar energy and converts it to a flowing fluid (water or air). The most widely used solar collectors involving evacuated tube solar collectors (ETSC), flat-plate solar collectors (FPSC), and compound parabolic concentrators (CPCs) as discussed by Kalogirou ([Kalogirou, 2004](#)). ETSC has sparked a lot of interest in both industrial and home applications around the world. This is because they cover a broad range of working temperatures and provide better warm proficiency, besides they have very small convective and radiative losses all while being reasonably priced. ([Verma, Gupta, & Rakshit, 2020](#)) Due to, many researchers have been interested in applying the vacuum tube technique to solar air heaters SAH, Its efficiency has been studied, and some modifications have been inserted to improve heat transfer like baffles , helical and concentrating reflective . This makes it more effective for low and medium temperature applications ([Korres & Tzivanidis, 2018](#); [I. Singh & Vardhan, 2021](#); [Veera Kumar, Arjunan, Seenivasan, Venkatramanan, & Vijayan, 2021](#)) But the length of the air path has a significant impact on heat transfer because it increases the heat exchange time, and this challenge leads to an increase in the number of evacuated tubes in order to extend the air path. Therefore, most of the published papers achieve the experiment between 15-30 vacuum tubes to reach the longest path .

The connection in series between the evacuated tubes was the best solution to double the air path with the least number of evacuated tubes.although this matter was not investigated except in two papers of Wang et al([Pin-Yang Wang et al., 2014](#); [Ping-Yang Wang, Li, & Liu, 2015](#)) .Reported the outlet temperature reached 230 °C when using 30 unit connected in series , each unit included a vacuum tube and CPC. In the another research the temperature dropped to 200 when used 10 units, indicating that controlling the number of connected tubes has a direct effect on outlet temperature. Energy storage was an essential role to stay on the energy source when disappearance of sunlight. Therefore, many researchers were interested in study of phase change materials (PCM) and using them with solar heaters in order to store heat for a longer time. ([Farid, Khudhair, Razack, & Al-Hallaj, 2004](#)) In solar air heaters system integrated with PCM, Many research has experimented with acetamide ([Mehla & Yadav, 2016, 2018](#)), paraffin ([Abokersh, El-Morsi, Sharaf, & Abdelrahman, 2017](#); [Algarni et al., 2020](#); [Essa, Mostafa, & Ibrahim, 2018](#); [Z. Wang et al., 2020](#)), and another material such as Stearic acid, mannitol-graphite, erythritol ([Chopra, Tyagi, Pathak, Pandey, & Sari, 2019](#); [Li & Zhai, 2017](#); [Yongtai, Lixian, & Yaohua, 2019](#)) All found that PCM increase the efficiency of thermal performance and the thermal storage where the heat lasts longer after the disappearance of sunlight. More details on evacuated tubes integrated with PCM reviewed in ref)[Aramesh & Shabani, 2020](#)(.Despite the common use of paraffin wax as PCM because it is availability in a wide range of melting points and latent heat capacities, low costs, nontoxicity, physical and chemical stability; but their thermal conductivity is low which negatively affects heat transfer ([Chaichan, Abaas, & Kazem, 2016](#)). One of the solutions discussed to overcome the problem of heat transfer is the addition of nanomaterials, which have physical

properties that increase thermal conductivity([Qureshi, Ali, & Khushnood, 2018](#)). Numerous studies were conducted with adding nanoparticles at PCM with different ratios for enhancing the thermal conductivity of storage materials ([Abdullah et al., 2020](#); [Nižetić, Jurčević, Arici, Arasu, & Xie, 2020](#); [Olfian, Ajarostaghi, & Ebrahimnataj, 2020](#)) It was found that the range of thermal conductivity was increased between 20% and 100%. Nano- enhanced of phase change material (NE-PCM) integrated with ETSC has discussed by many reviewer; They pointed out that most of the NE-PCM were applied in evacuated tube collectors were TiO_2 , CuO , Al_2O_3 , CeO CeO_2 , GNP ,Cu in addition to SWCNTs and MWCNTs have been considered by ([Babapoor, Karimi, & Sabbaghi, 2016](#); [Dsilva Winfred Rufuss, Suganthi, Iniyan, & Davies, 2018](#); [Kumar, Tiwari, & Said, 2021](#); [Xiong, Zheng, & Shah, 2020](#)). To increase the thermal performance of the system, it is critical to select the right material from among the available nanomaterials with the PCM. This emphasises the need of evaluating the physical characteristics of the resultant composites, which will considerably influence the selection of acceptable materials as nanoparticles.

