Thermal Storage Efficiency Enhancement for Solar Air Heater Using a Combined SHS_m and PCM Cylindrical Capsules System: Experimental Investigation

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ABSTRACT

The present work aims to enhance the thermal storage efficiency and thermal behavior for solar air heater integrated with cylindrical capsules system. The cylindrical capsule has diameter 50 mm and length 600 mm, placed in the cross flow of airstream. In this experimental study, a high specific heat of latent heat storage materials (PCM-paraffin wax) were invested to increase the stored ability for sensible heat storage materials (pure sand). Three cases are tested under constant incident irradiation $1000 Wm^{-2}$, in the first case cylindrical capsules packed with pure sand, second case cylindrical capsules packed with compound (sand+10% PCM) and third case cylindrical capsules packed with compound (sand+20% PCM) , for both natural convection and forced convection with different mass flow rates (0.5 , 1.132 kg/min). The experimental results indicated that the compound (sand+20%PCM) gives the best thermal storage duration (380 min),with increase in outlet air temperature by approximately 5.6 % in forced convection with (0.5 kg/min) compared with pure sand (240 min). For forced convection with (1.132 kg/min), compound (sand+20%PCM) gives (355 min) thermal storage duration with increase in outlet air temperature by approximately 9.2 % compared with pure sand (220 min). Increase of mass flow rate leads to decrease the outlet air temperature period time of the discharge process.

Keyword: Thermal storage efficiency, PCM, cylindrical capsules, latent heat storage materials.

Latin Symbols:

A = area of collector (m^2).

H = high of collector (m).

D = diameter of cylindrical capsule (m).

C_p= specific heat of air at constant pressure.

$\dot{m}_a$= air mass flow rate (kg/s).

T_{ain} = air inlet temperature (°C).

T_{aout} = air outlet temperature (°C).

A_d = Duct area (m^2).

P_{atm} = air pressure (101325 Pa).

R= specific gas constant for dry air (287.05 J/kg.K).

U_l =Overall heat transfer coefficient ($W/m^2.°C$).

Q_l = heat loss (W).

Qu = useful heat gain (W).

Greek Symbols:

φ = Dimensionless temperature [-].

$\eta_{storage}$= thermal storage efficiency %.

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v = air speed in (m/s).
ρ_a = density of air (kg/m^3).
Abbreviations:
SAH= solar air heater.
SHS_m= sensible heat storage materials.
LHS_m= latent heat storage materials.
PCM = phase change material

INTRODUCTION

Utilization of thermal energy storage technology in solar air heaters (SAH) is of increasing importance to balance the energy demand in domestic and industrial process heat applications, such as solar air dryers by lowering time needed for drying agricultural crops. The thermal energy storage material (TESM) can be essentially classified into three groups according to method of heat storage: as sensible heat, such as concrete and sand. As latent heat, such as paraffin wax and Glauber salt (sodium sulfate) and as chemical heat in chemical combinations. Many researchers have investigated sensible and latent heat storage materials in solar air heater (SAH). The combined sensible and latent heat storage were studied experimentally by Nallusamy et al. [1], for solar water heaters. Spherical Thermal energy storage units contain paraffin wax as latent heat storage (LHS) and packed in a storage tank. Heat is transferred from the solar collector to the thermal energy storage tank by heat transfer fluid (water) which works also as sensible heat storage (SHS). Results show that the performance of combined sensible and latent heat storage system is most appropriate for a lot of applications when compared with conventional sensible heat energy storage systems. Mahmud et al. [2], constructed and studied experimentally a solar air heater (SAH) integrated with (paraffin), (paraffin + aluminium composite) cylinders as a storage unit to illustrate the effect of these materials on the performance of solar air heater. The experimental results indicate that the thermal storage efficiency increases and reduces the charging time approximately 70% when (PCM+ aluminum composite) is used.

Shalaby. [3] presented an experimental investigation of forced convection solar dryer with and without using energy storage material to demonstrate the effect of using sensible heat storage materials (sand) on the performance of the solar dryer. Results show that the drying time of 1 kg of grapes is reduced by more than 3 hours when using the sand as heat storage material. Paraffin wax was used as a latent heat energy storage due to its high storage density, less volume changes during phase change, small change in its thermo physical properties during melting / solidification cycles, cheap and safe. Ahmed et al. [4], investigated theoretically the influences of Reynolds number and ratio of pitch to diameter of the cylinders on the temperature distribution for cylindrical capsule filled with phase change material (octadecane) as thermal energy storage. The results indicated that the increment of Reynolds number and the ratio of the pitch to diameter lead to decrement in the final time of melting of PCM in the cylinders.

Miqdam et al. [5], presents an experimental investigation of a combined sensible and latent heat storage material for solar water heater. Used pebbles as sensible heat storage material (SHS_m) and paraffin wax as latent heat storage material (LHS_m) enhanced thermal energy storage efficiency and increased saving time of storage energy of the system.

