NANOFLUIDS (CuO & TiO_2)-WATER AS HEAT TRANSFER FLUID IN A THERMAL ENERGY STORAGE SYSTEM FOR APPLICATIONS OF SOLAR HEATING
An Experimental Study

by

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The present work aims to exploit the thermal performance of a packed bed of combined sensible and latent heat of storage unit with an integrated solar heat source. A cylindrical insulated storage tank in the thermal energy storage (TES) unit is filled with spherical capsules separately which contains PCM as paraffin wax and stearic acid. The PCM usage has the benefits that it can be used as a thermal management tool and it reduces the cost and size of the system as it offers higher isothermal behavior and thermal storage capacity. The thermal conductivity of heat transfer fluid (HTF) can be enhanced by using nanoparticles mixed in water. Nanofluids are the more efficient fluids for the applications of heat-transfer. The water based nanofluids are used to transfer heat between the solar collector and storage tank which is a sensible heat storage material. The HTF materials are varied and experimental trials have been conducted separately. Experimentation was carried out first by considering only water as HTF and is extended by adding water with one of the nanomaterials i.e. The TiO_2 and CuO, each in 3 HTF vol.% as 0.2, 0.5, and 0.8. The variable source of heat supply considered is solar flat plate collector. The study was transpired by varying the flow-rates of nanofluids as 2.0, 4.0, and 6.0 Lpm. The novelty of this work is to envisage the enhancement of heat transfer and to study the effects on the melting time of the PCM of these fluids which were carried out. The performance parameters like charging time and system efficiency, instantaneous stored heat, cumulative stored heat were studied for the different HTF and for the PCM-paraffin and stearic acid. The batch wise process experiments for discharging were carried out to recover the heat stored, and the results are presented.

Key words: *paraffin wax, stearic acid, nanoparticles, nanofluids, charging, discharging, thermal energy storage system, PCM*

Introduction

Energy researches are carried out in vast applications like heat exchangers, air conditioning, and waste heat recovery *etc.* are increasing with TES. A study account on TES and

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its applications scope were given by the researchers. Wu Shuying *et al.* [1] studied the thermal properties of Al_2O_3-water nanofluids. The explorations were of varied dimensions through their study that involved different types of thermal tests. The research concentrated on the thermal conductivity enhancement and use of such fluids in varied thermal applications in the day to day life. Harikrishnan *et al.* [2] explored the critical chemical compatibility, thermal properties, and physical interaction of TiO_2 nanoparticles used as HTF in harvesting solar energy for domestic applications. Naveen Kumar *et al.* [3] experimentally valued the properties of thermophysical with different volume concentrations for TiO_2-water and CeO_2-water nanofluids and observed that low concentration of nanofluids showed better stability than water. Nagappan *et al.* [4] studied the use of different PCM the transfer of heat at different levels of temperature and its effectiveness on enhancing the characteristics of heat transfer and observed that the usage of copper balls showed the highest heat transfer in the PCM encapsulation with an attachment of fin which is annular inserted in the balls. Lokesh *et al.* [5] investigated the characteristics of solidification and melting of enhanced PCM and noted the 42% solidification and 29% melting time was achieved and in the case of nanoparticles enhanced PCM with 0.9% and 0.3%, respectively. Reddigari *et al.* [6] considered stearic acid and paraffin as PCM in the TES to store sensible heat as well as latent heat in their observational inquiry. Prakasam *et al.* [7] investigated with nanofluid of Al_2O_3-water as HTF with less percent of volume about 0.01% and varied the rate of flow from 1.0 Lpm to 3.0 Lpm for the performances of solar flat plate collector and noted that the efficiency of the collector is 14.3% increased compared when usage of distilled water is as HTF with 2 Lpm flow-rate. Valan *et al.* [8] investigated on paraffin wax with and without nanoparticles of alumina *i.e.* Al_2O_3 in a heat exchanger with double pipe (concentric) and found the enhanced charge and discharge rates with PCM of nanoparticles. Abdollahzadeh *et al.* [9] made analytical study on the enhancement of lowered latent heat, low heat capacity and thermal conductivity for nanofluid mixed with PCM-nanoparticles compared to the base fluid. The convective heat transfer is enhanced by the nanoparticles Brownian motion is much more than the conductive transfer. The sonication time effects on properties of 0.5 vol.% of Al_2O_3 and water dispersed nanofluid was analysed by Mahbubul *et al.* [10]. The sonication of the nanofluid was varied for cycle from 0-180 minutes using the ultrasonic homogenizer. The increased sonication time showed better particle dispersion, increased density. Thermal conductivity and lowered viscosity was observed. It was also concluded that better performance of the nanofluid is obtained at 2 hours of ultrasonication. Kumaresan *et al.* [11] experimented ethylene glycol-water mixture based nanofluids at varied temperatures and measured the thermo physical properties and observed that maximum thermal conductivity was enhanced by 19.75% at 40 °C for the nanofluid of 0.45% volume. Prasanth *et al.* [12] blended metals of Al and Zn nanoparticles with paraffin as the PCM and found out the latent heat capacity was raised as the loading value is below 1.0 wt.%. The value of 0.7 wt.% was found to be maximum. Al-Azawii *et al.* [13] processed on materials like alumina, sand, solid particles to find their use in sensible and latent storage heat. Energy storage is transpired in PCM as it undergoes the transformation of solid-liquid. Yang *et al.* [14] experimentally investigated on foam composite of paraffin-copper and observed that the melting of PCM is reduced 1/3rd times in composite than pure paraffin.

