Experimental Investigation of Solar Energy Storage Using Paraffin Wax as Thermal Mass

Mohammad A. Taher*‡, Mohammad N. Fares**

* Department of Chemical and Petroleum Refining Engineering, College of Oil and Gas Engineering, Basra University for Oil and Gas, Iraq, Basra, 6002

** Department of Chemical Engineering, College of Engineering, Basra University, Iraq, Basra, 6002

(moh1973may@gmail.com, ma1234@gmial .com)

‡ Corresponding Author; Mohammad A. Taher, Basra, Iraq, Tel: 09647722748739, moh1973may@gmail.com

Received: 09.04.2017 Accepted:31.05.2017

Abstract- World energy demands are expected to increase significantly due to global strong and continuous economic growth. On the other hand, energy availability, cost and environmental impacts are vital factors in the selection of future energy. Renewable energy resources such as solar, wind, and geothermal energy are promising alternatives for conventional fossil fuels. Solar energy is increasingly used as one of the most important renewable energy sources. The main advantages of solar energy are its easy deployment for different purposes and its power consistency throughout the year. However, solar energy has some drawbacks such as its limited availability during daytime only. This drawback can be overcome using solar energy storage using different available methods like battery bank and thermal mass. As a thermal mass method, phase change material (PCM) is widely used as an effective method for storing solar thermal energy using latent heat. PCMs provide many advantages including high energy capacity and constant temperature process. In the present study, a shell and tube air heater has been designed for solar energy storage using paraffin wax as phase change material (PCM). Electricity generated using photovoltaic panels is stored as latent heat of fusion of PCM in a bank of tubes. For charging period of 8 hours, a maximum of 61 ^{o}C has been reached for the PCM and a maximum of energy efficiency of 77% has been achieved.

Keywords Solar energy; Phase change material; Thermal storage; Energy efficiency.

1. Introduction

A major threat is growing due to the deficiency of global energy supply to meet the continuous increase in the global demand for more efficient and clean energy. Renewable energy sources such as solar energy are promising alternatives for conventional energy sources [1-3]. However, the implementation of renewable energy is facing many challenges such as its relative low efficiency. The later drawback can be overcome by energy storage which has become an attractive area of research, as it can greatly contribute in increasing of energy efficiency and meeting global future needs of energy

Solar energy can be stored as electricity in batteries [2] or as thermal heat in thermal mass materials [4-6]. The later have drawn attentions of many researchers to investigate the storage of energy in different forms for both industrial and domestic sectors [4-14]. Solar thermal energy can be stored within thermal mass materials in two forms, sensible heat, where the temperature of the material is changed with the amount of energy stored, and latent heat, where the phase of the material is changed by melting or freezing storing energy at constant temperature [8]. Phase change energy storage technique has found to be better than the sensible heat option due to its many advantages such as large energy storage per unit volume and uniform energy storage/supply [9].

This paper establishes experimental investigations of solar energy storage as thermal energy using paraffin wax as a phase change material (PCM) in a bank of horizontal tubes within a shell and tube heat exchanger. Solar-based electricity is converted into heat using a heating element (an electrical resistor) which is then stored in PCM. Different capacities of the solar panel were investigated during the energy charging mode.

The stored energy in the PCM is used for air heating in the discharging mode using different air mass flow rates. The effect of air mass flow rate on the performance of the system was also studied

2. Methodology

2.1. The Phase Change Material

A commercial paraffin wax was used as thermal mass material. Specifications of the paraffin are shown in Table 1. The range of fusion temperature was 54.3±2°C.

Table 1. Paraffin wax specifications

Properties	Value	Unit
Fusion temperature	54.3	°C
Fusion Latent heat	184480	J/kg
Solid specific heat	2384	J/kg °C
Liquid specific heat	2440	J/kg °C
Solid thermal conductivity	0.15	W/m°C
Liquid thermal conductivity	0.172	W/m.°C
Density of the PCM (liquid phase)	775	kg/m^3
Density of the PCM (solid phase)	833.60	kg/m^3
Thermal Expansion Coefficient	$7.14 X 10^{-3}$	1/°C

2.2. Shell and tube heat exchanger

The experimental setup is illustrated in Figure 1. Shell and tube heat exchanger has been designed with the specifications listed in Table1 where thirty copper tubes are used, see Figure 2 An electrical element is fitted in the centre of each tube before being filled with the PCM. Both ends of each tube are plugged as shown in Figure 3. Each tube was filled with commercial grade paraffin wax as PCM. Nine thermocouples were fitted with three different tubes for measuring the temperature of the PCM at different distances of the heat exchanger. Two more thermocouples were also used to measure the inlet and outlet air temperatures. Temperatures at different thermocouples were measured at an interval of 30 minutes.