In this work, the solar air heater SAH studied by five unit of evacuated tube connected in series to more the air path and thus boost the heat transfer. The Paraffin wax and copper oxide nanoparticles are mixed to enhance the thermophysical properties and improve the thermal storage performance of SAH to meet the needs of both domestic and industrial customers with simple design and low-cost materials. The experiment was conducted at five different flow rates (0.006-0.008-0.05-0.03-0.01 kg/s). Also within three consecutive months June and July and August. The experiment has achieved the thermal performance of the system with NE-PCM. This study is a unique experience in solar air heaters integrated with nanomaterials and serves as a base for future studies in the operation of SAH with evacuated tube connected in series.

2 Selection of materials

2.1 Paraffin wax as PCM

The use of PCM in solar applications has become mandatory to maintain of more operating time for application, and reducing the thermal fluctuation produced by the instantaneous solar radiation intensity fluctuation. In this work, Paraffin wax ($\text{C}_n\text{H}_{2n+2}$) it is composed of straight chain hydrocarbons with melting temperatures ranging from 23 to 67 °C([Sharma, Kitano, & Sagara, 2004](#)). Paraffin wax is an organic heat storage PCM for commercial uses; it was nominated, as a PCM for several major reasons such as is a reliable, chemically stable, high stability for very long melting cycles, nontoxic, inexpensive, and availability. Therefore, it is a good chosen as a thermal storage material in solar collector systems. Table 1 displays the properties of paraffin wax used in this experimental.

Table 1. properties of Paraffin wax used in this experimental

Property	Value
Melting temperature (°C)	59
Latent fusion heat (kJ/kg)	190
Solid state density (kg/m ³)	920
Liquid state density (kg/m ³)	790
Thermal conductivity (W/m°C)	0.21
Specific heat (kJ/kg°C)	2.3

2.2 CuO nanoparticles

Many researchers ("[Enhancements of thermal conductivities with Cu,CuO.pdf](#)," : Ghaderian & Sidik, 2017)

Adding nanomaterials into the PCM to improve the thermos-physical properties of heat storage materials. Hence improves the performance of the system in the long run of operation and obtains high thermal storage efficiency. According to Fig 1, by (Olfian et al., 2020) CuO is more common in ETSC, due to high thermal conductivity is related to its price and preparation method. In this experiment, CuO Nano- enhanced PCM was used 0.2% by weight of paraffin wax to improve the thermal conductivity and heat transfer. This ratio was chosen for two reasons. The first reason is that the cost of the solar heater is economical, as the cost of the nano is relatively expensive. The second reason is that increasing the concentration of CuO nanoparticles leads to a decrease in the melting and solidification temperature of paraffin and thus lowers the sensible and latent heat respectively(Mandal et al., 2019)

Table 2 shows characteristic of CuO nanoparticles.

Fig 1 The most common nanomaterials in scientific research

Property	Specification	148
Appearance	Black powder	149
Avg. Size	45± 7 nm	150
Density	6300 kg/m ³	151
Melting Point	1250 °C	152
Boiling Point	2000 °C	153
Thermal conductivity	33 W/m K	

2.3 NE-PCM preparation

To fill all the tubes in this experiment, the volume produced between the first and second aluminum tubes was calculated. Approximately 2.5 kg of paraffin wax was used and 5 grams of CuO nanoparticles were added as 0.2 % by weight. The ultrasonic vibrator type (TELSONIC ULTRASONICS CT-I2) is used for mix CuO nanoparticles with paraffin wax under temperature 60 °C and frequency 30 KHz. To ensure homogeneous mixing the device was used for 2 hours, and the paraffin wax color turned into black. Fig 2 depicts the steps of the compound's development, beginning with the solid state of paraffin wax and then heating it until it becomes a liquid, following which nanoparticles were added and well mixed till the compound turned black.

Fig 2 the stages of formation of the NE-PCM compound

2.4 Centrifugal air pump

The first step in choosing a fan is to figure out how much overall airflow it needs to deliver. To calculate the overall airflow demand, select an airflow rate, estimate the total quantity of application to be serviced by the fan, and multiply the airflow rate by the needed quantity.

