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Performance of a new solar air heater with Cu nanoparticles and PCM storage energy for nocturnal use

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ABSTRACT

This paper presents an experimental investigation of using of a phase change material (PCM) consists of paraffin wax with 1 wt% Cu nanoparticles, this composite used as a thermal storage compound in a solar air heater, the compound supposed be encapsulated in cylinders as a solar absorber in cross flow of pumped air. Hourly efficiencies were calculated in opened cycle mode. The solar energy was stored in the storage system through the diurnal period and extracted at sunset time. The experimentally obtained results are used to analyze the performance of the system, based on temperature distribution in different mass flow rates.The results show that the air temperature gained due to thermal energy discharge process decreases with increasing of air mass flow rate, and discharge time takes long time interval for the lower mass flow rates.

KEYWORDS: Thermal storage, Solar air heater (SAH), Double-pass,PCN,copper nanoparticle.

INTRODUCTION

Energy storage is not only plays an important role in the conservation of energy but also improves the performance and reliability of wide range of energy systems, and become more important where the energy sourceintermittent such as solar. The applications of solar energy for heating, can be used for many engineering applications. However, the needs for a continuous heat supply became an important issue.In the solar heating systems, water is still used as a heat storage material in liquid based systems, while a rock bed is used for air based system. When compare the volume requirements for the storage of heat energy between water and phase change material. It can be seen that the water heat storage requires almost five times amount of space as the PCM heat storage, this space savings would result in reduced costs for insulation and construction.[1]. The low thermal conductivity represents the common problem to PCMs. In recent years, several studies have been reported in the literature for enhancing the thermal conductivity of the PCMs. The proposed techniques are:-(a)providing various types of fins in the system [2,3],(b) insertion of a metal matrix [4], (c) dispersing high conductivity particles in the PCMs [5,6], and(d) encapsulating the core by multi-layers of shell materials [7]. All the above practices have certain impacts on improving the thermal conductivity, but the limitations are also obvious, like increase in the weight and volume of the storage system.Due to rapid developments of nanotechnology, a new concept of using nanoparticles with the base material has been attempted by the researchers to improve the thermal transport properties of the baseproperties of the materials. This consists of a base material and the suspendednano-sized particles of size less than 100 nm. Nanoparticles can be either nanopowders such as Al, Cu, SiC, CuO etc. or carbon nanotubes (CNT). Various nanoparticles have been usedto enhance the heat exchange between PCM and heat transfer fluid like aluminumpowder -PCM composite material.[8].Eman-Bellah *et al*. [9] investigated a method of enhancing the thermal conductivity of paraffin wax by embedding aluminum powder in paraffin wax in a water base collector. The time wise temperatures of the

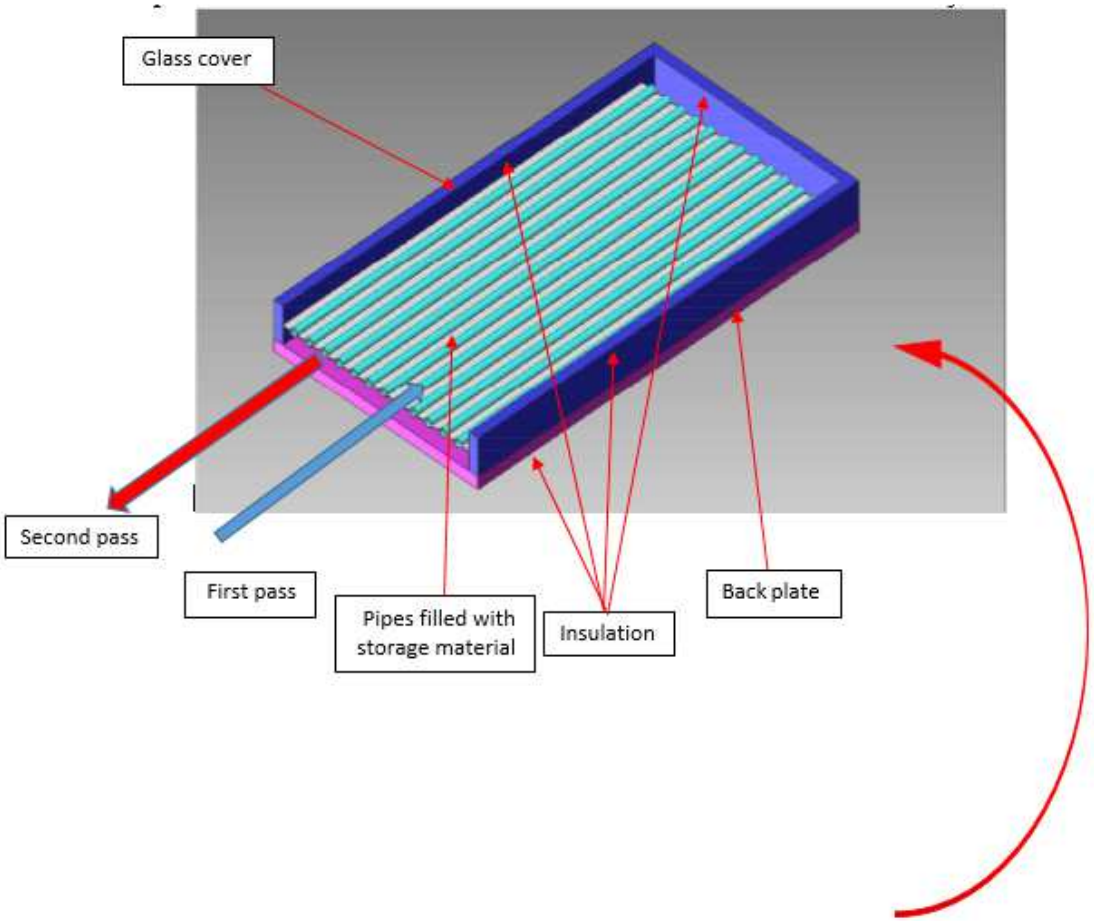
PCM were recorded during the processes of charging and discharging. In the discharging process, experiments were conducted for different water flow rates of 9-20.4 kg/h. It was found that the useful heat gainedincreased when adding aluminum powder in the wax as compared to the case of pure paraffin wax.Alkilani et al. [1] investigated theoretically of thermal and physical properties of a phase change material (PCM) consists of paraffin wax with 5% aluminum powder, this composite used as a thermal storage compound in a solar air heater, the compound supposed to be encapsulated in cylinders as a solar absorber in cross flow of pumped air. An indoor simulation supposed that the PCM initially heated by solar simulator until liquid phase temperature reaches (50°C) while the pumped air over the cylinders at room temperature (28°C), results show that the air temperature gained due to thermal energy discharge process decreases with increasing of air mass flow rate, and the freezing time for this compound takes long time interval for the lower mass flow rates. In this study a prediction of output air temperature and freezing time due to the discharge process from a PCM unit in a solar air collector, the absorber consists of PCM containers as a set of cylinders detached from each other to handle the PCM unit easily.