In this present work, a solar air heater is designed, fabricated and indoor tested experimentally under constant incident irradiation of 1000Wm^{-2}. The SAH integrated with sensible heat storage materials (pure sand) and combined sensible and latent heat storage materials (sand, PCM) cylindrical encapsulation. The effect of different parameters, such as the mass flow rate of air and the thermal storage materials on the thermal behavior and thermal energy storage efficiency of the SAH are examined.

EXPERIMENTAL PART

System configuration

An experimental Test-Rig is designed and constructed to implement this work. Figures 1 and 2 show the photographs and schematic layout of the flat plate solar air heater (SAH) with an area [(1×0.6) m^2]. The experimental rig consists of five main parts which are: solar air heater (SAH), thermal energy storage units, insulated duct, halogen lamps and air blower. 10 mm thick wood was used for fabrication of the solar air heater collector's cabinet. The exit airflow of the collector is opened with dimensions of (540 mm×75mm) and connected to insulated duct with front sectional area of [(0.11×0.12)m^2], end sectional area [(0.54×0.075)m^2].An electrical centrifugal air blower of specification (3000 RPM and 350 W) was used with variac voltage regulator to control airspeed. The entrance airflow of the collector is opened with (0.54 m×0.075 m) dimensions. 20^{th} Aluminum cylindrical capsules packed with sensible heat storage material (sand) and combined sensible and latent heat storage materials (sand, paraffin wax) are used in the experiments as thermal energy storage units, see fig (3). Each capsule contains 1.6 kg of a combined SHS_m and LHS_m. The cylindrical capsule has a diameter of 50 mm and a length of 600 mm, placed in the cross flow of airstream and painted with matte black coat. A single transparent cover glass with [(1.040 × 0.64) m^2] and 0.004 m thickness was used as a cover for thermal trap through the solar radiation. A constant incident irradiation of (1000Wm^{-2}) on the solar air heater, provided by two Halogen lamps (1500 W) was used to substitute for the sunlight. Gap between the glass and cylindrical capsules thermal energy storage units also called the Natural-Circulation Greenhouse (NCG) was fabricated with appropriate size (0.01 m) to have a retained for air circulation and controlled air flow.

Experimental Measurements

Thirteen chromel alumel calibrated thermocouples (Type K) were tapped in positions which are: three thermocouples placed inside the cylindrical capsule at the distances r =10 ,25 and 40 mm, two thermocouples placed on the surfaces of cylindrical capsules, one thermocouple placed in the air entrance region, four thermocouples placed inside solar air collector, one thermocouple placed on the transparent glass cover, the last two thermocouples placed in the outlet region. All thermocouples are connected to the selector and temperature recorder type (BTM-4208SD) with accuracy (± 0.01 %) and temperature measuring range (-100 to 1300 °C). Air velocity was measured by vane anemometer type (Kaendl/wind master) with accuracy (±4%).Solar irradiation was measured by solar radiation sensor type (Protek / DM-301) instrument (1mV =1 W m^{-2}) with accuracy (±4%) and measuring range (0.1 mV to 1000 V).

Experimental Procedure.

Thermal behavior and thermal storage efficiency of the charging and discharging process of solar air heater (SAH) is studied using natural and forced convection. Experimental tests were conducted on three cases, the first case was cylindrical capsules packed with pure sand The second case was cylindrical capsules packed with (sand + 10% PCM) and the third case was cylindrical capsules packed with (sand + 20% PCM). Firstly, the gained thermal energy from the solar radiation, stored interior the cylindrical capsules as sensible heat until the paraffin wax reached its melting point temperature. The thermal energy accumulates inside the cylindrical capsules as a result of the charging process finally, the paraffin wax reaches its melting point temperature and the energy storage is achieved. Thermo-physical properties of paraffin wax are given in (table 1). The measurement tests conducted at varying air mass flow rate to show the effect of mass flow rate on solar air heater performance. The charging process is continued for 45 minutes until the temperature reaches ≈78 ^{0}C. The temperatures of the combined (sand, PCM) are recorded at an interval of 5 minutes.

Thermal conductivity, specific heat experimental tests

Indoor experimental tests of thermal conductivity, specific heat were done in department of materials engineering /university of technology (UOT) to determine the experimental value of thermal conductivity, specific heat for two samples of combined sensible and latent heat storage materials (sand +10%PCM), (sand +20%PCM) as shown in (table 2). Fig 4 shows the test apparatus (thermal constant analyzer - Hot Disk) type (TPS 500) with tested samples.

