Investigation of Paraffin Wax with ZnO Nanorods for Performance Enhancement of Solar Thermal Energy Storage

M. Ib. Sokar, S. *A. Mansour, A. A. Abdel Aziz* and M. H. Elnekiety

Abstract—This paper discusses the influence of paraffin wax inoculated with ZnO-nanorods on the latent heat of thermal energy storage (LHTES) of solar water heating system. The main objective of the experimental study is to determine the percentage increase in thermal storage capacity of using paraffin wax with 0.15 wt.% ZnO-nanorods as nano-composite phase change material (NCPCM) to the raw paraffin wax as base phase change material (PCM). The experiments were performed by 33-liter insulated stainless-steel storage shell TES tank containing 21 copper tubes 5/8-inch in diameter. The TES tank is filled with circulating water and the tubes are filled with either the pure PCM or NCPCM. The water is the heat transfer fluid (HTF) in the TES tank. The experiments were done at different HTF flow rates to study the best flow rate that increases both the amount of heat transfer and melting rate of PCM. It was found that 0.15 wt.% ZnO NCPCM decreases the charging and discharging time compared to the pure PCM, and a percentage increase is achieved in thermal energy storage by 20% when using 0.15 wt.% ZnO nanorods. The results also reveal that the maximum discharge energy was raised from 266 kW for pure paraffin wax to 306 kJ for 0.15 wt.% ZnO NCPCM. The NCPCM at 6 l/min HTF flow rate provides the highest energy recovery ratio (ERR), while the smallest occurs at 9 l/min.

Corresponding Author: M. Ib. Sokar, is assistant professor at the Department of Mechanical Engineering at Shoubra, Benha University, Cairo 11629 Egypt (e-mail: mohamed.sokar@feng.bu.edu.eg).

S. A. Mansour is professor at Basic Engineering Science Department, and Advanced Materials/Solar Energy and Environmental Sustainability (AMSEES) Laboratory, Faculty of Engineering, Menoufia University, Shebin El-Kom, Egypt (e-mail: shehab_mansour@yahoo.com).

I. INTRODUCTION

THE intermittent nature of the solar energy is an impediment to the total dependence on it as an alternative to a person's daily energy requirement. So that, many researchers have developed various techniques to overcome this point. Increasing the latent heat of thermal energy storage (LHTES) of phase change material (PCM) is one of these techniques. PCM such as paraffin wax has high storage energy densities per unit mass/volume and nearly

A. A. Abdel Aziz, is professor at the Department of Mechanical Engineering at Shoubra, Benha University, Cairo 11629 Egypt (e-mail: ali.ali@feng.bu.edu.eg).

M. H. Elnekiety, is MSc student at the Department of Mechanical Engineering at Shoubra, Benha University, Cairo 11629 Egypt (e-mail: mk_genx@yahoo.com)..

constant heat energy, this gives the possibility of excess energy storage at constant temperature, but it suffers from low thermal conductivity. Adding nanoparticle to the base PCM to create a nano-composite phase change material NCPCM is considered one method to increase the thermal properties of the paraffin wax.

In the literature, many experimental studies were performed using paraffin wax and different nanocomposite materials. used Paraffin wax with titanium dioxide TiO_2 nanoparticles were used by [1, 2]. The results showed the improvement in both charging and discharging efficiencies from 4% to 6% compared to using of pure paraffin wax, also the heat transfer rate is increased depending on the position of the spherical ball into the tank. Another experimental investigation was done by [3, 4] using nanocomposite paraffin wax with Alumina Al_2O_3. The results showed that the melting and solidification time reduced by 50% and both charging and discharging efficiencies enhanced by 6% and 4%, respectively, by using of Al_2O_3 as nanoparticle with paraffin wax up to 2% mass fraction compared to pure paraffin wax. although the marginally increase in heat transfer enhancement after this fraction. Experimental study to confirm the enhancement occur in the thermal energy charging and discharging rates by adding Al_2O_3 and TiO_2 as nanoparticles with different mass fraction respectively, compared to pure paraffin wax PCM was done by [5]. Another experimental investigation using a combination of paraffin wax with silicon dioxide SiO_2 as a nano-composite phase change material (NCPCM) was done by [6, 7 & 8]. The results showed that thermal conductivity of SiO_2 NCPCM was increased to 22.78% compared to the base paraffin wax, the composite material melting point decreased and the measured latent heat became lower than the calculated values with the decreasing in Nano-SiO_2 pore size. Experimental analysis studying the effect of adding of Al_2O_3 and CuO as Nano particles with different weight percentages (0.1, 0.3 and 0.5 wt.%) to PCM on the thermal properties of paraffin composites was done by [9, 10]. Maximum enhancement in thermal conductivity was observed for CuO based PCM and a higher reduction in charging time in case of using CuO compared to Al_2O_3 Nano-particles. Four nanoparticles, Fe_3O_4, CuO, TiO_2, and ZnO, respectively, with paraffin wax as PCM were experimentally studied in [11] to enhance in thermal properties of PCM. Results showed that the CuO gives a higher increase of latent heat compared to other nanoparticles. Un-finned metallic plate with a micro finned plate through a cooling solution of paraffin wax as PCM and Nano CuO enhanced PCM was experimentally evaluated the LHTES system by [12-14]. The results showed that using the NCPCM enhanced the charging and discharging rates and a higher cooling potential in micro-finned surfaces was obtained compared to the un-finned surfaces and there is an enhancement in both thermal conductivity and required time for reaching melting point in case of NCPCM compared to the base PCM. Experimentally evaluation for the enhancement in thermal characteristics of Nano copper (Cu) powder added into paraffin wax with different weigh concentration was done by [15]. Results showed that paraffin wax thermal conductivity percentage was increased with increasing Nano Cu dispersion in the PCM