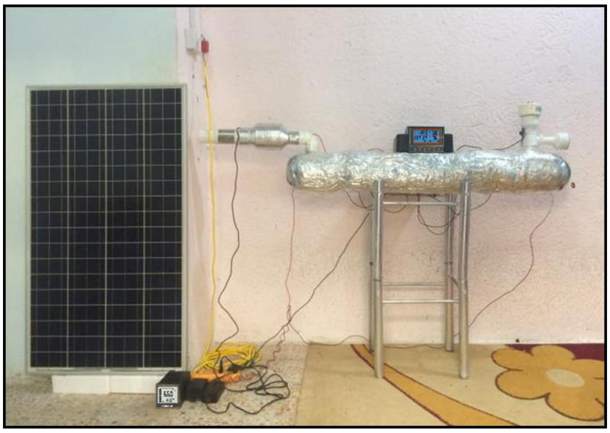
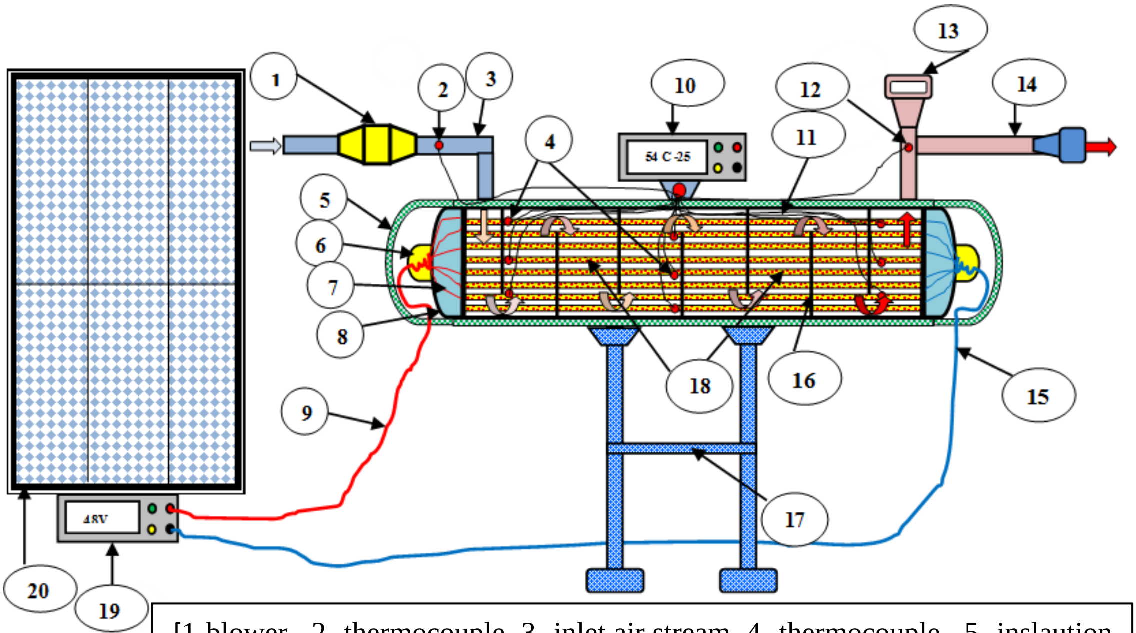


Fig.1. The experimental setup.



[1-blower 2- thermocouple 3- inlet air stream 4- thermocouple 5- inslaution 6- wires connections 7- heating element 8- shell wall 9- cable 10- data loger 11- thermocouple wire 12- thermocouple 13- manometer 14- outlet air stream

Fig.2. Sketch of the experimental setup

Table 2. Technical specifications of the heat Exchanger.