The second step to selecting the fan is to determine the fan pressure needed to feed all the pipes in the system.

The relation between the mass flow rates and the pressure drop is direct proportion. Moreover, the number of

tubes in the system need a higher pressure to avoid the negative impact of pressure drop. Other factors such as pump size, purchase price and noise can also be considered, but the most important factor is the flow rate that is proportional to the expected operating pressure. In this experimental has been used air pump (650 W/13000 rpm) and volume flow rate is 2.8m³/min as maximum value, flow rates were changed to various value by pneumatic control valve.

3 Experimental work

3.1 Design of ETSC system

The experimental system consists of five units; each unit contained an evacuated tube with 1800 mm in length, 58 and 47 mm outer and inner diameter respectively. All the tubes are inserted with two aluminum co-axial pipe of length 1700 mm. The first is 16 mm and the second is 30 mm in diameter were welded together to form one concentric pipe and installed inside the vacuum tube as shown in Fig 3. The empty volume between the two conjoined aluminum pipes shall be filled with NE-PCM. Table 3 presents the specifications of the design.

Experimental Stand was made from aluminum metal, taking into account the right dimensions of the design as follows: 1470-length×850 high ×750 mm wide and 30° as inclined angle on the horizontal as suggested by [\(Bracamonte, Parada, Dimas, & Baritto, 2015\)](#). The evacuated tubes were set on the structure with the appropriate safeguards for non-movement induced by wind or environmental conditions in consideration. The schematic and photographic view of the setup shown in Fig 4

Fig 3 Photograph of the experimental work

Fig 4 schematic of experiment design

3.2 Experimental procedure

The system operation begins with the centrifugal pump running to flow air into the first co-axial pipe (concentric tube) into the vacuum tubes, which in turn absorbs heat and gains it on the aluminum pipe. Air is pumped to pass through each unit on a connecting track about 18 meters long. In addition, that coated with thermal insulation from the outside to reduce heat loss. Added a layer of metal mesh between the vacuum tube and aluminum pipe for more stability, and the swirling air to enhance heat transfer. The necessary filling has been placed and provided with the gaskets and rubber all test areas are sealed tightly to ensure no air leakage. Heat is transmitted to the inlet air by thermal conduction from the axial tube and when exited the air gets the heat coming directly from the vacuum tube. In other words, the inlet air runs two flights, once while entering the axial pipe and the second as it exits the vacuum tube, heading for the next unit. Therefore, the airflow inside the single pipe exceeds 3.5 meters. This means that the total distance traveled by the airflow into the five pipes is approximately 18 m during which the heat is gained. A blower is connected at the inlet of the header using 65 mm diameter flexible air hose and provided with a manually operated ball valve that regulates the rate of airflow. This experiment was done in Kafr El-Sheikh on the roof of the faculty engineering at Kafr El-Sheikh University (31.416667° N, 31.821389° E), Egypt.

Fig 5 Schematic of the air path inside the unit

Table 3 Specifications of the evacuated tube

Specifications of test rig	Value
Evacuated tube	
Number of tubes	5
Length	1800 mm
Outer Diameter (Do)	58 mm
Inner Diameter (Di)	47 mm

Collector area (A_c)	0.82 m ²
Tube material	Borosilicate glass
Transmittance (τ)	0.90
Emissivity (ϵ)	0.045
Absorptivity (α)	0.94
Co-axial Aluminum pipe	
Outer Diameter	16 mm
Inner Diameter	3 mm
Length	1700 mm
Structure frame	
Dimensions	1470×850×750 mm
Inclined angle	30°
Material	Aluminum
Blower	
Power output	620 W
No-load speed	13000/min
Max .air flow	2.8m ³ /min