with weight from 0.5% to 2% in step of 0.5. On the other hand, numerical studies were performed on a LHTES system by dispersing Al_2O_3 [16] and copper [17] as nanoparticles into PCM of paraffin wax. Results showed that the charging speed and reduction melting time have been enhanced by 19.6%. In addition, the increasing in nanoparticles volume fraction increase the energy storage rate of LHS system. The thermal storage capacity of a mixture of three materials (Paraffin wax, Palmitic acid and Eutectic mixture) was investigated by [18]. It was concluded Eutectic mixture has better thermal storage capacity and time to keep the high temperatures comparing with the base materials. Kanimozhi and Bapu [19] experimentally investigated the thermal performance of PCM storage unit when increases the number of vertical tubes filled with PCM in TES unit to 50 small diameter tubes TES unit. The results showed that small diameter copper tubes improved the heat transfer between HTF and PCM during both charging and discharging processes. An experimental and numerical investigation were done by [20] to study the thermal characteristics of shell-and-tube type LHTES system using paraffin wax as a PCM and ZnO nanoparticles with different concentrations. Results showed that the large water Prandtl number caused a slow heat transfer from the heat transfer fluid (HTF) to the PCM which means a large quantity of heat is moved downstream with the water, while a small quantity of heat was transferred to the paraffin upstream.

It was found from the previous studies, that there is a lack of using Zinc Oxide, ZnO as nanocomposite with paraffin wax especially in nanorod shapes in solar storage systems. The synthesized ZnO nanorods of diameter less than 100 nm was well dispersoid in the paraffin wax for 30 min using to high power ultrasonic homogenizer equipment. Therefore, the present research is carried out to design and construct an experimental setup that investigate the enhancement in thermal performance of solar storage system with synthesized 0.15 wt.% ZnO nanorods as NCPCM and different flow rate of heat transfer fluid.

II. EXPERIMENTAL SETUP AND PROCEDURES

A. Experimental setup

An experimental test rig had been designed and fabricated in Cairo, Egypt to build a solar LHTES system as shown in the circuit diagram of Fig. 1.
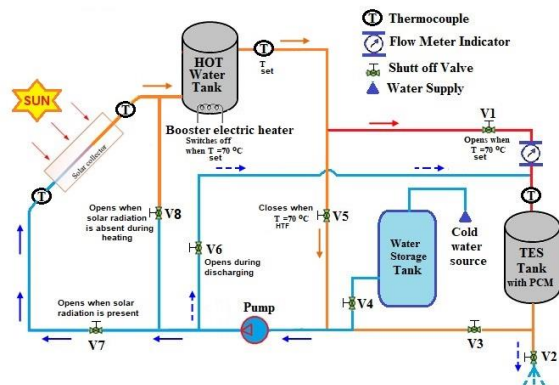

Fig. 1. Circuit diagram of the experimental setup

Fig. 2 shows the actual outdoor components of the test-rig used in this study. The test rig consists of TES cylindrical tank 33-liter storage capacity made of 1.5 mm thickness 316- type stainless steel. The tank was insulated by glass wool isolation of thickness 60 mm from outside to reduce heat loss to the environment, hot water storage tank with the same specifications of the TES storage tank, 160-liter PVC plastic water storage tank, booster electrical heater 1.2 kW power immersed in 50-liter insulated shell combined with the hot water tank. 160 cm length by 60 cm width flat plate solar collector having 11 m copper tube ¼ inch in diameter, a circulating pump of 0.3 hp and control valves. These elements are interconnected via the piping system which is made from ½ inch in diameter propylene tubes.

Fig. 2. Photograph of the outdoor experimental test rig

Fig. 3 shows the test section element which consists of 26 cm diameter horizontal stainless-steel discs of 2 mm thickness. Twenty-one copper tubes of 5/8-inch diameter filled with PCM. Proper capping for all copper tubes to ensure effective insulation inside the TES tank was done. Twenty-six calibrated T-type thermocouples, each of length 2 m and 0.25 mm diameter are immersed at different positions along the pipes to record the temperature during the experiments.
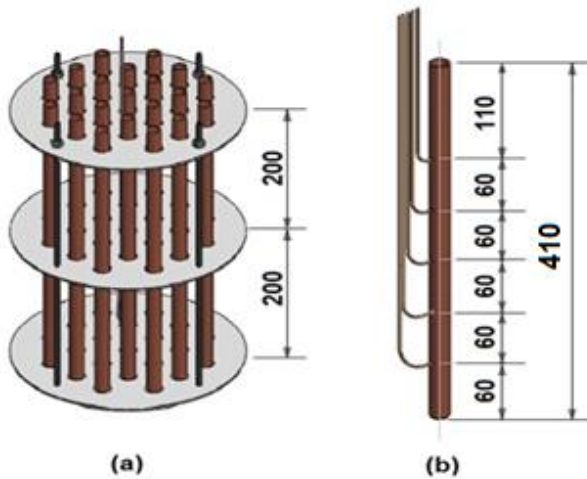