Many studies have been reported to increase the thermal conductivity and mechanical stability of the NFPCM for meeting requirements with thermal stability in diverse industrial applications. Shaikh et al., [10] have performed an experimental and theoretical study with regard to a change in the latent energy of shell wax, doped with single wall carbon nanotubes (SWCNT), multiwall carbon nanotubes (MWCNT) and carbon nanofibres (CNF). It was concluded that there was better enhanced thermal conductivity in the wax/SWCNT composite because of greater intermolecular attraction between them, resulting in increased latent heat. It was also proposed that the heat of fusion could be increased if the CNT/wax interaction potential is greater than that between the wax molecules. The predicted numerical values from the analytical model showed good comparison with the measured latent heat values, and laid the platform for further developments in the parametric study of the various phase change properties with the addition of nanoparticles. Liu et al.[11] performed experimental studies on the thermal conductivity and storing capacity of BaCl2 with dispersed TiO2 nanoparticles. The value of thermal conductivity increased up to 15.65%, and varies linearly with the volume fraction of nanoparticles and temperature. It was observed that nanoparticles suspended in PCMs not only enhance the heat transfer rate, but also act as nucleating agents reducing the super cooling of the suspensions. It is stated that the ending time for latent heat storage decreased considerably byfaster nucleating and improved thermal properties ofnanofluids PCM.Ho et al.,[12] have measured experimentally the effectivethermo physical properties, such as density, dynamic viscosity,latent heat of fusion and thermal conductivity foralumina nanoparticles (Al2O3) in paraffin emulsion. Theresultsrevealed that there were considerable difficulties inemulsifying the alumina nanoparticles in paraffin, especiallyfor the natural convection dominated thermal energystorage applications due to relative increase of dynamicviscosity. The enhancement in thermal conductivityshowed the non-linear dependence of the temperature andmass fraction ofnanoparticles.Wu et al.,[13] studied the melting/freezing characteristics of Cu/Paraffin nanofluids . The changes in the melting and freezing temperature were small and negligible, but with maximum latent heat reductions were 11.1 and 11.7% respectively. Shuying et at., [14] conclude that, the addition of nanoparticles enhanced the heat-transfer rate of PCM significantly. The Cu nanoparticlehas better effects than Al and C/Cu nanopowders.The results indicate that when Cuparticles are added to paraffin, the changes in themelting andfreezing temperatures are in negligible magnitudes. However,the latent heats for melting and freezing are reduced. Themaximum reduction is 11.1% for melting latent heats and11.7%for freezing latent heats, respectively.After 100 heatingand cooling cycles, Cu/paraffin still has a good thermalreliability because of the little changes in latent heat andphase-change temperature. The heat-transfer rate of the compositePCM was obviously higher than that of pure paraffin.The heating and cooling rate tests showed that the heating andcooling times were reduced by 30.3 and 28.2%for 1 wt%Cu/paraffin, respectively. The experimental results reveal that theaddition of nanoparticles to paraffin is a good method toenhance the heat-transfer performance of paraffin, because ofits good thermal properties, thermal and chemical reliability,and heat-transfer. Vellaisamy et al. [15]. prepare a novel class of nanofluid phase change material (NFPCM) by dispersing a small amount of multi-walled carbon nanotubes (MWCNT) in liquid paraffin, to enhance the heat transfer properties and examine the characteristics of the NFPCM during the solidification process. The stable NFPCMs are prepared bydispersing the MWCNT in liquid paraffin at 30_C with volume fractions of 0.15, 0.3, 0.45 and 0.6% without any dispersing agents. The differential scanning calorimetric results showed that there is no observable variation in the freezing/ melting temperature of the NFPCM, and only a small observable change in the latent heat values. The thermalconductivity of various NFPCM is measured. The enhancement in thermal conductivity increases with the increased volume fraction of the MWCNT, and shows a weak dependence on the temperature. Further, for the NFPCM with a volume fraction of 0.6%, there is an appreciable increase in heat transfer with a reduction in the solidification time of 33.64%.