3.3 Measuring instruments

This experience has been implemented and measured variables and results during the day from 7:00 Am to 5:00 Pm. The duration between each of them is 2 hours and comparing the results with the change in solar radiation intensity and different mass flow rates. Arduino software records and transfers measurement data to a computer display. All sensors are connected to the Arduino board and connect them to the computer to read the data. The temperature sensors were placed between each tube inside the connector hose to read out data for each separate tube. In addition to putting sensors inside the NE-PCM to measure its temperature during the day. The flow inlet and outlet temperatures of every unit were measured using LM35 temperature sensors of accuracy ± 0.5 °C. Two temperature sensors have been installed at the entry and exit of the unit for measured temperature rise (ΔT). The results were recorded as integer numbers and the decimal fractures were rounded. PYR-1307 pyranometer of ± 10 W/m² accuracy used to detect the intensity of solar radiation. In addition, wind speed of the surrounding across the surface of the collector is measured by anemometer PS-2174 weather anemometer with ± 3 % accuracy of reading. BMP280 and DH22 sensors measure the pressure and humidity respectively; the sensor used in this experiment has low cost and high precision at medium and low temperature.

However, do not recommend using them in industrial or high temperature applications. Table 4 show the characteristic of used sensors in the experimental.

Table 4 Specifications of measuring sensors.

Sensor	Measurement	Range	Accuracy
LM35	Temperature	-55 -150	$\pm 0.5^{\circ}\text{C}$
DH22	Humidity	0-100%	$\pm 2.5\%$
BMP280	Pressure	30-110 kpa	$\pm 10\text{ pa}$
Anemometer	Wind speed	0.5-29 m/s	$\pm 3\%$
Pyranometer	Solar radiation intensity	0–1400W/m ²	$\pm 10\text{ W/m}^2$

3.4 Error analysis

The instrumental error, environmental variables, measurement and observation errors, adequate experimental design etc. have caused experimental uncertainty. In this investigation, several sources of uncertainty were addressed throughout tests such as temperature, humidity, air velocity, intensity of radiation, pressure drop and mass flow rate. The overall measurement of uncertainty and error analysis was carried out in the way reported in Ref. ([I. Singh & Vardhan, 2021](#)).

Thus, the error of direct and indirect measurements can be calculated according to equation (1) and Table 4.

$$\frac{\delta R}{R} = \sqrt{\left(\frac{\partial R}{\partial x_1} \delta x_1\right)^2 + \left(\frac{\partial R}{\partial x_2} \delta x_2\right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} \delta x_n\right)^2} \quad (1)$$

Where $\delta x_1, \delta x_2, \delta x_3, \dots, \delta x_n$ are feasible errors in measurements of $x_1, x_2, x_3, x_n, \dots$. δR is known as absolute uncertainty and $\delta R/R$ is known as relative error and shown in Table 5

Table 5 Relative errors of measurement variables.

Parameter	Unit	Relative Error
Intensity of radiation	W/m ²	2 %
Temperature	$^{\circ}\text{C}$	0.5 %
Pressure	pa	1%
Humidity	-	2-5%
Velocity	m/s	2%

4 Thermal efficiency calculations with and without NE-PCM

It is clear that the thermal efficiency is the ratio of useful thermal energy gain by the fluid to heat absorbed by the solar collector area and intensity of radiation. The thermal efficiency of the system increases as the mass flow rates increase. The reason for this is that a reduction in pressure produces an increase in pumping power. The intensity of the solar radiation also increases the efficiency; where the maximum value appeared at 13:00 am. To calculate the total thermal energy gain, (Q_g) from system as a whole can be used

$$Q_g = \dot{m} C_p (T_o - T_i) \quad (2)$$

Where $T_o - T_i$ ($^{\circ}\text{C}$) is the difference between outlet and inlet temperatures. $\dot{m}$ denotes the mass flow rate (kg/s), C_p is specific heat of air (J/kg. $^{\circ}\text{C}$). The amount of actual thermal energy is absorbed by ETSC Q_a (J) can expressed by

$$Q_a = R A_c N \quad (3)$$

Where R is solar of radiation (W/m^2), A_c is area of collector and N is number of evacuated tubes. ([Dhiman, Thakur, Kumar, & Singh, 2011](#))

After subtracting losses from gained energy can express the actual energy gain Q_a , by

$$Q_a = \dot{m} C_p (T_o - T_i) - \frac{P_m}{C} \quad (4)$$

Where P_m (W) denotes the mechanical power, calculated from pressure losses ΔP (N/m^2) and volumetric flow rate v (m^3/s) as follows: ([Vijayan, Arjunan, Kumar, & Matheswaran, 2020](#))

$$P_m = \Delta P \frac{\dot{m}}{\rho} \quad (5)$$

The conversion factor C considering various efficiencies (thermal to mechanical) and is taken 0.2 ([Gupta & Kaushik, 2009](#)) .