Fig. 3 Schematic of (a) the test section element (b) Thermocouples positions

B. Preparation and characterization of NCPCM

The used PCM in the present work are pure commercial paraffin wax (PW) loaded by ZnO nanorods to form NCPCM by mixing. The used ZnO nanorods synthesized using the thermal decomposition technique. The typical preparation of such technique was reported elsewhere [21]. In this respect, 15 g of zinc acetate dihydrate (Winlab, purity: 99.999%) in alumina crucible was subjected to heating at 350 °C for 3.5 h in order to achieve the decomposition process and convert to ZnO nanorods. The microstructure characterization of the final powder using X-ray diffraction (XRD) confirmed the formation of pure wurtzite hexagonal phase ZnO phase as discussed elsewhere [21]. The morphology of the synthesized ZnO nanorods was characterized using the high transmission resolution electron microscope (HRTEM), model JEOL-JEM-1230. Fig. 4 shows the HRTEM micrographs of the synthesized ZnO. Such micrograph refers to the formation of ZnO in rod-like shape with a reasonable degree of uniformity in the diameter of the particles. Moreover, the diameter of the particles is less than 100 nm that is confirmed the nano-size structure of the investigated particles.
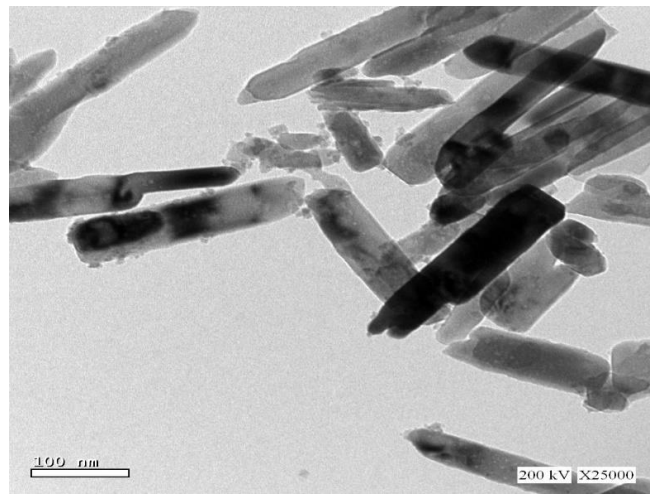

Fig. 4. HRTEM micrograph of the synthesized ZnO nanorods

In order to create NCPCM sample, the synthesized ZnO nanorods was mixed with melted PW at 80 °C with 0.15 wt.% of ZnO nanorods. The mixing process was achieved during sonication process for 30 min using to high power ultrasonic homogenizer equipment (SONICS, VCX-500). The fabricated NCPCM and pure PW samples were labeled as PW-0.15 and PW-0, respectively. The thermophysical properties such as the melting point, T_m, and latent heat of fusion of PW-0 and PW-0.15 samples had been determined using differential scanning calorimetry (DSC) using non-isothermal measurements with constant heating rate 20 °C/min using DSC131 evo (SETARAM Inc., France). The thermophysical characteristics were determined and listed in Table I.

TABLE I
THERMOPHYSICAL PROPERTIES OF PW AND NCPCM

Sample	T_m (°C)	Latent heat (J/g)	Liquid fraction @Tm
PW-0	60.8	234	0.528
PW-0.15	62.8	280	0.572

C. Experimental Procedures

The experimental tests are carried out with a constant inlet conditions of temperature and flow rate of HTF. The charging and discharging experiments are conducted under various experimental parameters of HTF volume flow rate. The HTF inlet temperature to TES tank is kept constant at 70 °C and 24 °C during charging and discharging processes, respectively. The initial temperature inside the water storage tank is maintained at 20 °C, which considered the initial PCM temperature for all charging experiments, while during all discharging experiments the PCM is maintained in liquid phase at 70 °C.

To prepare the experiment, the system is first filled with water, which is used as HTF during charging and discharging processes of the TES tank. Then the pump is switched on to continually circulate the HTF through the solar collector at an adjusted flow rate to absorb the heat solar energy in order to increase its temperature to 70 °C. In case of low solar intensity, the booster electrical heater is switched on, until the HTF temperature reaches 70 °C, at this temperature the thermostat switches the electrical heater off. The HTF is kept in both hot water tank and electrical heater shell. During the charging process, the HTF is allowed to flow into the TES tank via valve V1 in order to charge the PCM inside the copper tubes, and then to the electrical heater tank in order to keep the inlet temperature of the TES tank constant at 70 °C. The process is repeated until the charging process is completed.

In discharging process, pump delivers the HTF from the cold-water tank at 24 °C across valve V6 to flow through the TES tank absorbing the heat stored in the PCM. During the discharge process the outlet HTF is purged through valve V2, the circulation is continued until thermal equilibrium occurs. Both charging and discharging processes are considered done when the PCM and HTF temperatures are equal (70 °C during charging and 24 °C during discharging). The same procedure is repeated at different mass flow rates, and the heat transfer rate and heat absorption are calculated in each case.

D. Basic calculations and error analysis

The heat absorbed and heat rejected during the charging and discharging processes can be calculated as follows;

$$Q_{abs} = \int_{T_i}^{T_m} m\, Cp\, dT + ma_m\, \Delta h_m + \int_{T_m}^{T_f} m\, Cp\, dT \qquad (1)$$

$$Q_{rej} = \int_{T_m}^{T_i} m\, Cp\, dT + ma_m\, \Delta h_m + \int_{T_f}^{T_m} m\, Cp\, dT \qquad (2)$$

The Energy Recovery Ratio (ERR", which is also known as "Energy Conversion Efficiency", is defined as the ratio of the discharge heat to the charging heat of paraffin wax, can be calculated as follows;

$$ERR = \frac{Q_{rej}}{Q_{abs}} \qquad (3)$$

The enhancement in energy recovery ratio due to adding ZnO nanoparticles to pure PCM can be calculated as follows:

$$Enhancement\ Ratio = \frac{ERR_{NCPCM}}{ERR_{PCM}} \qquad (4)$$

Uncertainty or error analysis for the main measurements used in experiments such as temperature, flow rate, and heat absorbed respectively are calculated as follows,

$$\omega_{\Delta T_t} = \pm \sqrt{\left(\frac{\partial \Delta T_{HTF}}{\partial \Delta T_i}\omega_{T_i}\right)^2 + \left(\frac{\partial \Delta T_{HTF}}{\partial \Delta T_o}\omega_{T_o}\right)^2} \qquad (5)$$

$$\omega_{\dot{V}} = \pm \sqrt{\left(\frac{\partial \dot{V}}{\partial V}\omega_V\right)^2 + \left(\frac{\partial \dot{V}}{\partial t}\omega_t\right)^2} \qquad (6)$$

$$\omega_{Q_{abs}} = \pm \sqrt{\left(\frac{\partial Q_{abs}}{\partial m}\right)^2 \omega_m^2 + \left(\frac{\partial Q_{abs}}{\partial T_i}\right)^2 \omega_T^2 + \left(\frac{\partial Q_{abs}}{\partial T_m}\right)^2 \omega_T^2 +}$$

$$\left(\frac{\partial Q_{abs}}{\partial T_f}\right)^2 \omega_T^2 + \left(\frac{\partial Q_{abs}}{\partial a_m}\right)^2 \omega_{a_m}^2 \qquad (7)$$

Summary of uncertainty analysis is presented in Table II.