2. Experimental set-up and equipment:

2.1. Experimental set-up:

The photographic view of the experimental setup constructed for this study is shown in plate (1). An electrical centrifugal blower (0.75 kW, 2 m^3/s, 1500 rpm) is used to deliver air with a constant flow rate to the air heater. Ambient air which is sucked by the electrical centrifugal blower, flows through an intermediate tunnel to enter the SAH. The tunnel has internal guide vanes to ensure uniform distribution of the air over the width of the air heater. SAH has $(2 \times 1 \times 0.15)m^3$ inner dimensions. The top of the SAH is covered with a single transparent glass cover; (3 mm) thickness. Each pass has spacing between about 7.5 cm. The air heater frame is constructed from mild steel plate of 1.5 mm thickness. To improve the system performance, the conventional absorber flat plate is replaced by a twelve copper pipes filled with water (4 cm diameter each ,193 cm length and 0.1 cm thickness) were used to store the excess thermal energy. The spaces between the pipes are joined by copper plates. Each plate has $(193 \times 4 \times 0.05)\ cm^3$ dimensions. The copper plates and copper pipes are painted with selective coating black layer (α=0.92, ε=0.28) to increase the absorptivity of the solar radiation and reduces the heat losses to the ambient [16]. The air is heated first while passing between the transparent glass cover and absorber plate. The air then reverses direction in the lower channel. Addition heating for the air while passing between the absorber plate and the rear plate. The system is insulated from all sides and bottom by a 0.05 m thickness glass wool to reduce the heat losses to the ambient air. The whole solar air heater is oriented due south and tilted 47º with respect to the horizontal to maximize the solar radiation incident on the air heater [17]. Blower is connected to the inlet of the air heater through a gate valve. The gate valve is used to control the mass flow rate of air and air flow meter is used to measure the mass flow rate. To measure the inlet and exit air temperatures, absorber plate temperature, glass temperature and back plate temperature, K type thermocouples were placed at different locations and connected to the digital data logger as shown in plate-1. Solar meter is used to measure the solar radiation intensity.



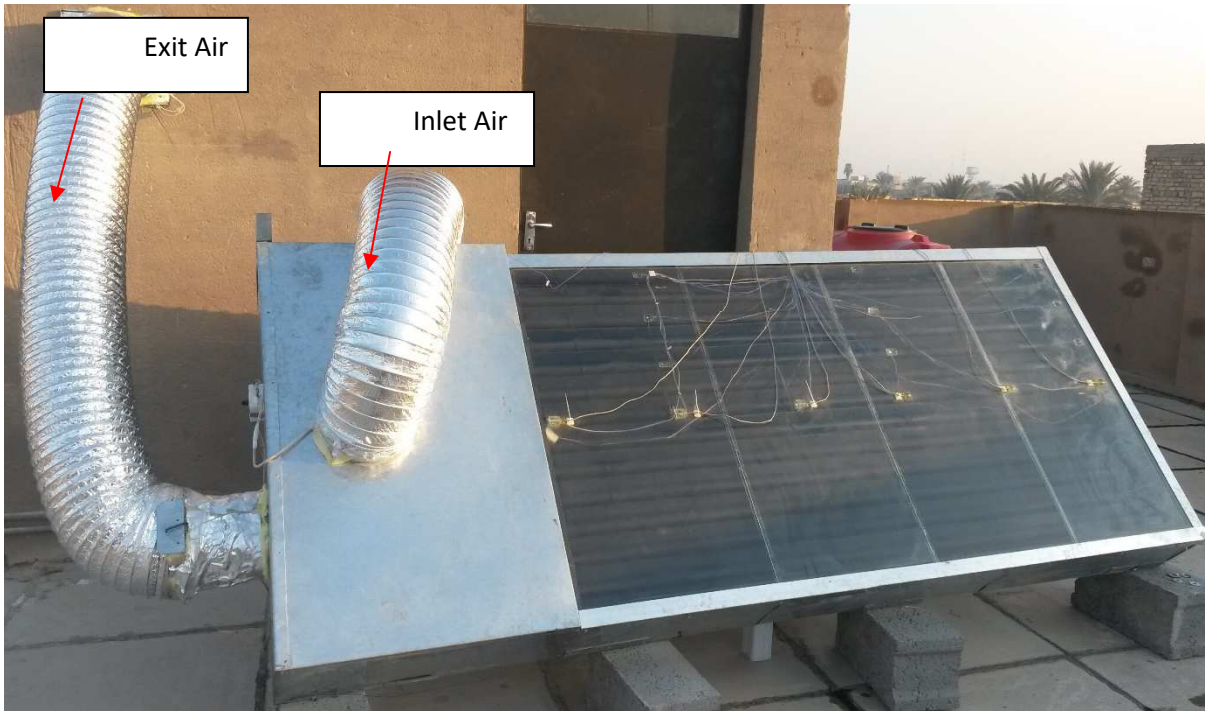


Plate 1: Double pass SAH with thermal storage.

2.2 Preparation of NCuPCM:

The details of the PCM and the carbon nanoparticles used in the present investigation are given in this section. Paraffin with the melting temperature 60℃ is used as the PCM in the preparation of the NCuPCM as the base material, and this PCM was procured from Al-Dora-Factory, Baghdad-Iraq. The thermo-physical properties of paraffin are given in Table (1). The copper nanoparticlesare procured from USA and the properties of Cu-nanoparticles are shown in table (2). Figure (1) shows the Transmission Electron Microscope (TEM) image of the copper nanoparticles. Two steps are used to prepare the mixture of PCM (paraffin wax) and nanoparticles. The PCM melt to temperature 60℃ and the nanoparticles directly dispersed in a 1000 ml Pyrex flask which can be sealed by a PVC cap. The flask fixed to the stainless steel basket inside the ultrasonic water path (type Elmasonic P 80H and supply by Elma, Germany) as shown in plate-2.Plate-3 show the NCuPCM after 3 months. As shown in the plate there is good stability without any visual sedimentation.

Table 1: Material properties of paraffin wax storage Material. [18]

Property	Solid	Liquid
Specific heat	2.871(kJ/kg.K)	2.871(kJ/kg.K)
Density	850 (kg/m^3)	770 (kg/m^3)
Thermal Conductivity	0.21(W/m.K)	0.21(W/m.K)
Latent Heat Capacity	176 (kJ/kg)	
Melting temperature	60^oC	
Dynamic viscosity	0.03499 (kg/m.s)	

Table 2: Physical Properties of Cu Nanoparticles [19].