Data Reduction

The amount of solar energy gained by a solar air heater (SAH) can be calculated from the following relation [2],[6].

$$Q_u = \dot{m}_a \times C_p \times \Delta T_a = \dot{m}_a \times C_p \times (T_{aout} - T_{ain}) \qquad (1)$$

The air mass flow rate can be calculated as follow [7]:

$$\dot{m}_a = \rho_a \times A_d \times V \qquad (2)$$

where:

ρ_a , A_d , v are density, cross sectional area of the duct at the outlet of (SAH) and air average velocity.Density of air can be calculated from ideal gas law

$$\rho_a = \frac{P_{atm}}{R \times T_a} \qquad (3)$$

The heat loss can be calculated by [2]

$$Q_{lo} = U_{lo} \times A_{as} \times \Delta T = U_{lo} \times A_{as} \times (T_s - T_a) \qquad (4)$$

where:

: Overall heat transfer coefficient (W/m^2. °C). U_{lo}

A_{as} :Area (m^2) .

The thermal storage efficiency of the solar air heater (SAH) was calculated as [2]

$$\eta_{storage} = \frac{Retrievable\ heat}{Retrievable\ heat + Lost\ heat} = \frac{Q_u}{Q_u + Q_{lo}} \qquad (5)$$

5-dimensionless temperature can be defined as [8] :

$$\varphi = \frac{T_l - T_{ain}}{T_{aout} - T_{ain}} \qquad (6)$$

Error analysis and uncertainty

The difference between the real value and measured value of any variable can be defined as an error. By estimating a value of this error, the uncertainty or doubt will be identified. The uncertainty in the result having the same confidence level is compute by a formula [9]

$$E_r = \sqrt{\left({\partial R}/{\partial v_1} \times E_1\right)^2 + \left({\partial R}/{\partial v_2} \times E_2\right)^2 + \dots + \left({\partial R}/{\partial v_n} \times E_n\right)^2} \qquad (7)$$

where:

E_r: represents the uncertainty in the results.

$R = R\ (v_1, v_{2,}\ \ldots, v_1)$

$E_1, E_{2,\ldots,} E_n$: represents the uncertainties of each independently measured variables. The experimental accuracy for measuring properties by some selected devices used in the experiments shown in table (3). By using these values and compensated in the equation (7), the uncertainties can be calculated.

$$E_r = \sqrt{(0.01)^2 + (0.03)^2 + (0.05)^2} = \mp 0.06$$

Discussion of The Results

The experimental investigation was done in an indoor condition with constant irradiation of 1000 Wm^{-2}, natural and forced convection during charge and discharge process. **Figures 5, 6, 7** show the outlet air temperature of (SAH) for sensible heat storage material (SHS_m) and compound sensible and latent heat storage materials in natural convection. In charge process, compound SHS_m and LHS_m (sand+20% PCM) gives higher outlet temperature compared with pure sand and compound (sand+10% PCM), that is caused by decreasing thermal conductivity of the compound which leads to decreased heat absorbed. In discharging process, compound SHS_m and LHS_m (sand+20% PCM) gives the best results in comparison with others, The compound (sand+20% PCM) gives heat, during (485 min), but compound (sand+10% PCM) gives heat about (410 min) and pure sand (280 min). In forced convection with (0.5 kg/min) (**fig 6**), the compound (sand+20% PCM) gives heat after charging process, during (400 min), (360 min) compound (sand+10% PCM) and pure sand (245 min).When the mass flow rate of air increases (1.132 kg/min), the compound (sand+20% PCM) gives heat, during (365 minute), (310 minute) compound (sand+10% PCM) and pure sand (220 min). **Figures 8,9,10** show the effect of the mass flow rate on the outlet air temperature for sensible heat storage material (pure sand) and compound sensible and latent heat storage materials (sand+10% PCM), (sand+20% PCM). The experimental results show that, the outlet air temperature period time decreased when the air mass flow rate increased due to increased heat exchange process between the cylindrical capsule surface and air layers. Figures 11, 12 show the thermocouple reading fixed in center of cylindrical capsule (charge and discharge process) in natural and forced convection. In charge process the pure sand gives higher temperature compared with others. That is caused by high thermal conductivity of the pure sand compared with compound (sand+10% PCM) and (sand+20% PCM), which leads to increased heat absorbed. In discharging process (after 70 min), compound (sand+20% PCM) gives higher temperature for long duration time.

Fig. 13 represents the dimensionless temperature variation versus the length of (SAH). The dimensionless temperature gradient used to defined the temperature profile along (SAH), can be observed that, dimensionless temperature increases along solar air heater for forced convection with 0.5 kg/min. **Fig 14** clarifies the useful heat gain for sensible and compound sensible and latent heat storage materials in forced convection with 0.5 kg/min. In charge and discharge process, compound (sand+20% PCM) gives the best results compared with pure sand and compound (sand+10% PCM). In the discharge process, specifically on the period from (50-100) minute, pure sand gives good results, but rapidly dropped and gave the final value in (290 min). As the mass flow rate increases, the useful heat gain time decreases as shown in **fig 15** for the same sensible and compound heat storage materials. **Fig. 16** illustrates the system thermal storage efficiency behaved in forced convection with air mass flow rare 0.5 kg/min. During discharge process, pure sand exceeded other materials and gave a pick value (77 %) and reached its final value after (285 min). but the compound (sand+20%PCM) gave best performance for a longer time and reached its final value after (425 min) and compound (sand+10%PCM) gave its final value after (400 min). This experimental result was expected as a result of adding the phase change materials (paraffin wax) with pure sand, which operated to decrease the thermal conductivity and increases the specific heat for the compound SHS_m and LHS_m. That means increased the susceptibility of these materials to store thermal energy. As the mass flow rate increases, the thermal storage efficiency time decreases as shown in **fig 17.**