TABLE II
AVERAGE UNCERTAINTIES IN MAIN PARAMETERS

Parameter	Uncertainty (ω)
Temperature	±0.5°°C
Mass flow rate	±1.67%
Heat absorbed	±2.7%

III. RESULTS AND DISCUSSION

A. Experimental validation

In order to validate the experimental measurements obtained in this study, a comparison of the measured date from this test rig to the results introduced by Kanimozhi and Bapu [19] for pure PW at 70 °C HTF inlet temperature. Exploratory tests have been performed for pure PW at 6 l/min flow rate. Figure 5 shows a good agreement between the absorbed heat by PCM during charging process versus the average temperature in this study to the results of Kanimozhi and Bapu [19] with maximum deviation of 4% noticed at the start of energy storage in sensible heat before the melting temperature. This comparison revealed the confidence in the experimental test rig and the measurements.
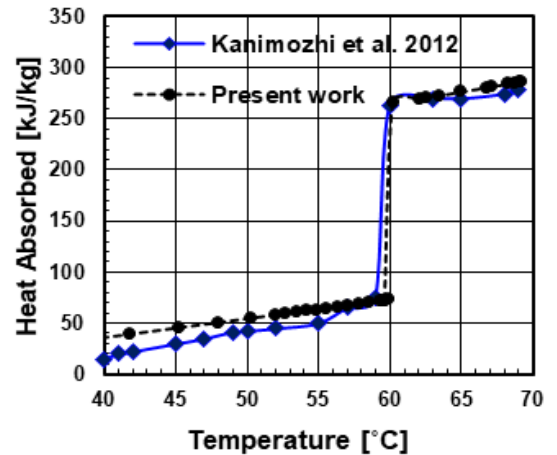

Fig. 5. Comparison between the present work and Kanimozhi and Bapu [19]

Numerous experimental tests were conducted to study the thermal performance of the solar TES system during both charging and discharging phases. The HTF, at different volume flow rate (4, 6, 8, 9 and 10 l/min), is allowed to inter the TES tank at constant temperature (s) of 70 °C during

charging and 24°C during discharging. Due to the intermittent nature of solar energy and the variation of solar radiation, a backup electrical heater was used to keep the temperature of HTF constant at 70°C. Figures 6 and 7 show the local temperature variation of the pure paraffin wax PCM and with 0.15% ZnO nanocomposite PCM, respectively inside the shell and tube test section at five levels during each of the charging and discharging phases. The volume flow rate of the HTF was 4 l/min and the temperature of the HTF inlet to the TES tank was maintained constant at 70°C during charging and 23°C during discharging phases.

Fig. 6 reveals the rapid increase in the temperature occurs at the beginning of charging process, but still below the melting point of the PCM. The maximum temperature is located at the top of the tube (T_5) because the hot liquid PCM raises up and the colder PCM drops down where the natural convection is more significant. The temperature range obtained during charging process ensures that all PCM is melted.
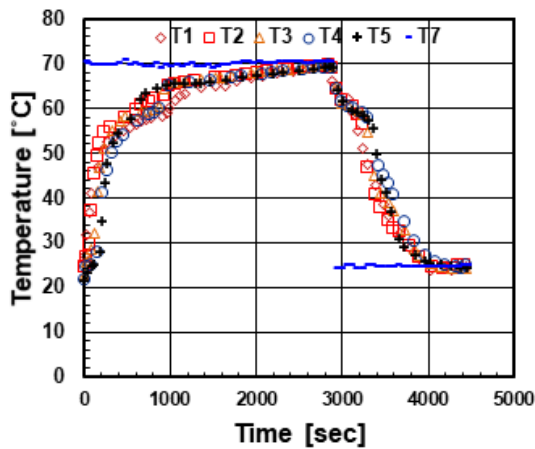

Fig. 6. Local temperature variation of pure paraffin wax PCM at 4 l/min

The local transient temperature variations inside the TES with NCPCM of 0.15 wt.% ZnO are shown in Fig. 7. In comparison with Figure 6, it is observed that NCPCM shows a significant effect on temperature variation before melting where a sensible heat is absorbed by conduction only. Thermocouple T_2 has a maximum temperature and then a rapid change in the slope of the temperature takes place earlier, where the thermocouple location T_2 is exposed to the inlet hot HTF. The temperature of thermocouple at location T_3 increases with a higher rate compared to the other thermocouple except T_2 due to the dominating of natural convection at this melting phase change where convective thermal current moves up. Also, it is found that the temperature for NCPCM is higher than that for pure PCM for all positions of the thermocouples. The time during melting process is reduced by 69.89% when NCPCM with 0.15 wt.% ZnO compared to pure PCM.
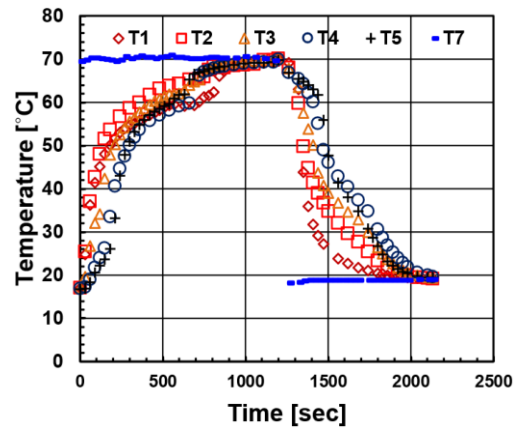