Copper Nanoparticles / Nanopowder (C`u Nanoparticles with 5.2wt% Cu2O Coated)	
Estimated Shell Thickness:	(0.5 - 1.00)nm - Cu_2O
Purity	99% (metal basis)
Average Particle Size (APS)	30 nm
SSA	35 m^2/g
Color	black brown
Bulk Density	(0.15 - 0.35) g/cm^3
True Density	8.94 g/cm^3
Thermal conductivity (k)	
Specific heat (c_p)	0.3831 kJ/kg.℃
Thermal diffusivity (α)	

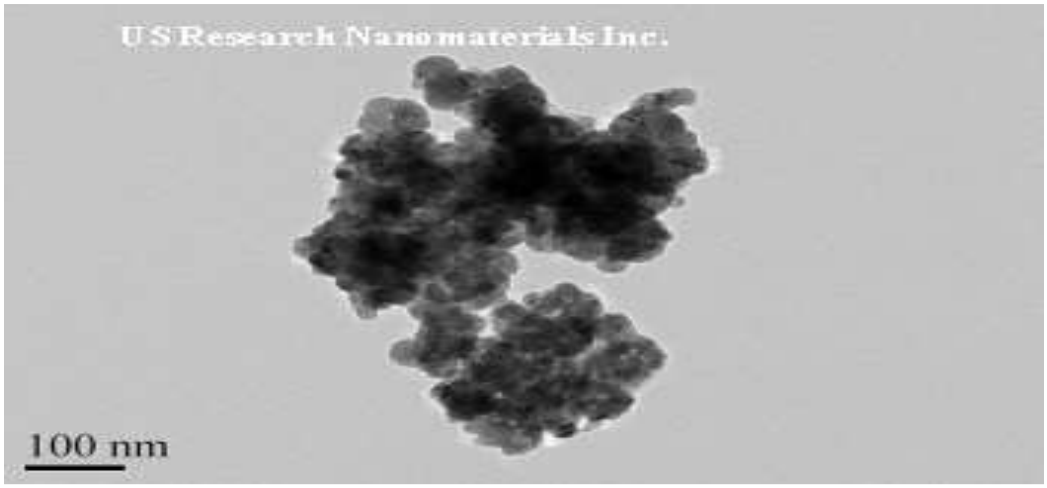


Fig. 1: TEM micrograph of Copper Nanoparticles.[19]

Plate-2:*Elmasonic P180H.*

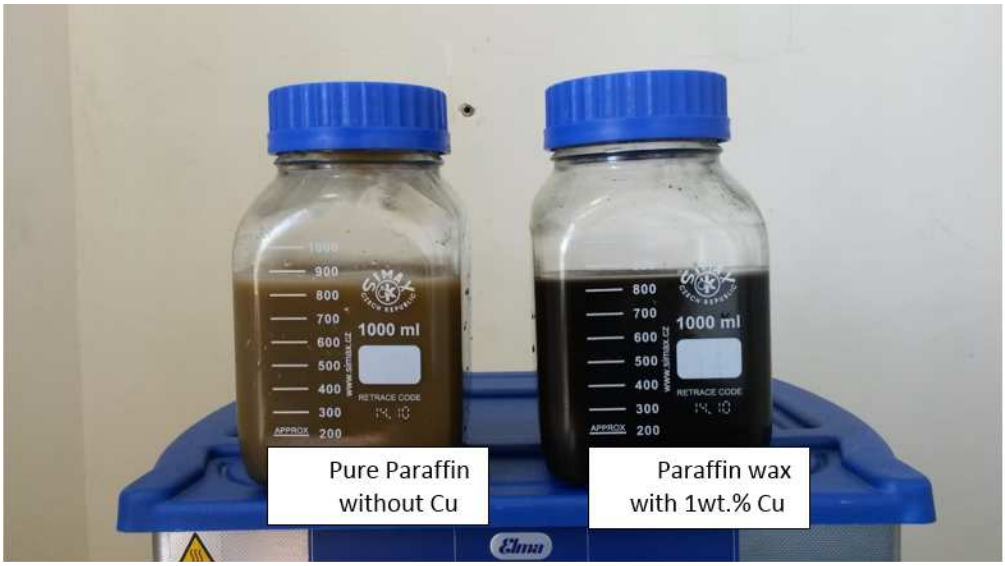


Plate3: View of 1wt% nanoparticle (Cu) dispersed in PCM (paraffin wax).

2.3Measurement of thermo-physical properties of NCu/PCM:

The variation in the thermal conductivity of the PCMs withrespect to temperature is important factor for thermal storage applications, when the PCMs are subjected to varying temperatures during the charging and discharging processes. Therefore, it is essential to predict the changes in thermal conductivity with respect to

temperature to study the heat transfer characteristics during the phase change process. This is measured using an experimental setup consisting of The Hot Disk TPS 500 Thermal Constants Analyser as shown in plate-4.Thermal conductivities, specific heat and thermal diffusivity of sample were measured by hot Disk TP500 the values of1wt% Cu paraffinare0.2313 $W/m.℃$, 1.891 $MJ/m.℃$ and 0.1222 mm^2/s in solid state. As compared to the properties of pure paraffine in table (1) there is 10.14% increasing in the thermal conductivity which is agree with result of [14].