CONCLUSIONS

1-Addition of phase change materials (paraffin wax) as a latent heat storage material to pure sand, leads to decrease the thermal conductivity and increase the specific heat for the compound as shown in (table2).

2- The compound (sand+20%PCM) gives the best thermal storage duration (380 min) during the discharging process of forced convection with (0.5 kg min-1) and (355 min) for forced convection with (1.132 kg/min) compared with pure sand (240 min), (220 min) for forced convection with (0.5 kg/min) and (1.132 kg/min) respectively.

3- Addition of phase change materials (paraffin wax), with 20% to pure sand, leads to increase the outlet air temperature by approximately 5.6 % and 9.2% compared with pure sand in forced convection (0.5 kg/min) and (1.132 kg/min) respectively.

4- The increase of mass flow rate leads to decrease the outlet air temperature period time of the discharge process.

Table (1) Thermo-physical properties of paraffin wax [10],[11]

Parameters	Values
Melting temperature [°C]	56.8
Specific heat [kJ/kg.K]	2.0 (solid phase) 2.15 (liquid phase)
Thermal conductivity [W/m.K]	0.24 (solid phase) 0.22 (liquid phase)
Density [kg/m^3]	910 (solid phase) 790 (liquid phase)
Latent heat of melting [kJ/kg]	190

Table (2) Measured Thermo-physical properties

Material	**Specific heat** (kJ/kg.K)	**Thermal conductivity (W/m.K)**
Sand-dry	0.8	0.32
Compound (sand+10%PCM)	0.992	0.290
Compound (sand+20%PCM)	1.180	0.265