Fig. 7. Local temperature variation of 0.15 wt.% ZnO NCPCM at 4 l/min

A. Effect of volume flow rate

The average temperature variations in the TES for pure PCM vs time for different volume flow rates during charging and discharging processes is shown in Fig. 8. The inlet volume flow rate of the HTF to the TES was regulated at a constant value by a control valve V7. For each experiment the HTF inlet temperature was kept at 70 °C and 24 °C during charging and discharging processes, respectively. The HTF volume flow rate which varies from 4 to 10 l/min, has a more significant effect on the average temperature of PCM with and without nanoparticles. The charge time of pure PW at each flow rate is 2820, 1980, 1470, 1050, and 2100 s corresponding to 4, 6, 8, 9, and 10 l/min, respectively. The time required to store the thermal energy decreases as the volume flow rate of HTF increases from 4 to 9 l/min but at 10 l/min the time rises again. Therefore, it is not recommended to store the thermal energy at a volume flow rate higher than 9 l/min. Because an increase in the HTF flow rate beyond 9 l/min only improves forced convection in the storage tank outside the heat exchanger pipes while the inlet temperature of HTF is constant. Therefore, the heat loss to outside the storage tank with large surface area increases compared to the heat transfer to the PCM pipes.
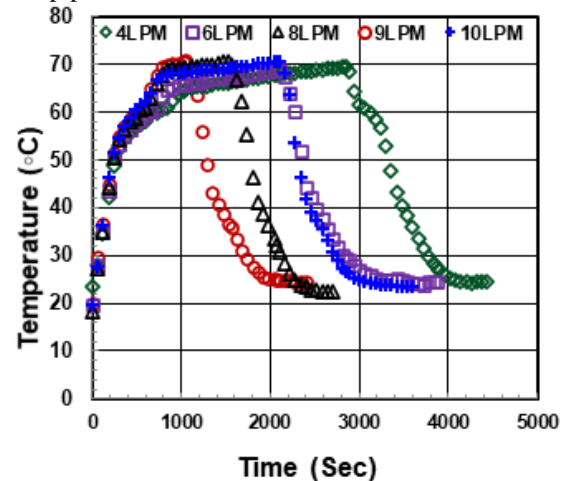

Fig. 8. Average temperature of pure PW during charging and discharging

The effect of the HTF volume flow rate on the instantaneous average temperature of NCPCM during charging and discharging processes is indicated in Fig. 9. The

curves show that the charging and discharging times decreases with increasing in the HTF volume flow rate until 9 l/min, at the same inlet temperature of HTF. Because the heat transferred by forced convection is improved around the PCM copper tubes and the thermal resistance is reduced.
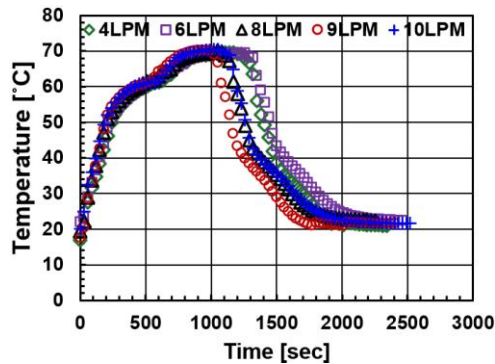

Fig. 9. Average temperature of NCPCM during charging and discharging

B. Effect of dispersoid Nano particles in paraffin wax

Fig. 10 shows the effect of 0.15 wt.% ZnO NCPCM on the instantaneous average temperature at each value of the HTF volume flow rate compared to the pure PW. During the charging process, the phase change is completed faster for NCPCM in comparison with pure PW. It is observed that, the NCPCM takes shorter time than pure PW to melt NCPCM. This is due to the enhancement in the heat transfer rate during charging and discharging phases. The period required to complete the phase change during charging process for pure PW and NCPCM are 1500 s and 1100 s, respectively at 8 l/min volume flow. It is found that there is a reduction in charging time of about 60.2% for NCPCM at 4 l/min. The 4 l/min flow rate for NCPCM is suitable for practical engineering due to minimum energy consumption and high thermal performance of energy storage system.
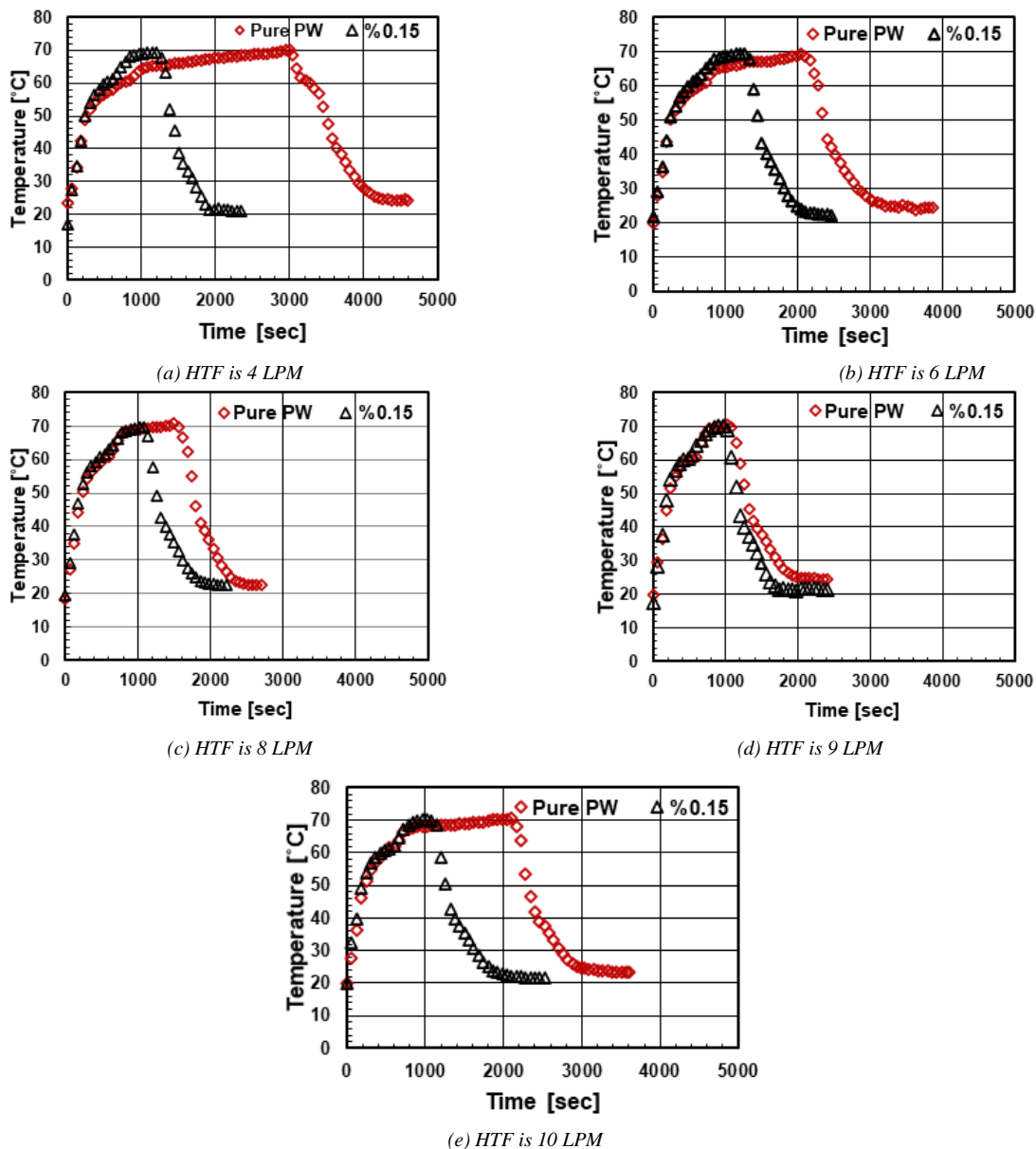