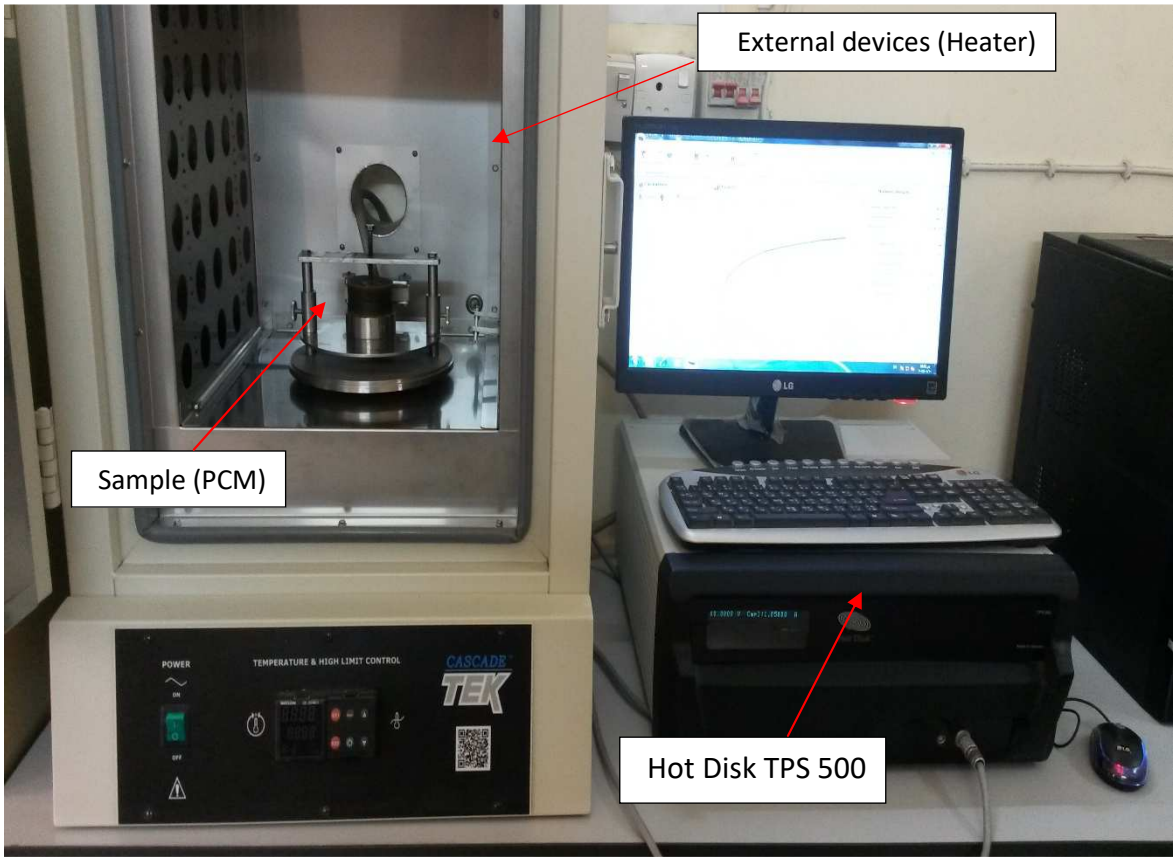


Plate4: The Hot Disk TPS 500 Thermal Constants Analyser.

2.4 Experimental trials:

The charging and discharging experiments are conducted to evaluate the performance of the new design of SAH with NCuPCM thermal storage units under different air mass flow rates. The temperatures of the air entering and leaving the solar collector and radiation intensity are measured at intervals of 10 minutes during the day. Charging and discharging experiments are conducted by supplying ambient air at the inlet. Three different mass flow rates of (0.03,0.04, and 0.05 kg/s) are used. Several experiments are conducted to check the repeatability of the readings.

2-5 Uncertainty analysis:

The accuracy of the experiments uncertainty analysis is needed due to errors in the measurement. The errors came from the sensitiveness of device and measurements uncertainties. The independent parameters measured in present work are: the inlet and outlet temperature of collector, ambient temperature, absorber temperature, glass temperature,air velocity, and solar radiation.The accuracy of the used measuring apparatus are given in Table(3).

Table 3: Measuring devices accuracy

Measuring device	Accuracy
Solar power meter	±5%
Thermocouple	0.2% + 1°C
Air flow meter	±1.0%

To determine uncertainty of the air mass flow rate, the useful energy and thermalefficiency as follows [20]:-

$$\frac{w_{\dot{m}}}{\dot{m}} = \left[\left(\frac{w_{V_{av}}}{V_{av}}\right)^2 + \left(\frac{w_{T_a}}{T_a}\right)^2\right]^{1/2} \quad (1)$$

$$\frac{w_{Q_u}}{Q_u} = [\left(\frac{w_{\dot{m}}}{\dot{m}}\right)^2 + \left(\frac{w_{(T_e-T_i)}}{(T_e-T_i)}\right)^2]^{1/2} \quad (2)$$

$$\frac{w_{\eta}}{\eta} = [\left(\frac{w_{\dot{m}}}{\dot{m}}\right)^2 + \left(\frac{w_{(T_e-T_i)}}{(T_e-T_i)}\right)^2 + \left(\frac{w_I}{I}\right)^2]^{1/2} \quad (3)$$

The above formula gives the total uncertainty as shown in table (4)

Table 4: the total uncertainty

Mass flow rate (kg/s)	$\frac{w_{\dot{m}}}{\dot{m}}$	$\frac{w_{Q_u}}{Q_u}$	$\frac{w_{\eta}}{\eta}$
0.025	0.0102	0.0104	0.05299
0.03	0.01198	0.01039	0.05208
0.04	0.01018	0.01042	0.05208
0.05	0.01020	0.0104	0.05287

RESULTS AND DISCUSSION

Figs. (1) show the variation of the temperatures of the outlet air, upper surface, lower surface and PCM (paraffin wax with NCu) and solar radiation, during the day. Measured data explain that the maximum temperatures are obtained in 1.30 P.M after one –half hour from noon of maximum solar radiation. This delay of peak temperature hour due to the effect of storage capacity of PCM. It may be concluded that the temperatures in general increase with the increase of solar radiation. The increase in the incident radiation flux increases the temperature level of the pipe surface that has an effect on and lead to melt the paraffin wax.