Part Name	Size/Material
Shell Material	PVC
Shell Diameter	110mm
Shell Length	1400mm
Shell Thickness	3mm
Tubes Material	Copper
Tubes Outer Diameter	12.6mm
Tubes Thickness	1mm
Tube Length	1300mm
Number of Tubes	30
PCM	Paraffin Wax
Mass (PCM)	4kg
Type of Heating element	Nichrome
Resistivity of Heating element	40 μΩ -cm
Temperature coefficient of resistance	0.0004 /°C
Melting point	1400°C
Heating element Length	1350 mm
Size of Insulation (Glass wool)	(1500*1000*25) mm

2.3. *The heat charging process*

The joule's law of heating can be used to calculate the heating generated by the electrical element.

$$Q_{gen} = I^2 Rt \quad (1)$$

Where; Q_{gen} is heat generated in joules, I is the current in amperes, R is the resistance in ohms and t is the time in seconds.

Heat stored by the PCM can be calculated by equation 2 below,

$$Q_{str} = Q_1 + Q_{lnt} + Q_2 \quad (2)$$

$$Q_1 = m_{pcm} Cp_{pcm} (T_{mlt} - T_{int}) \quad (3)$$

$$Q_2 = m_{pcm} Cp_{pcm} (T_f - T_{mlt}) \quad (4)$$

Where: Q_{str} is the storing heat by joules, Q_1 and Q_2 are heat stored in joules in the form of sensible heat below and above melting point of PCM respectively. Q_{lnt} is the latent heat of fusion of PCM (joules), m_{pcm} is the mass of PCM (g), Cp_{pcm} is heat capacity of PCM (joules/g.C), T_{int} and T_f are the initial and final temperatures (°C) of PCM respectively, and T_{mlt} is the melting temperature(°C) of PCM.

The efficiency of heat stored is expressed by:

$$\lambda = Q_{str} / Q_{gen} \quad (5)$$

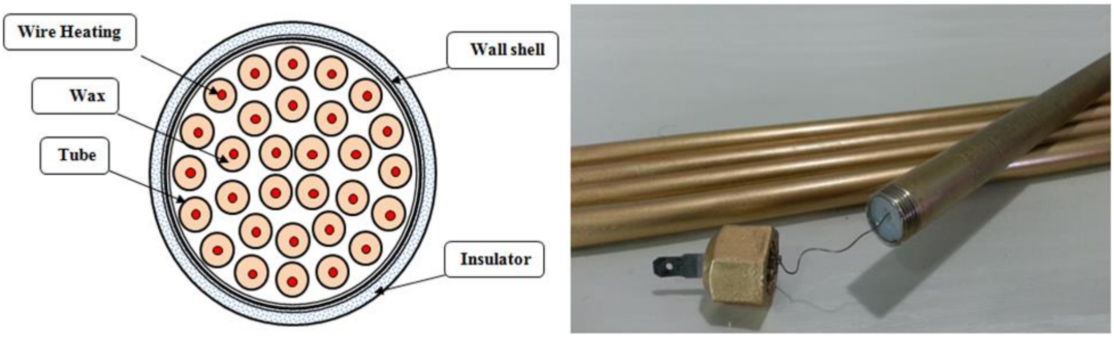


Fig.3. A cross section of the shell and tube heat exchanger. b. copper tubes filled with wax.

2.4 The heat discharging process

The heat stored by the PCM is used to heat a stream of air. The heat discharging process can be expressed by equation 4.

$$Q_{dsg} = m_{air} Cp_{air} (T_{out} - T_{in}) t_{dsg} \quad (6)$$

Where: Q_{dsg} is the discharging heat (joules), m_{air} is mass flowrate of air (g/sec), Cp_{air} is the heat capacity of the air (joules/g.C), tdsg is the time of heat discharging (sec).