The pressure drop can be calculated by taking the diameter D and the length L into account may be computed as follows ([Bagherzadeh et al., 2019](#); [Batchelor & Batchelor, 2000](#)):

$$\Delta P = f \left(\frac{L \rho V^2}{2D} \right) \quad (6)$$

Where ρ , V and f denote the density, velocity and the friction coefficient, respectively. The friction coefficient for smooth pipes may be determined as follows.

$$f = 0.316 Re^{-0.25} \quad (7)$$

$$\text{In which } Re = \frac{\rho V D}{\mu} \quad (8)$$

Thus, the effective efficiency of ETSC η_c can be calculated after the pressure loss is taken into account in the following:

$$\eta_c = \frac{Q_{\text{gain}}}{Q_{\text{actual}}} \quad (9)$$

Because PCM have sensible and latent heat, the beneficial heat gain when engaging Ne-PCM may be separated into three parts: When the PCM are in a solid state, heat gain is represented as

$$Q_{g,pcm} = m_{pcm} C_{p,pcm} (T_o - T_i)_{pcm} \quad (10)$$

The thermal energy gains when the PCM undergoes a phase change process are estimated as follows:

$$Q_{g,pcm} = m_{pcm} L_{pcm} \quad (11)$$

Where L_{PCM} is the latent heat for PCM in (J/kg)

$$\eta_{pcm} = \frac{\dot{m} C_p (T_o - T_i) - \frac{P_m}{C}}{R A_c N + m_{pcm} C_{p,pcm} (T_o - T_i)_{pcm} + m_{pcm} L_{pcm}} \quad (12)$$

5 Result and discussion

The experiments was based on connecting the tubes to each other and the changes caused by each individual tube were observed after the air passed through them. The thermal and hydraulic performances of the ETSC solar air heater in the time interval from 7:00 to 17:00 are evaluated based on the temperature rise and thermal efficiency during the months of June, July and August 2021. The effect of weather condition, mass flow rate, solar radiation and number of tubes on the thermal performance was also studied in the subsequent sections. The results were compiled daily, every two hours under different climatic conditions such as ambient temperature (T_a) 30- 40 °C, humidity(H) 50-70%, wind speed (Ws) 1- 3 m/s and solar radiation intensity (R) 950-1120 W/m². While presenting the results of the experiment, will focus on comparing the results in the month of July in particular, since it was the most radiant and compatible with the optimum temperatures. The ambient temperature and thermal efficiency increase directly with the solar radiation as discussed in ([Abi Mathew & Thangavel, 2021](#)). In the month of July, the ambient temperature was recorded between 36-40 °C. Table 6 lists the average values during the months of the experiment for solar radiation, ambient temperature, wind speed and humidity. Solar flux starts from 7:00 to 17:00; this means the ability to extract solar energy about 10 hours a day. Experimental measurements results have been recorded every two hours due to it does not happen substantial change in the solar radiation only after the passage of almost two hours.

327 *Table 6 Average value of weather parameter at different months*

Parameter in average value	June	July	August
Solar radiation	1034 W/m ²	1070 W/m ²	992W/m ²
Ambient temperature	34 °C	38°C	31°C
Wind speed	1.5 m/s	1.8 m/s	2.5 m/s
Humidity	63 %	68%	52 %

328

329 *5.1 Effect of weather conditions on outlet temperature*

330

331 The outcomes resulted in an increase in the outlet temperature from 7am to 13pm in the afternoon, after that,
 332 the intensity of solar radiation gradually decreases but the outlet temperature remains very close until 15pm. The
 333 outlet temperature for the system remains slightly good thanks to the presence of storage materials that derive
 334 energy until the disappearance of radiation at 17pm. Fig 6 shows the outlet temperatures with the onset of solar
 335 radiation until sunset, in other words, during the charging cycle for storage materials. In the period between 19
 336 pm and 1 am, the outlet temperature drops rapidly with no storage materials. In contrast, the outlet temperature
 337 gradually decreases with the presence of NE-PCM. Fig 7 shows ambient temperatures with solar radiation changes
 338 and their impact on the outlet temperature.