Table (3) Experimental Accuracies

Measurement	Accuracy
Temperatures	0.01
Air flow rate	0.03
Time	0.05

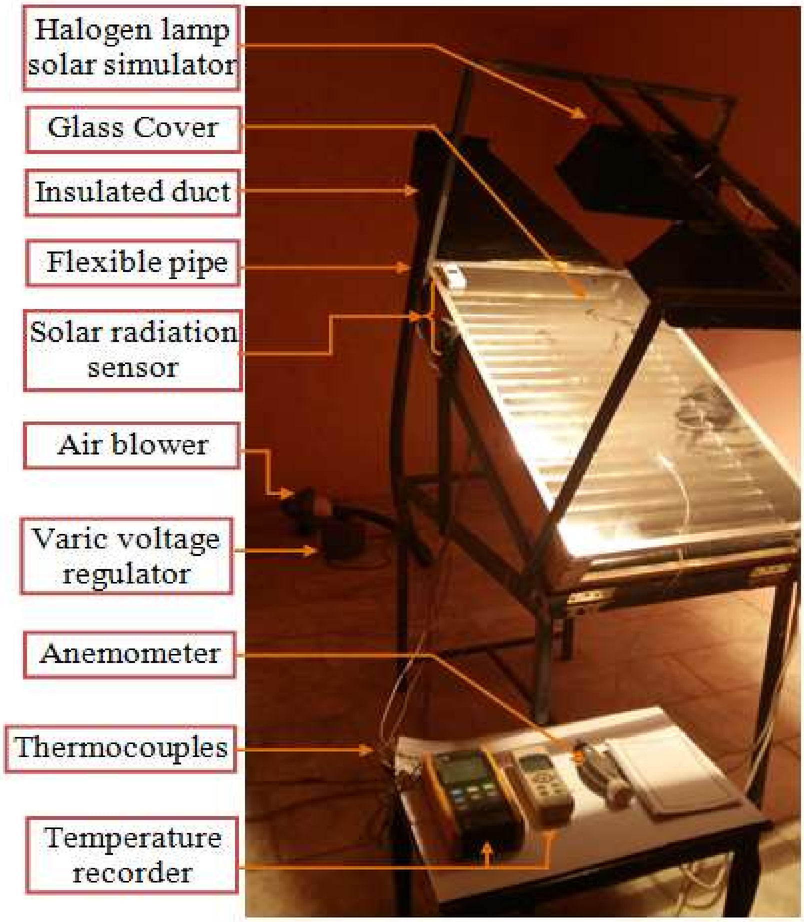

Figure (1) photography of the experimental test rig

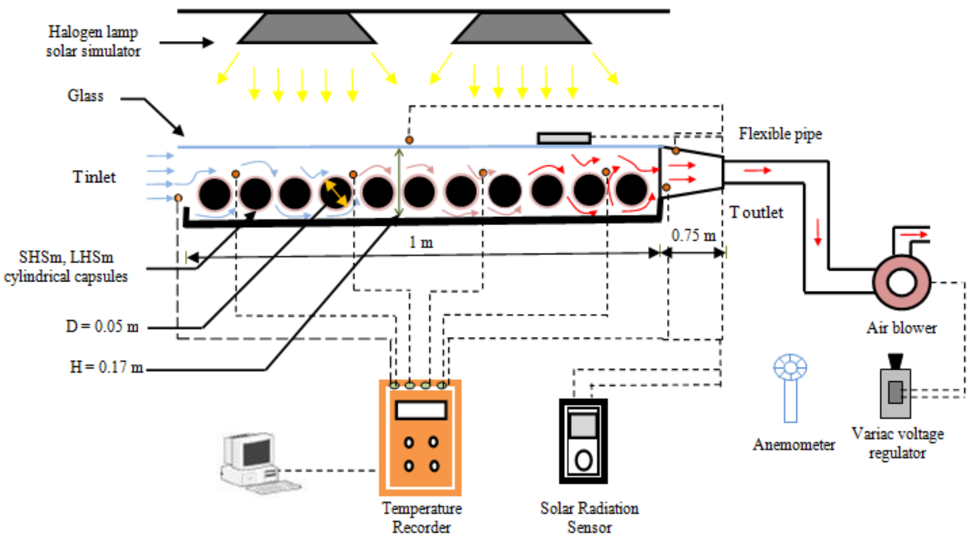

Figure (2) Schematic diagram of test rig

Figure (3) Sealing cylindrical capsules and packing of combined SHS_m and LHS_m

Figure (4) Hot Disk apparatus with samples

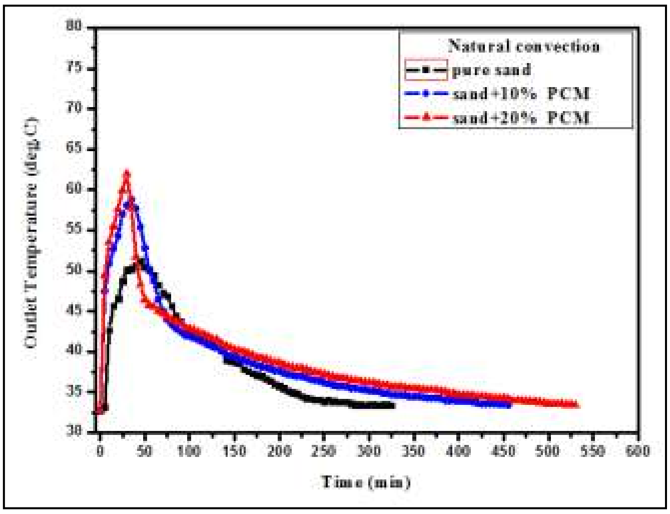

Figure (5) Outlet air temperature in natural convection versus time with various storage materials.

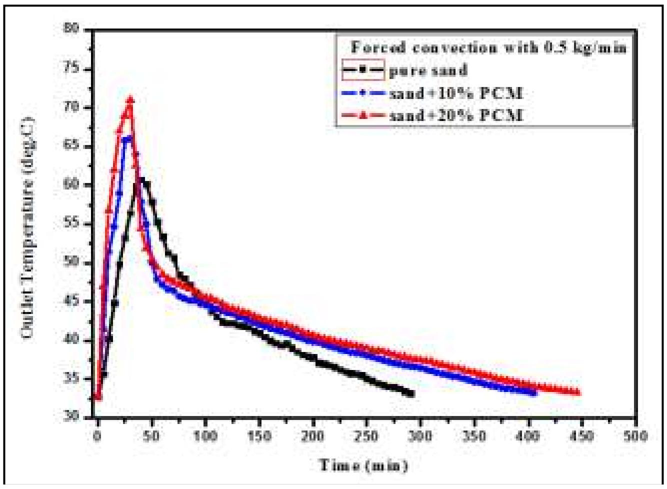

Figure (6) Outlet air temperature in forced convection (0.5 kg/min) versus time with various storage materials

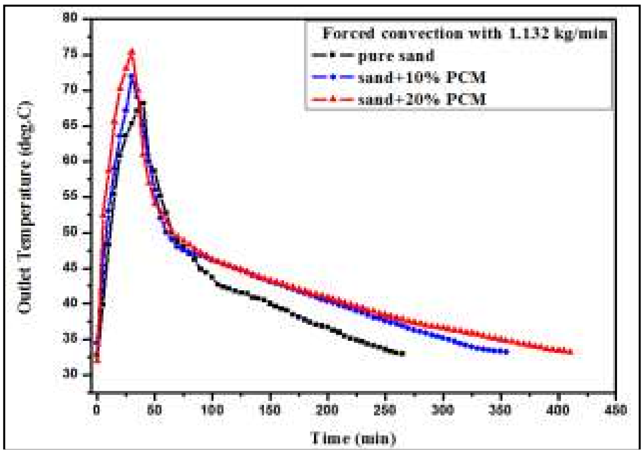

Figure (7) Outlet air temperature in forced convection (1.132 kg/min) versus time with various storage materials