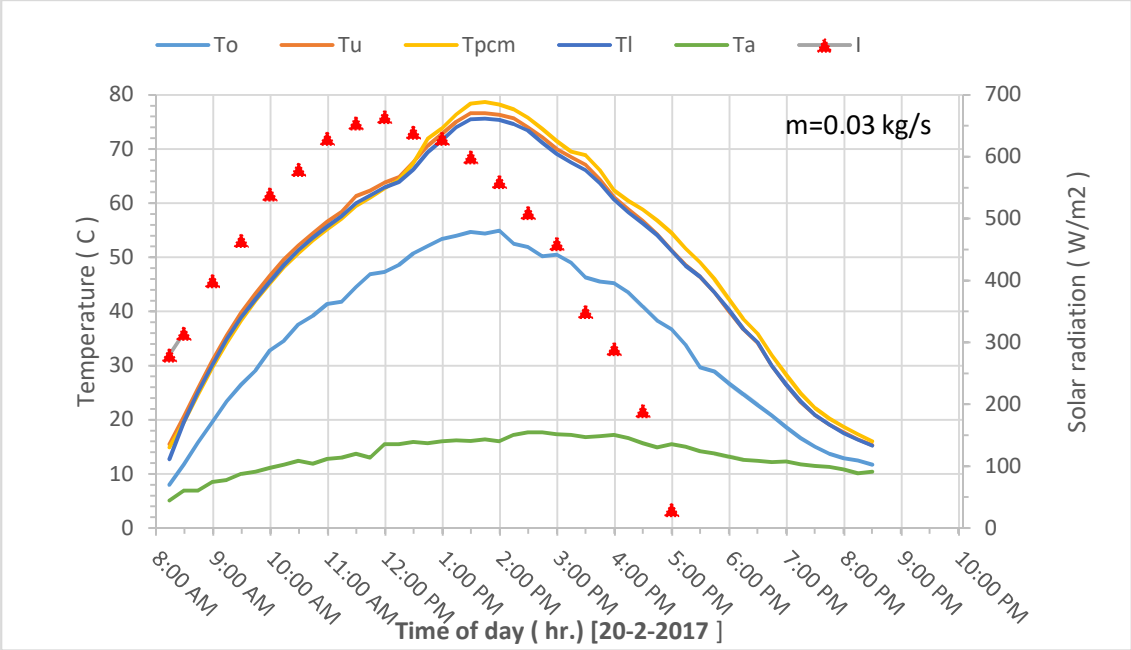


Fig. 1: Outlet air, absorber, ambient temperatures and solar radiation versus standard local time of the day for DPNPCM.

Fig.2 illustrates the variation of air temperature difference during the charging and discharging processes for various mass flow rates. The SAH air temperature difference is an important parameter for the heating of buildings and many engineering applications. It may be observed from Fig.2 that the air temperature difference decreases with increasing air mass flow rate. With further increase of mass flow rate, average air temperature difference decreases with higher rate. This is due to the fact that when the air flow rate increases, the amount of air to be heated with the same quantity of solar energy increases. Also it maybe observed from Fig.3 that the difference of air temperature exhibit the same behavior as the solar radiation.However, they achieve their maximum values at 1.30 P.M. The observed maximum difference air temperatureranged between 25 °C at mass flow rate 0.05 kg/s and 39 °C at mass flow rate 0.03 kg/s.

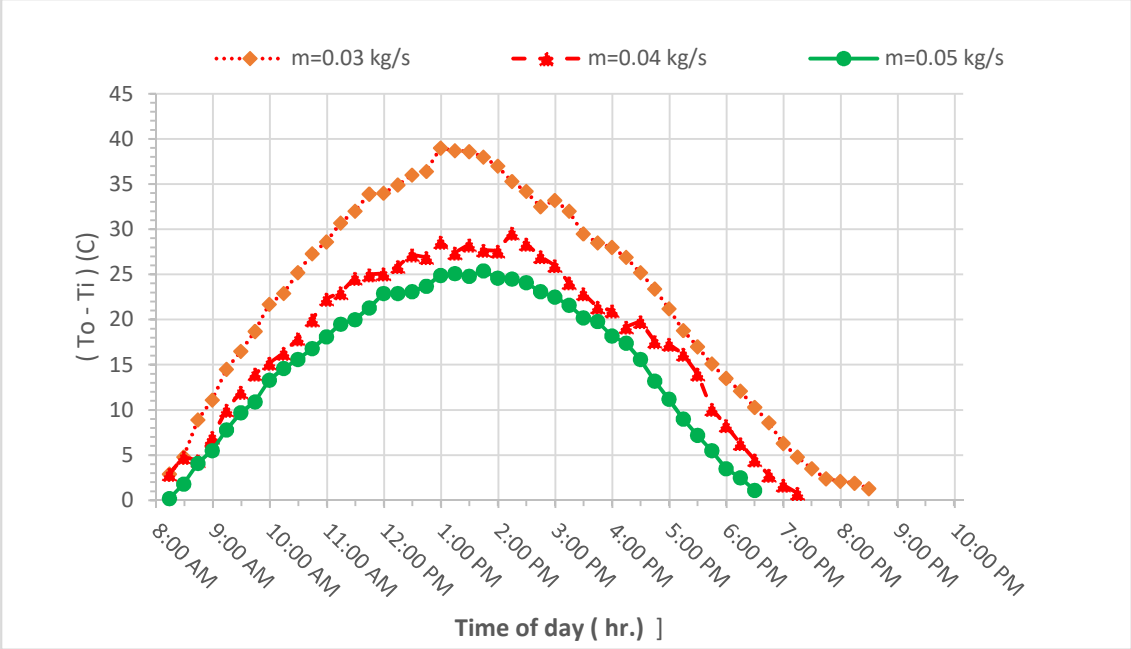


Fig. 2: Air temperature difference versus local time of the day at different mass flow rates for double-pass DPNPCM

It is seen from the Fig-3 that the difference of temperature continue beyond the sunshine time due to discharging fromthe PCM and the time of discharging depend on the mass flow rate.By using paraffin wax, the maximum value of the outlet temperature of the flowing air was obtained as 41.4°C greater than the inlet temperature at noon when the mass flow rate of air is 0.025 kg/s. Also It is seen from the figure that the discharging of heat is possible for duration of 4 h, 4 h, 3 h, and 2 h, when the mass flow rate is 0.03 kg/s , 0.04 kg/s and 0.05 kg/s respectively