(a) HTF is 4 LPM

(b) HTF is 6 LPM

(c) HTF is 8 LPM

(d) HTF is 9 LPM

(e) HTF is 10 LPM

Fig. 10. The instantaneous average temperature of NCPCM vs Pure PW during charging-discharging processes at different volume flow rates

C. Heat absorbed during charging process

The instantaneous variation of heat absorption for pure PW during charging process is shown in Fig. 11 for different values of HTF volume flow rates. It is noticed that, the heat absorbed increases vs. the time of charging process. The pure PW starts to store energy in the form of sensible heat until the melting temperature and after that in the form of latent heat at constant temperature and again energy stored in the form of sensible heat in liquid phase. The total time for complete charging process decreases by 58% of the original time when the HTF volume flow rate increases from 4 to 9 l/min. The heat transfer rate by convection outside the PCM copper tubes increases due to the increase in flow rate and it is expected to take a short period during charging process. When the HTF flow rate increased from 9 to 10 l/min, the charging time increases because the heat transfer by convection outside PCM copper pipes increases and more heat losses outside the storage tank which is higher than the natural convection heat transfer inside the PCM. Therefore, increasing the HTF flow rate from to 10 l/min is energy-inefficient and not recommended because it effectively maximize the heat losses to outside.
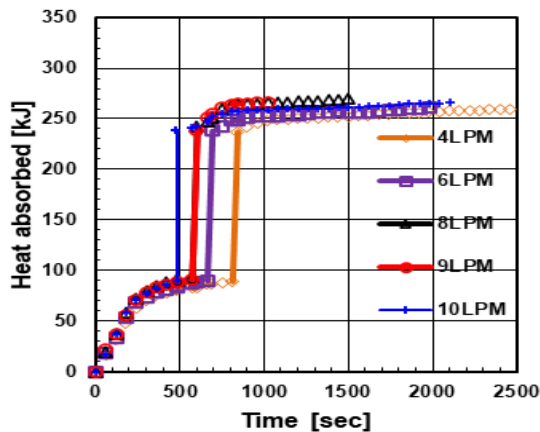

Fig. 11. Heat absorbed by pure paraffin wax PCM during charging process at different HTF volume flow rates

Fig. 12 shows the effect of 0.15 wt.% NCPCM on the instantaneous heat absorption (energy storage) at different values of HTF volume flow rate during charging process. The flow rate of HTF has a more significant effect on the absorption heat at 0.15 wt.% NCPCM as shown in the graph during the charging process. The effect of adding nanoparticles has better effect on the absorbed heat (charge energy) than that of the HTF flow rate. It is noticed that, increasing the volume flow rate results in shorter charging time. Therefore, the effect of the HTF flow rate on the heat absorption isn't high for pure PCM and 0.15 wt.% NCPCM.
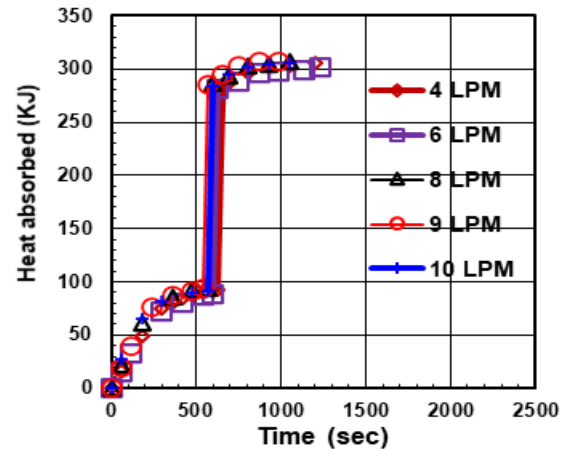

Fig. 12. Heat absorbed of NCPCM during charging process at HTF different volume flow rates