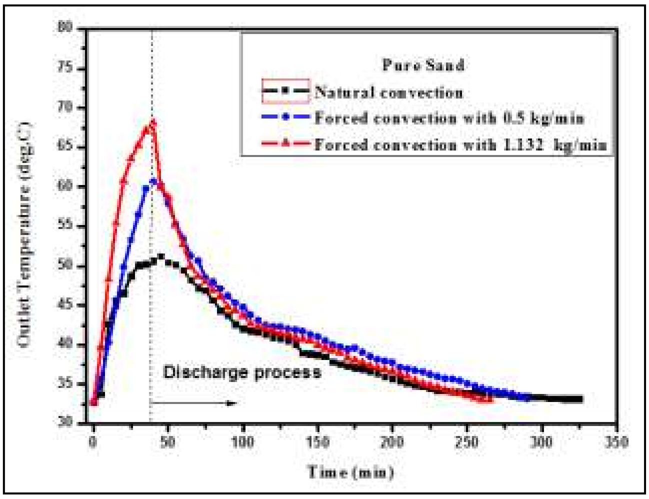

Figure (8) Effect of mass flow rate on outlet air temperature for pure sand

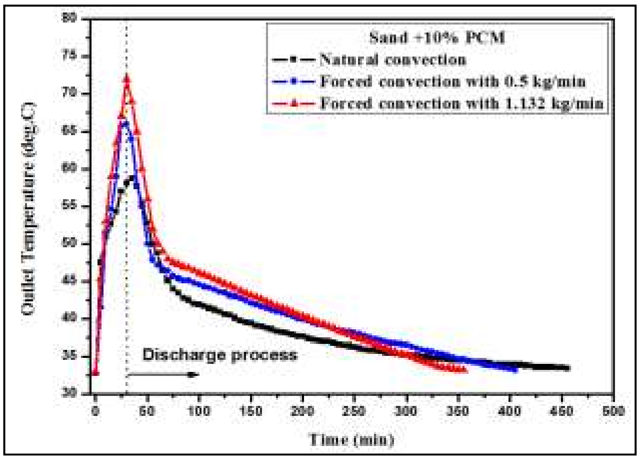

Figure (9) Effect of mass flow rate on outlet air temperature for compound (sand+10%PCM)

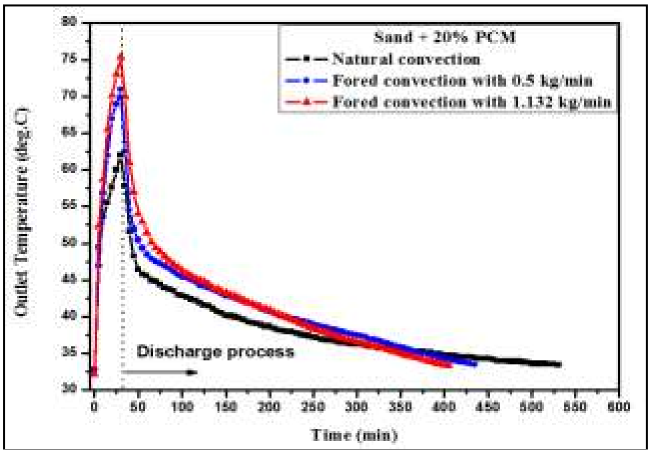

Figure (10) Effect of mass flow rate on outlet air temperature for compound (sand+20%PCM)

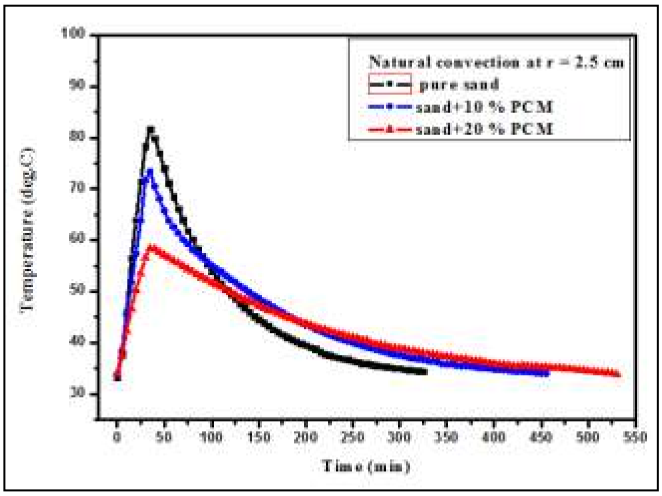

Figure (11) Thermocouples reading fixed in center of cylindrical capsule (charge and discharge process) in natural convection