2. Experimentation

Solar panel is connected with the shell and tube heat exchanger. Experiments were conducted at different capacities of the solar power which varies according to the solar panel area. The experimental procedure consists of two modes, heat charging and discharging as explained below:

(a) Heat charging mode

In this process, heat is generated by electrical elements which powered by electricity produced from the solar panel. The generated heat is absorbed i.e stored, by the PCM which surrounds the electrical elements inside tubes. At the beginning, the temperature of the PCM is lower than its melting temperature. Therefore, the PCM temperature increases storing energy as sensible heat. The temperature of the PCM gradually increases until it reaches its melting point. As the heat charging continues, the PCM melts whereas heat is stored at constant temperature of 54.32^{O}C as latent heat. Once the whole PCM melted, the temperature of the PCM increases again storing energy as sensible heat where the PCM becomes superheated. The charging process lasts for 8 hours, from 8 am to 4 pm.

Temperature of the PCM was recorded at different times. It has been noticed that the time required for the PCM to reach its melting temperature gradually decreases with the increase in the solar panel area. The results of the largest area of the solar panel (1 m^2) shows faster increase in the PCM temperature where about 1.5 hours were needed for the PCM to reach its melting temperature compared to 4.5 hours for the 0.25 m^2 solar panel.

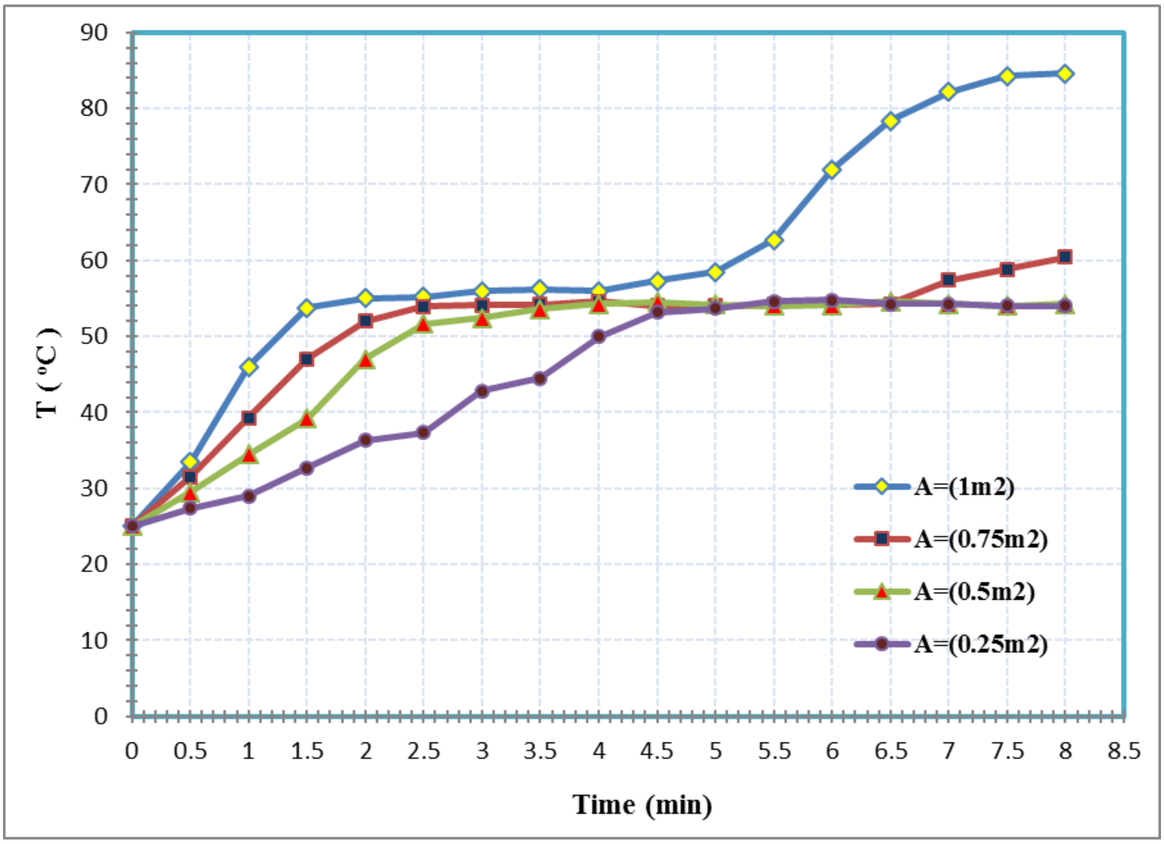


Fig.4. The results of charging process for different areas of solar panels (1, 0.75, 0.5 and 0.25 m^2).