Fig. 13 shows the effect of 0.15 wt.% NCPCM on the energy storage (heat absorption) at 6 l/min HTF flow rate. At the beginning of charging process, the heat absorbed increases with a high rate due to the large temperature difference between the PCM and the HTF. The heat absorbed increases linearly during the latent heat phase change and increases nonlinearly during the solid and liquid phase. The heat absorbed of NCPCM is higher than that of pure PW. The time required for charging process is reduced by 38% for NCPCM.
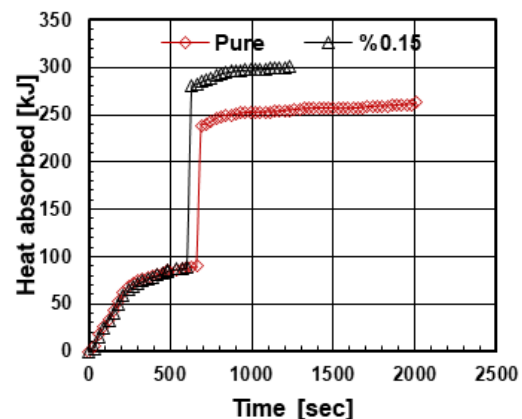

Fig. 13. Heat absorbed by both samples during charging process at 6 LPM

D. Heat rejected during discharging process

The instantaneous variation of heat rejected by pure PW and NCPCM during the discharging phase at different values of HTF volume flow rate are presented in Fig. 14 and Fig. 15, respectively. It is clear from these two figures that, the heat rejected to the HTF increases when using NCPCM and the total time of discharging process is reduced, especially for the sensible heat rejected at the end of discharging process.
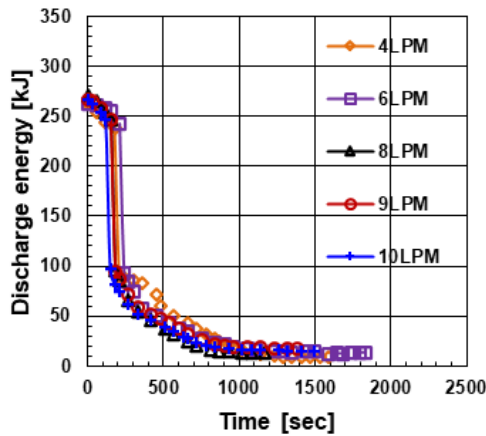
Fig. 14. Heat rejected of pure PW during discharging process at different HTF volume flow rates
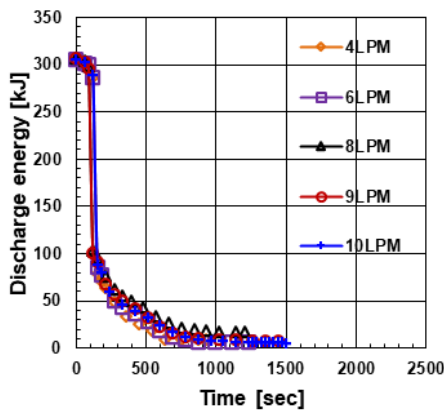

Fig. 15. Heat rejected of NCPCM during discharging process at different HTF volume flow rates

E. Effect of Nano concentration and volume flow rate on charging and discharging time

Figure 16 shows the effect of NCPCM and variation of volume flow rate on the charging times. The results indicated that, a reduction in charging time to 60.2%, 43.3%, 34.7%, 6.25%, 51.5% occurs by using NCPCM at HTF volume flow rates 4, 6, 8, 9 and 10 l/min, respectively.
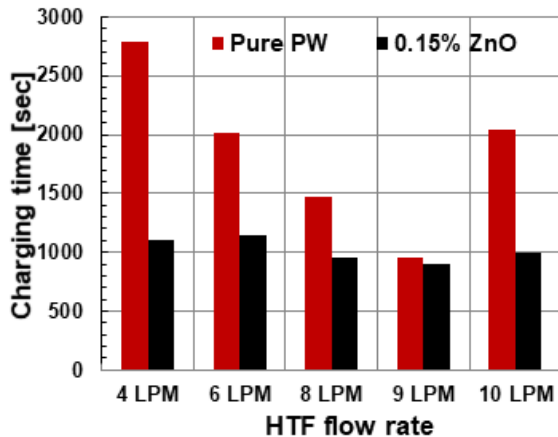

Fig. 16. Effect of both NCPCM and HTF flow rate on charging time

Figure 17 shows that the discharging times of NCPCM are smaller than pure PW at all HTF flow rates, due to the increase in thermal conductivity resulting from adding nanoparticles. The NCPCM at 4 l/min HTF flow rate is considered suitable for practical use due to minimum energy consumption and high thermal performance of energy storage system.
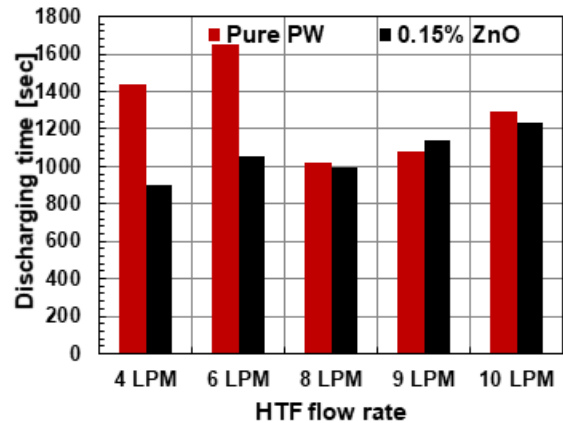

Fig. 17. Effect of both NCPCM and HTF flow rate on discharging time

The energy recovery ratio (ERR) which is the ratio of the energy regained to the energy absorbed under the same operating conditions is presented in Figure 18 for different values of HTF flow rate with and without NCPCM. The use of 0.15 wt.% ZnO nanorods at 4 l/min HTF flow rate is recommended for its efficient energy use.
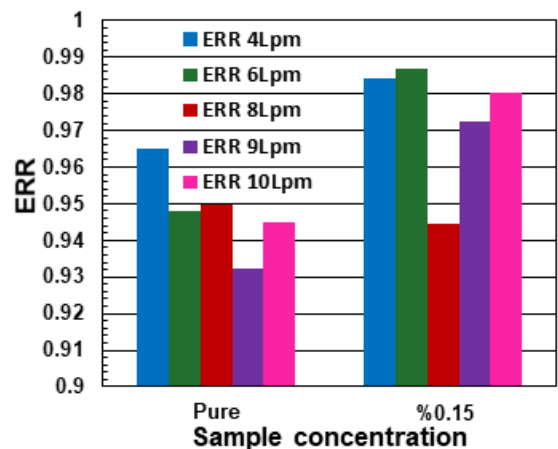
Fig. 18. Energy recovery ratio against sample concentration