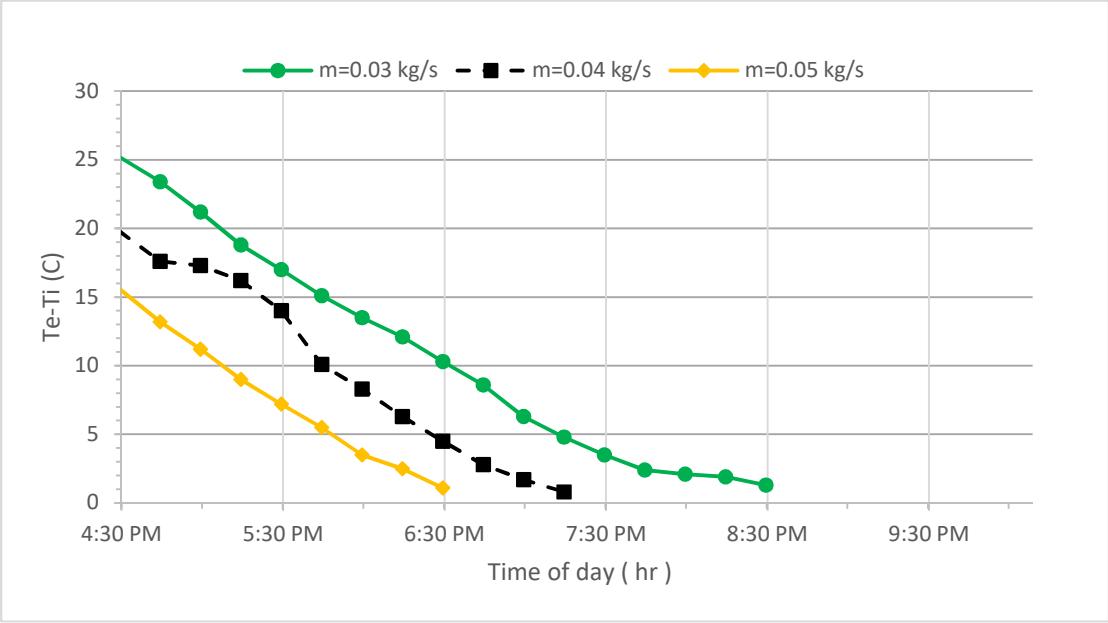


Fig. 3: Discharge air temperature difference versus local time of the day at different mass flow rates for double-pass DPNPCM

Figure (4) shows the transient temperature variation of outlet air temperature , upper and lower pipe surface and NCu-PCM temperatures during discharge. It is seen from the figure that the temperature difference of the NCu-PCM and surfaces pipe is small due to increasing of the thermal conductivity of paraffin wax. Also it can be seen that there is large difference with the outlet air temperature due to the low heat transfer of the air.

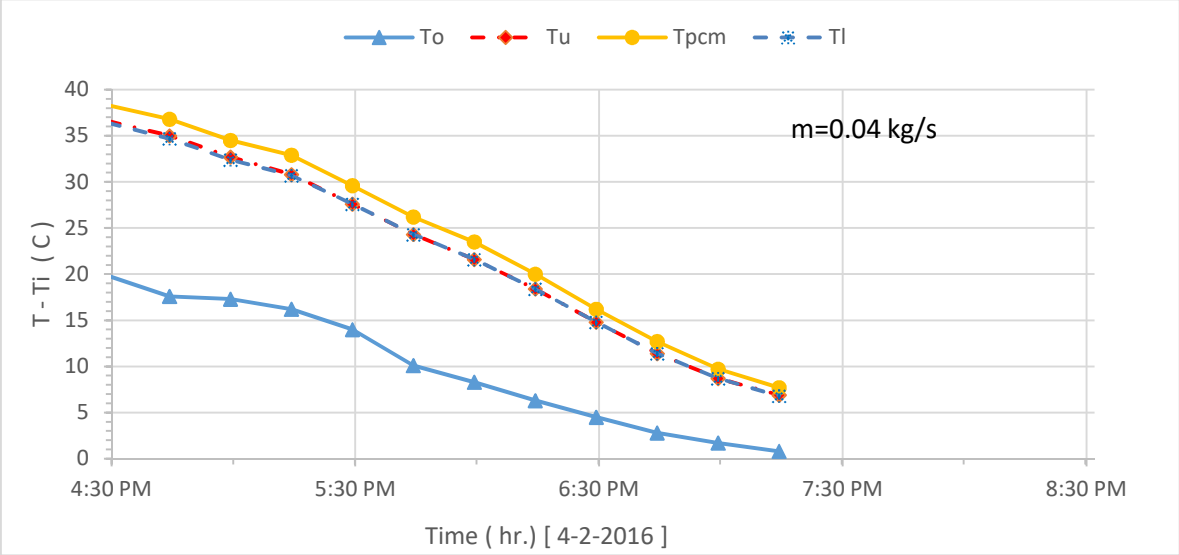


Fig. 4: Outlet air, absorber and PCM temperatures difference versus discharging local timeof the day for DPNPCM.

Fig.5 illustrate variation of useful energy for different values of mass flow rate .It can be remarked that the maximum value of heat gain occurs at m=0.04kg/s. Further, it may be concluded from the figure that the useful energy decreases by decreasing the mass flow rate.