Furthermore, the results show that the time needed for the whole PCM amount to be melted were different, Figure 5. The results show that in case of 1 m^2 solar panel, about 3.5 hours were needed to melt the whole PCM amount compared to 4.5 hours in the case of 0.75 m^2 solar panel.

For the 0.5 and 0.25 m^2 , the eight hours' charging period was not sufficient for complete melting of the PCM.

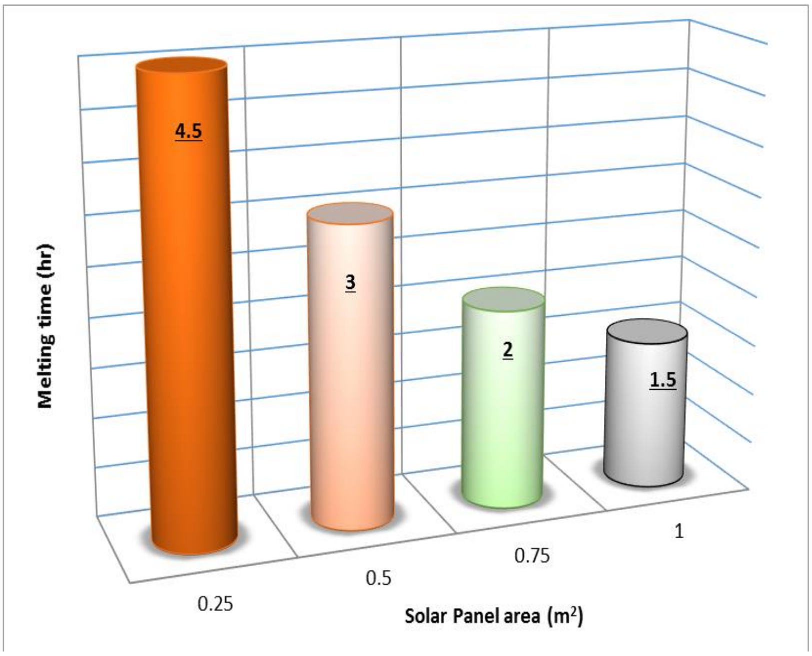


Fig.5. Melting time at different solar panal areas

(b) Heat discharging mode

Stored energy in the PCM as latent and sensible heat will be used for heating of a stream of air. In the discharging process, air at temperature of 25 ºC is pumped into the shell side of the heat exchanger. Different air flowrates were examined, 10, 15, 20 and 25 kg/hr, and the results are shown in Figure 6. The results show that the air heating time decreases with the increase of air flowrate. The maximum heating time was 270 minutes which was recorded for the flow rate of 10 kg/h whilst only 110 minutes were needed in the case of 25 kg/h air flowrate.