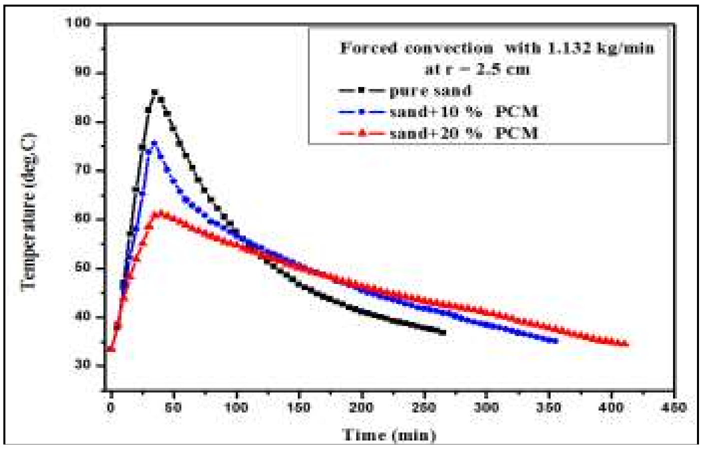

Figure (12) Thermocouples reading fixed in center of cylindrical capsule (charge and discharge process) in forced convection

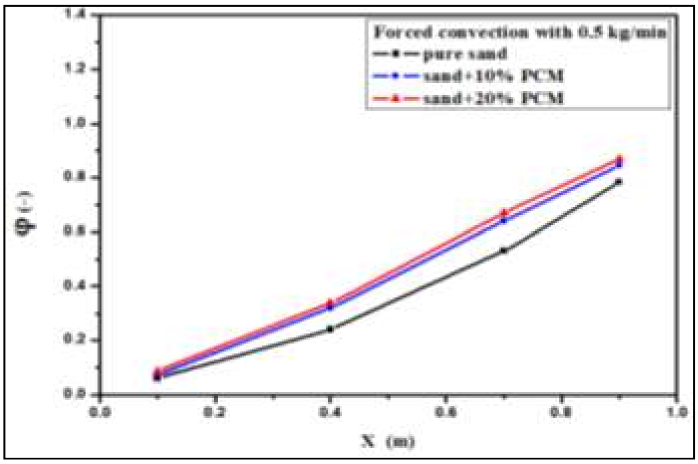

Figure (13) Dimensionless temperature along (SAH) with (0.5 kg/min)

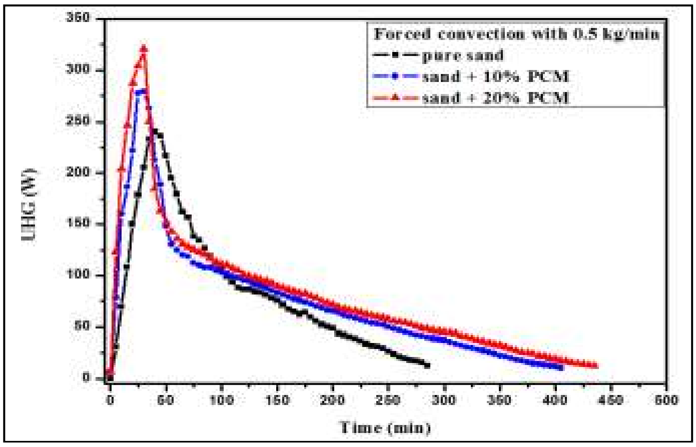

Figure (14) Useful heat gain versus time in forced convection (0.5 kg/min) with various storage materials

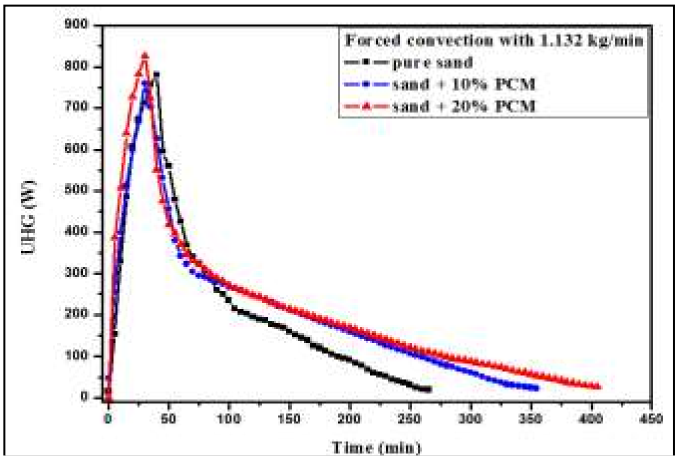

Figure (15) Useful heat gain versus time in forced convection (1.132 kg/min) with various storage materials