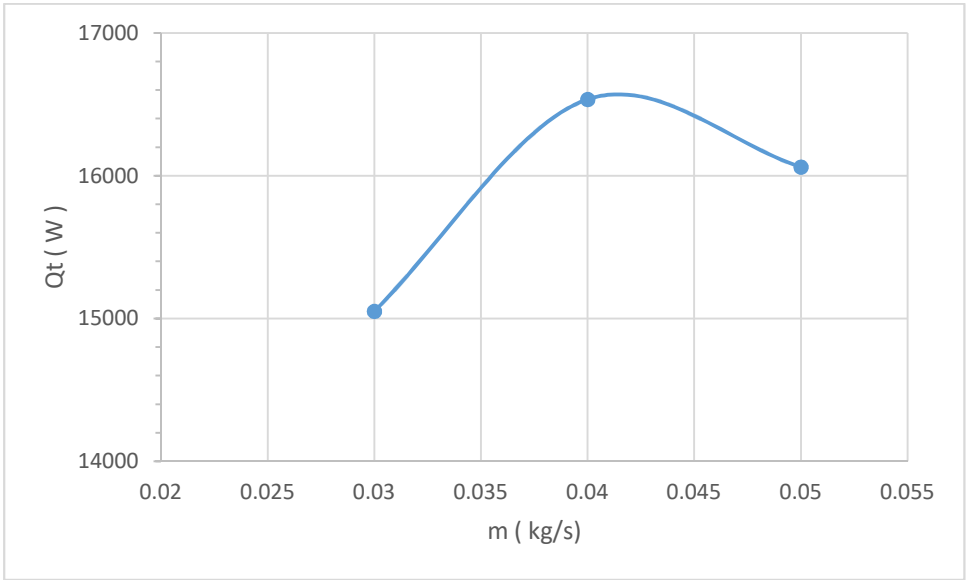


Fig. 5: Variation of the total useful energy for different values of mass flow rate.

Fig.6shows the variation of the thermal efficiency of SAH for different values of mass flow rate. The thermal efficiency increases with increasing mass flow rate.This is due to the reduction in the heat losses associated with the decrease of the average temperature of thecollector and to the increase in the value of the heat transfer coefficient at a higher mass flow rate.

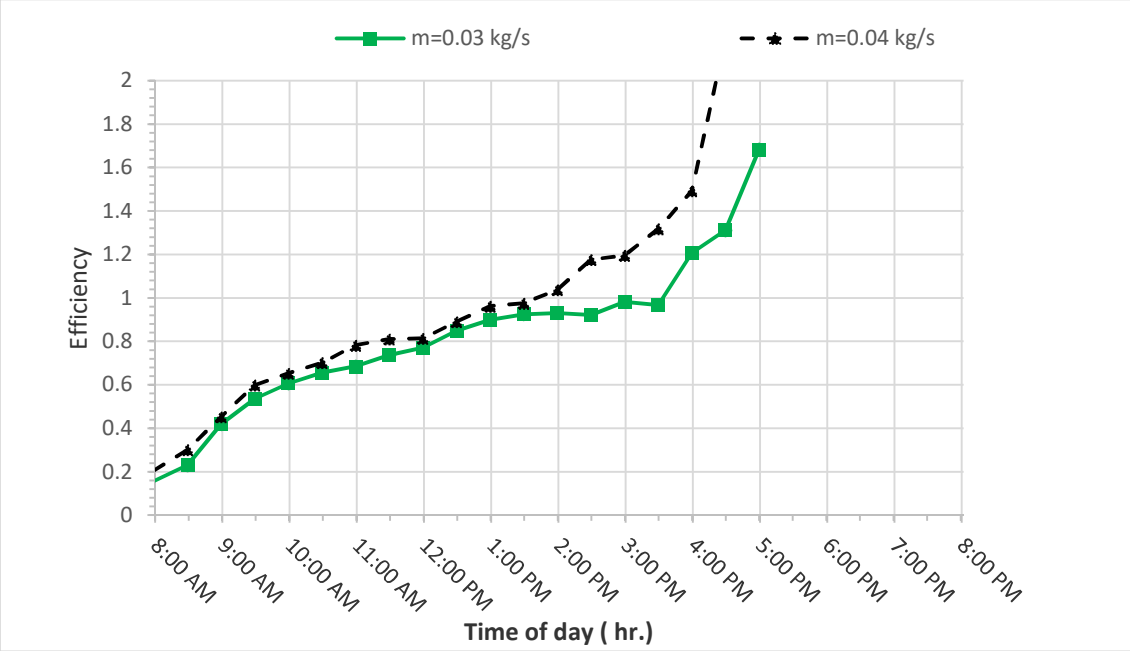


Fig. 6: Variation of the thermal efficiency for different values of mass flow rate.

Conclusions:

A detailed investigation on enhancing the thermal performanceof the PCM with the addition of the NCu particles as a thermal storage iscarried out, to make the PCM suitable for a latent heatthermal storagesystem. The improvements in the performance of double pass SAHof various mass flow rates are analysed and the followingconclusions are arrived at based on the experimental results.

1. An enhancement in the thermal conductivity of 10.14% is achieved in the solid statesof the NCuPCM compared to that of pure PCM.

2. The presence of carbon acts as the nucleatingagent to initiate the freezing process and hencethe onset of freezing temperature is higher than that ofpure PCM.

3.The addition ofN-Cu particles in the pure PCM can be considered as the mostpotential storing medium for LHTS, due to its enhancedthermo-physical properties.

4· The temperature difference between the outlet and the inlet increases with decreasing the air mass flow rate.

5· The maximum value of the outlet temperature of the flowing air was obtained as 39°C greater than the inlet temperature for mass flow rate 0.03 kg/s.

6. The presence of the PCM with N-Cu particles at the absorber plate gave outlet air temperature above the inlet temperature for 4 hours beyond sunset time.

Nomenclature:

Letter	Description
A	Collector area (m^2)
C_p	Specific heat at constant pressure
I	Solar radiation (W/m^2)
M	Mass flow rate (kg/s)
Q_u	Useful heat gain (W)
DPNPCM	Double pass solar air heater with Nano copper particles and paraffin wax
SAHWS	Solar air heater with storage
NCuPCM	Nano copper particles with paraffin wax
T_a	Ambient air temperature (°C)
T_i	Inlet air temperature (°C)
T_{PCM}	Temperature of PCM (°C)
T_o	outlet air temperature (°C)
T_e	Exit air temperature (°C)
T_u	Upper surface temperature (°C)
T_l	Lower surface temperature
V_{av}	Average velocity
α	Absorptivity
ε	Emissivity

	Thermal efficiency

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