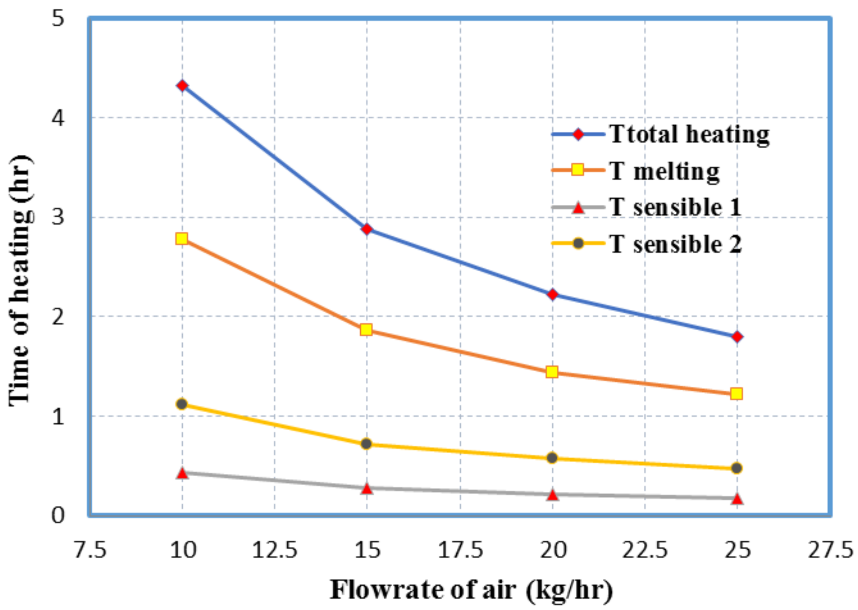


Fig.6. Air heating time at different air flowrates

Figure 7 shows the change in the air outlet and PCM temperatures with discharging time. The results show that the air outlet temperature drops from 53 °C to about 46 °C in 50 minutes. Then, the air temperature stabilizes around 46 °C for about 160 minutes to be declined again to 26 °C in further 60 minutes. The air heating duty is shown in Figure 8. The average value of heating duty was 60W for the valuable heating period.