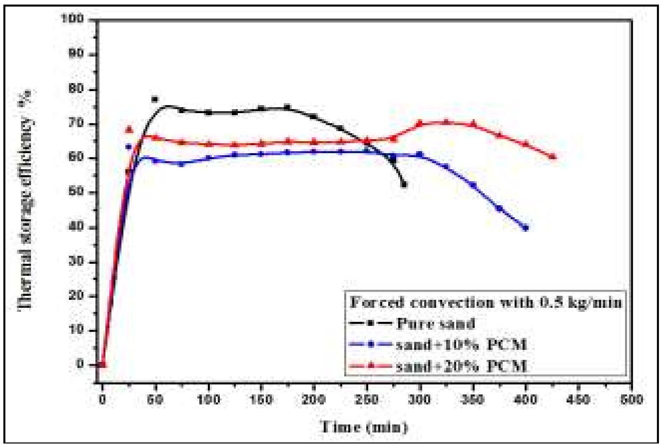

Figure (16) System thermal storage efficiency versus time in forced convection (0.5 kg/min) with various storage materials

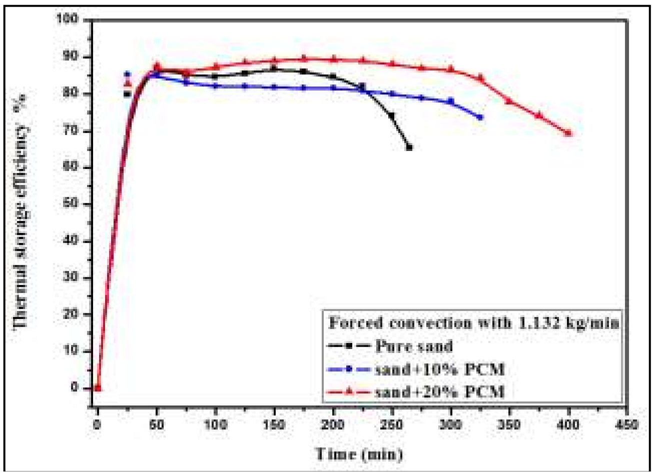

Figure (17) System thermal storage efficiency versus time in forced convection (1.132 kg/min) with various storage materials

REFERENCES

[1] Nallusamy. N, Sampath. S. and Velrajbi .R,"Experimental investigation on a combined sensible and latent heat storage system integrated with constant/varying (solar) heat sources", Renewable Energy, Vol. 32, Issue 7, pp. 1206-1227, 2007.

[2] Mahmud M. Alkilani, Kamaruzzaman Sopian and Sohif Mat, "Fabrication and Experimental Investigation of PCM Capsules Integrated in Solar Air Heater", American Journal of Environmental Sciences 7 (6): pp.542-546, 2011.

[3] Shalaby .S. M, "Effect of Using Energy Storage Material in an Indirect-mode Forced Convection Solar Dryer on the Drying Characteristics of Grapes", Journal of Medical and Bioengineering (JOMB), Vol.1, No.1, 2012.

[4] Ahmed K. Al shara and Mohammed Kh. Kadhim,"Numerical Investigation of Energy Storage in Packed Bed of Cylindrical Capsules of PCM", Ene. & Tech. Journal, VoL32,Part (A),No.2, 2014.

[5] Miqdam T. Chaichan, Khalil I. Abaas and Humam M.Salih,"Practical Investigation for Water Solar Thermal Storage System Enhancement Using Sensible and Latent Heats in Baghdad-Iraq Weather", Journal of Al Rafidain University College, No. 33,2014.

[6] Hayder Mohammad Jaffal, "Theoritical Analysis on Thermal Energy Storage using Phase Change Materials Capsules for Solar Organic Rankine Cycle Power Generation System" Nahrain University, College of Engineering Journal (NUCEJ) Vol.17, No. l, pp.15-35, 2014.

[7] Papade .C.V. and Boda .M.A. "Design & Development of Indirect Type Solar Dryer with Energy Storing Material", International Journal of Innovative Research in Advanced Engineering (IJIRAE), Volume 1, Issue 12, 2014.

[8] Walid Aissa, Mostafa El-sallak, and Ahmed Elhakem,"An Experimental Investigation Of Forced Convection Flat Plate Solar Air Heater With Storage Material", Thermal Science: Vol. 16, No. 4, pp. 1105-1116, (2012).

[9] ASHRAE Guideline, “Guide engineering analysis of experimental data”, Guideline 2-1986 (RA96).

[10] Freund. M, Csikos.R, Kezthelyi.S and Mozes.Gy “Paraffin products : properties, technologies, applications”, Elsvier Scientific Publishing Company Amsterdam Oxford-New York 1982.

[11] د.لطيف حميد علي ، د.عماد عبدالقادر الدبوني " النفط المنشأ والتركيب والتكنولوجيا " ،مديرية دار الكتب للطباعة والنشر/ جامعة الموصل 1986 ، رقم الايداع في المكتبة الوطنية (٩٥٩-١٩٨٦).