339 After nearly two hours of sunset at 19 pm, the outlet temperature with storage materials is almost equal to
 340 the outlet temperature without storage material. This is due to the good thermal connectivity of aluminum, which
 341 maintains its warming for two hours after sunset. In the next part, results are discussed at different flow rates and
 342 approximately equal climatic conditions.

343

Fig 6 Outlet temperatures variation during the day as solar radiation changes

Fig 7 Outlet temperatures variation with and without NE-PCM as ambient temperature changes

5.2 Effect of mass flow rate on outlet temperature

The experiment was run on five different flow rates during the same day and under close conditions to observe the effect of flow rates on the outlet temperature with and without NE-PCM. The mass flow rate is one of the main influencing parameters of the output temperature in the vacuum pipe system. The outlet temperature is inversely proportional to the flow rate of the mass where the temperature at the exit increases as the flow rate of the mass decreases due to the increased contact duration of the heat transfer. Fig 8 displays the effect of mass flow rate during the solar radiation is available in outlet temperature. This experimental study was conducted on five different mass flow rates 0.006, 0.008, 0.01, 0.03, 0.05 kg/s. The highest air outlet temperature was observed at 110 and 116 °C with and without NE-PCM respectively at a mass flow rate of 0.006 kg/s where the solar radiation was 1120 W/m² at 13:00 pm, and then the temperature was reduced. The maximum values of outlet temperature at other mass flow rate was recorded in July at 13:00 pm without NE-PCM 96, 97, 102, and 116 °C at mass flow rate 0.05, 0.03, 0.01 and 0.008 kg/s, respectively.

The ambient temperature cannot ignored because it has also had an effect in raising temperatures. The rise in temperature is noticeable when there is a change in flow rates, but the solar radiation has little effect at the beginning of the day, and the effect begins to be observed at midday, due to the continuous movement of the sun and thus irregular absorption of radiation.

380

Fig 8 Effect of mass flow rate on outlet temperature (T_o) at (a) 0.05 kg/s , (b) 0.03 kg/s , (c) 0.01 kg/s , (d) 0.008 kg/s and (e) 0.006 kg/s

5.3 NE-PCM temperature during the charge and discharge process

During the charging process before operating the system, NE-PCM acquires the heat from the solar flux and stores it, so the NE-PCM begins to melt from the top of the tube to the bottom. The temperature of the NE-PCM is derived from the ambient temperature until a solar flux is generated, and its temperature begins to rise. The temperature of NE-PCM within the units was measured for a whole day without the system running until temperature change is observed as shown in Fig 9. The temperature sensors were placed within the storage material at the top of the unit, middle and down to monitor the temperature change in storage material during operation in different flow rates as shown in Fig 10.

Fig 9 NE-PCM and ambient temperature during the experimental time

When the system is turned on, the air trajectory and flow rate have a major impact on the temperature of storage materials. The lower the flow rate, the greater the heat transmission as a result of air friction with the solar flux absorbed from the collector. NE-PCM change in the phase to the liquid situation of the highest tube due to the air running from the top. After that, the NE-PCM melts gradually to the center and then to the bottom of the tube during the absorption of solar radiation. On the other hand, the opposite happens at night, where NE-PCM loses energy from the bottom up. At an airflow rate of 0.006 kg/s, NE-PCM began to melt in the first unit at 9:30 am, while in the third unit at 9 am, and the fifth unit at 8:10 am.

In addition, the highest temperature of NC-PCM was set at 17:00 pm 83, 86 and 96 °C for the first unit, third and fifth respectively. After that, the temperature of NE-PCM decreases gradually and almost similarly in the five units, till the NE-PCM loses its heat and turns again to the solid-state. The temperature was measured at 1 am, while it ranged between 42 - 48°C, and it was noted that the temperature of NE-PCM is always higher than the ambient temperature despite the absence of sunlight. All flow rates follow the same approach, temperature rise during the period of solar radiation from top to bottom and from the fifth to the first tube. At night, the

415 storage materials lose heat from the bottom to the top of the tube and from the first tube to the fifth respectively.
416 The highest temperature of the storage material is observed at flow rates 0.008, 0.01, 0.03, 0.05 kg/s is 94, 91,
417 90, and 89°C respectively.
418