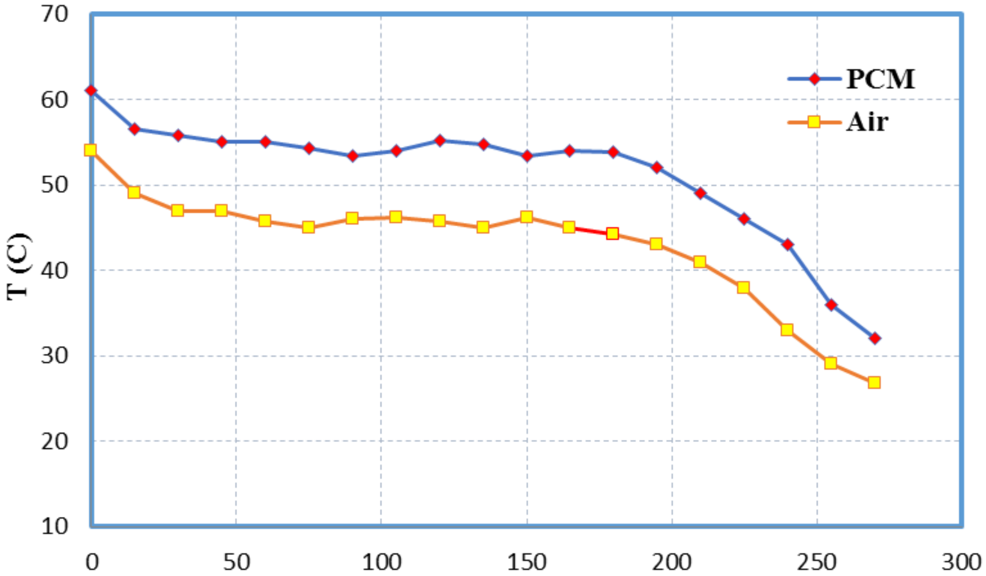


Fig.7. The change in the air and PCM temperatures with discharging time

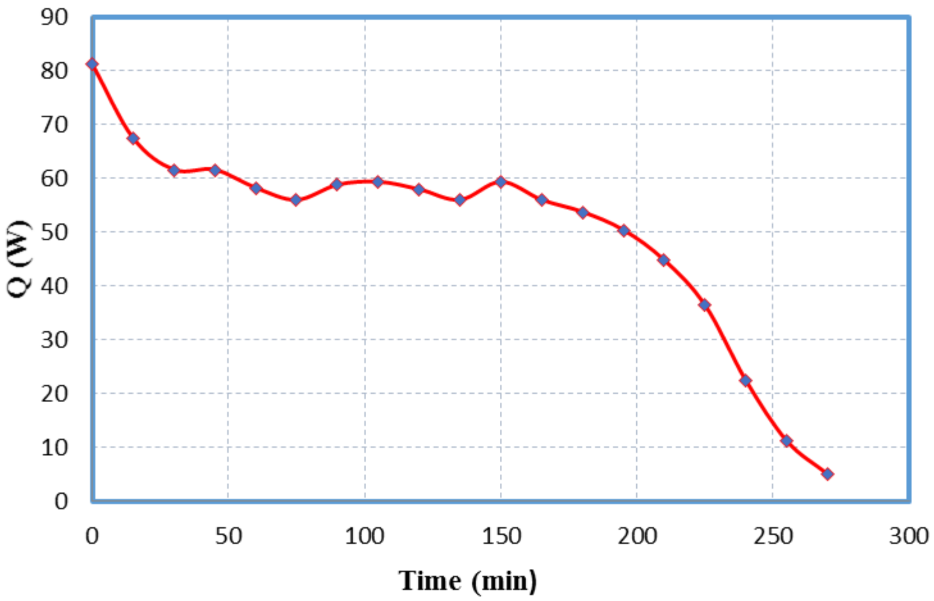


Fig.8. The air heating duty

3. Conclusions

Solar thermal storage using PCMs provides many advantages such as high energy capacity and constant temperature process. This work investigates the efficiency of storing solar energy using paraffin as thermal mass material. Solar based electricity has been stored in the form of sensible and latent heat using a bank of tubes filled with PCM. The stored heat was used for air heating. Different cases have been studied where several design parameters were investigated. The results show that a maximum of 61 ^{o}C was reached for the PCM through the total energy charging period of 8 hours. The storing efficiency of energy was 77% and a total of heat discharging time was 270 minutes.

References

[1] Russell W. Peterson, Application of solar technology to today’s energy needs, 1st ed., vol. 1. OTA Congress of the United States, pp.429-493, 1978. (Book).

[2] Anubhav U., Kesari J. P., and Mohd. Z., Designing of Solar Process Heating System for Indian Automobile Industry, International Journal of Renewable Energy Research, Vol.6, No.4, pp.1628-1636, 2016.

[3] Ali H. A. Al-Waeli1, Moanis M. K. El-Din, and Atma H. K. Al-Kabi, Asma Al-Mamari, Hussein A. K., and Miqdam T. Ch., Optimum Design and Evaluation of Solar Water Pumping System for Rural Areas, International Journal of Renewable Energy Research, Vol.7, No.1, pp.12-20, 2017.

[4] Buddhi, D., Bansal, K., Sawhney, R.L. & Sodha, M.S. Solar thermal storage systems using phase change materials. Int. J. Energy Research, 12, pp.547-555, 1988.

[5] Ghoneim, A.A., Klein, S.A., The effect of phase-change material properties on the performance of solar air-based heating systems, Solar Energy, Vol.42, No.6, pp.441 – 447, 1989.

[6] Beasley, D.E. & Ramanarayanan, C., Thermal response of a packed bed of spheres containing a phase change material, Int. J. Energy Research, 13, pp.253-265, 1989.

[7] Hasan A., Phase change material energy storage system employing palmitic acid. Solar Energy, Vol.52, pp.143–54, 1994.

[8] Keumnam Cho and Choi, S.H., Thermal characteristics of paraffin in a spherical capsule during freeing and melting processes, Int. J. Heat and Mass Transfer, Vol.43, pp.3183-3196, 2000.

[9] Ettouney, H., El-Dessouky, H. & Amani Al-Ali., Heat transfer during phase change of paraffin wax stored in spherical shells. ASME Journal of Solar Energy Engg., Vol.127, pp.357-365, 2005.

[10] Naranjo-Mendoza C., Rousse D. R. and Quesada G., Modeling of a solar absorption cooling system for Guayaquil, Ecuador, 2013 International Conference on Renewable Energy Research and Applications (ICRERA), Madrid, pp. 853-856, 2013.

[11] Evren M. T., Alper Y., Tufan B., Mustafa T., Ömer F. K., O'uzhan D., Hüseyin Ç., Design and development of solar flat mirror and heat storage system," 2014 International Conference on Renewable Energy Research and Application (ICRERA), Milwaukee, WI, pp. 821-827, 2014.

[12] Yaïci W. and Entchev E., Prediction of the performance of a solar thermal energy system using adaptive neuro-fuzzy inference system, 2014 International Conference on Renewable Energy Research and Application (ICRERA), Milwaukee, WI, , pp. 601-604, 2014.

[13] Adetifa B.O. and Aremu A.K., Investigating the Effect of Different Heat Storage Media on the Thermal Performances of Double Exposure Box-type Solar Cookers, International Journal of Renewable Energy Research, Vol.6, No.3, pp.1109-1118, 2016.

[14] Jakir H., Nazmus S., Eklas H., and Ramazan B., Modelling and Simulation of Solar Plant and Storage System: A Step to Microgrid Technology, International Journal of Renewable Energy Research, Vol.7, No.2, pp.723 -737, 2017.