Enhancement ratio is the ratio of the ERR for NCPCM to the ERR for pure PCM (i.e. PW). The higher the enhancement ratio, the better performance of the energy storage system. Fig. 19 shows the effect of PCM with ZnO nanoparticle and HTF flow rate on the enhancement ratio. It is found that the NCPCM at 9 l/min HTF flow rate provides the maximum enhancement ratio of 1.043, while the minimum enhancement
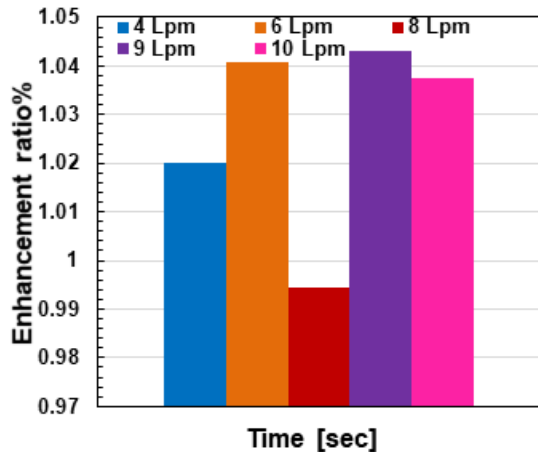
ratio of 0.99 is achieved at 8 l/min.

Fig. 19. Enhancement ratio at different HTF flow rates

Moreover, using a NCPCM can provide a nearly uniform temperature of PCM and decreases the charging time. Therefore, the novel 0.15 wt.% ZnO NCPCM has been fabricated and analyzed to study its effect of the energy storage system performance. Thermal energy storage systems are very important and have big advantages to shift the high electric load demand from on-peak period to off-peak. This NCPCM is able to store and regain energy for a short period of time and at high temperature than the pure PCM. This NCPCM can be recommended in domestic solar water heating systems to store energy effectively.

IV. CONCLUSION

LHTES system was constructed with small diameter copper tube bank filled with 0.15 wt.% ZnO nanorods as NCPCM in an insulated shell to increase surface area to heat transfer to compare the thermal performance with PCM during charging and discharging processes. The experimental results revealed that:

- At the same inlet temperature of HTF, both volume flow rate and NCPCM have great effect on the charging time. The charging time is reduced by 69.89% when using 0.15 wt.% ZnO NCPCM compared to pure PCM, and it is also reduced by increasing the volume flow rate of HTF from 4 up to 9 l/min, after this value it increases. Therefore, it is not recommended to store thermal energy at a volume flow rate higher than 9 l/min.
- The average temperature of NCPCM increases as the HTF volume flow rate increases, and the charging times decreases at the same inlet temperature of HTF.
- During the charging process, the phase change of NCPCM takes place faster than pure PW.
- A reduction in charging time of about 60.2%, 43.3%, 34.7%, 6.25%, 51.5% for the 0.15 wt.% NCPCM takes place at HTF volume flow rates 4, 6, 8, 9 and 10 l/min, respectively. It is found that, 4 l/min HTF flow rate when using NCPCM is suitable for practical use, due to minimum energy consumed and good thermal performance obtained. Therefore, the use of NPCM at 4 flow rates is

recommended for its efficient energy use, also 6 l/min HTF is considered acceptable from the point of view of energy consumed.

- The latent heat regained during substance phase change was higher for NCPCM than pure PCM. The maximum discharge energy of 0.15 wt.% NCPCM was about 306 kJ compared to 266 kW for pure PW.
- The NCPCM at 6 l/min HTF flow rate provides the highest ERR, and the smallest ERR occurs at 9 l/min.
- The NCPCM at 9 l/min HTF flow rate provides the maximum enhancement ratio which is equal to 1.043 while at 8 l/min HTF flow rate gives the minimum enhancement ratio (0.99).

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Title Arabic:

دراسة تحسين أداء تخزين الطاقة الحرارية الشمسية
باستخدام شمع البرافين المطعم بقضبان نانو من أكسيد الزنك

Arabic Abstract:

يناقش البحث تأثير شمع البرافين المطعم بقضبان نانو من أكسيد الزنك على الحرارة الكامنة لتخزين الطاقة الحرارية لنظام تسخين بالطاقة الشمسية. هدف الدراسة التجريبية هو تحديد نسبة الزيادة في سعة التخزين الحراري باستخدام شمع البرافين المطعم بنسبة 0.15٪ بالوزن من نانو أكسيد الزنك كمادة تغيير الطور مركبة مع النانو (NCPCM) مقارنة بشمع البرافين الخام. تم إجراء التجارب بواسطة خزان حراري معزول يحتوي على 21 أنبوب نحاسي. يمتلئ الخزان بالمياه الناقلة للحرارة وتمتلئ الأنابيب إما بالبرافين الخام أو المطعم بجزئيات النانو. تم إجراء التجارب بمعدلات تدفق مختلفة وقد وجد أن استخدام NCPCM يقلل من وقت الشحن والتفريغ مقارنة بالبرافين الخام، وتم تحقيق زيادة في تخزين الطاقة الحرارية بنسبة 20٪ عند استخدام قضبان نانو أكسيد الزنك. وزادت طاقة التفريغ القصوى من 266 kJ للبرافين الخام إلى 306 kJ باستخدام قضبان النانو مع البرافين. بالإضافة الى حدوث أعلى نسبة استرجاع الطاقة عند معدل تدفق 6 لتر/دقيقة للماء الناقل للحرارة، بينما تكون أصغر نسبة عند 9 لتر/دقيقة.