Fig 10 NE-PCM temperatures in each unit while operating the system with different flow rates
(a) 0.006 kg/s (b) 0.008 kg/s (c) 0.05 kg/s (d) 0.03 kg/s (e) 0.01 kg/s

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425

5.4 Thermal performance and storage efficiency

Based on data obtained from the solar air heater experience with the evacuated tubes connected in series, when the system is operated at different flow rates and variable solar radiation during the day. Fig 11 and Fig 12 shows the comparison in the results of thermal efficiency during the day for the system with and without NE-PCM as storage materials. It is noted that the addition of heat storage materials leads to an increase in the thermal efficiency of the system throughout the day compared to the absence of storage materials. This is because incorporating NE-PCM into the solar evacuated collector increases the system operational duration by supplying the system with thermal energy absorbed by storage materials when there is no solar radiation at night or cloudy day. Moreover, the incorporation of NE-PCM into solar collectors reduces heat loss returned via the heat pipe during the night when there is no solar radiation. It was recorded that the maximum daily thermal efficiency was achieved at an air flow rate of 0.05 kg/s by 38%, 26% with and without NE-PCM, respectively. In the pipes connected in a series, the efficiency does not increase much for two main reasons; the first is the pressure drop, which causes a loss in the gained energy. The second is because the rise temperature does not increase sufficiently with the increase in solar radiation. It is also worth noting that the thermal efficiency of the pipes connected in a series increases significantly when the air flow rates are increased and the number of system units is reduced to overcome the pressure drop. On the other hand, this may lead to a relatively lower temperature outlet, but it remains qualified for domestic applications and also drying agricultural crops.

Fig 11 Thermal efficiency with added storage material

Fig 12 Thermal efficiency without added storage material

6 Conclusion

The experimental study was based on testing the performance efficiency of solar air heater with evacuated tube solar collector connected in series at different times during the day from 7:00 am to 17:00 pm when the solar radiation changes between 950-1120 W/m². The heat transfer in the system is enhanced by combining copper oxide nanoparticles with paraffin wax to improve the thermophysical properties and increasing the distance of air travels inside the system units for heat exchange. Connecting evacuated tube in series showed a rise in temperatures when the number of tubes increased. By comparing and analyzing the results at five different mass flow rates taking into account the loss of pressure, it was observed that the temperature rises to the maximum value at a flow rate of 0.006 kg/s as the whole system. While the temperature rise between each unit increases in the first pipe and then the increase will reduce with other pipes in series. Although this technique faces some challenges, including pressure drop, which affects the overall efficiency of the thermal performance; However, it should be highlighted in the installation of solar air heater because it is remarkably effective in low and medium temperature applications. Some other conclusions are stated as below:

1- The proposed design achieved a maximum thermal efficiency of 38-26% with and without NE-PCM respectively at a flow rate of 0.05 kg/s and pressure drop was 2.2kpa of system as a whole. the efficiency of the collector decreases as the number of tubes increases, while the outlet temperature remains fixed or very little in rise. Therefore, we recommend applying this proposed system with three to five tubes only to obtain the best efficiency in series technique.

2- The highest temperature recorded 116, 115, 102, 97 and 96 °C at 13:00, with a mass flow rate of 0.006, 0.008, 0.01, 0.03, and 0.05 kg/s respectively by using 5 units in July Without adding NE-PCM.

3- The highest temperature for NE-PCM was 77 °C without running the system and 96°C when the system is operated at an airflow rate of 0.006 kg/s. in addition the maximum outlet temperature was 110°C at 13 pm.

4- The addition of CuO nanoparticles to the PCM integrated into evacuated solar collector gave an enhancement in the thermal conductivity and allowed to store more thermal energy, permitting to quickly retrieve the power after sunset.

5- In light of high-energy costs and strict emission standards, this design achieves alternative energy supply with low-cost equipment and easy installation system making it qualifications for solar air heater applications, such as heating system, drying and greenhouse.

Declaration

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

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Authors Contributions

Amr Elbrashy: Conducted all the experiments for evaluating the performance of the solar air heater

Magda Elfakharany: Processing of storage materials (paraffin wax, copper oxide nanoparticles) and mixed into the lab

Fadl Essa: Writing, formal analysis and software

Fawzy Aboutaleb: review and editing

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon request.

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