Abdul Hamid *et al.* [15] has investigated the thermal conductivity development of TiO_2 based nanoparticles mixed in water combined with ethylene glycol for volume concentrations ranging from 0.5% to 1.5%, respectively. Muthoka *et al.* [16] experimentally studied about several properties of water based nanofluid thermal conductivity behaviour, super cooling methods and latent heat of fusion. The study showed the effect of phase change and found that the super cooling degree is decreased due to embedding of MgO. Hassan *et al.* [17] has specially designed a TES system for residential areas and commercially constructed buildings which is best obtained by inclusion of a storage medium and concluded that, on the summation of charging time period of the clathrate formation, there is substantial effect of compactness of nanoparticles. Sekhar *et al.* [18] has presented the study of the properties of thermal conductivity of less concentrated levels of nanofluids-water based and understood that the thermal conductivity is amplified with temperature increase. Obaid *et al.* [19] added a small weight percentage pertaining to magnesium oxide MgO into the pure water in their research which is viewed as working fluid to prepare a solar heating system in low temperature gradient than the pure water. Senthilraja *et al.* [20] studied experimentally to know the thermic related conduction of CuO with water, Al_2O_3 and water and Al_2O_3-CuO along with the water based hybrid nanofluids.

Karabulut *et al.* [21] investigated both numerically and experimentally, the convection heat transfer coefficient of graphene oxide-distilled water nanofluid along a circular copper tube having a constant heat flux at the outside surface under turbulent flow regime. The heat transfer coefficient increment value for the nanofluid of 0.02 vol.% concentration and with a flow-rate of 1.5 Lpm (Re = 5032) has been obtained as about 48% for 5073.244 W/m^2 (350 W) heat flux according to the distilled water. Kilinc *et al.* [22] experimentally investigated the cooling performance of a vehicle radiator was using pure water, graphene oxide (GO) and graphene nanoribon (GNR) nanofluids. The mean enhancement values of U for all temperatures were obtained as 5.41% and 26.08% for 0.01% and 0.02% vol. concentrations of GO-water nanofluid and 15.62% and 20.64% for 0.01% and 0.02% vol. concentrations of GNR-water nanofluid, respectively. Karabulut *et al.* [23] numerically investigated the heat transfer and flow characteristics for cube and circular hollow models in channels with the cross flow-impinging jet flow by using water and 2% CuO-water nanofluid. The average Nusselt number, Nu_m, increases for CuO-water nanofluid at Re = 15000, $K = D$ and, 90° fin angle are 32.55% and 26.11% compared to without fin and water fluid for cube and circular hollow models, respectively.

Yet, only a few researchers have studied on effect on the PCM based TES performance with nanofluids and some have taken the probe on the essence of melting time on these fluids. Hence, the present study concentrates on nanofluids on mass flow-rates of 2.0, 4.0, and 6.0 Lpm to envisage the enhancement of heat transfer and the nanofluids effects on the performance of PCM based TES and PCM melting time.

Numerical analysis

The mathematical model used for this physical problem is based on the following assumptions:

- The tank is fully insulated.
- Velocity of the fluid at any cross section of the tank is constant. So the temperature of the fluid is varies axially.
- The heat flux which is present on the capsule surface is uniform.
- The temperature as well as the melt fractions varies only in radial direction for the capsule.
- Thermally and physically associated characteristics of HTF and PCM are considered to be incessant of temperature.

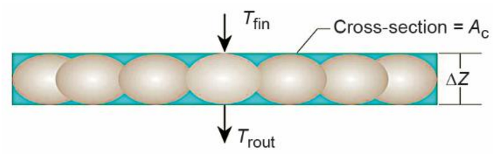


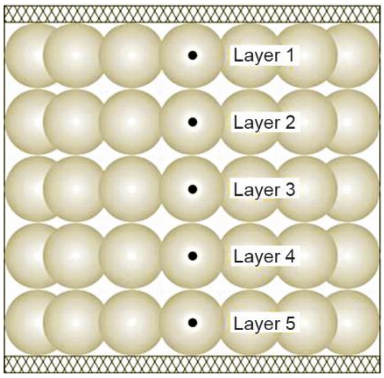
Figure 1. Spherical capsules control volume

Based upon the aforementioned assumptions, the equation pertaining to conservation of energy equation for the tank in cylindrical co-ordinate systems and the spherical capsule in spherical based co-ordinate system can be written for the controlling of volume is as given in fig. 1.

The energy balance for this elemental volume, $A_c\Delta z$, where the bed is considered as a porous media is given by:

$$\rho_f C_f \in \frac{\partial T_f}{\partial \tau} + \rho C_f \in u \frac{\partial T_f}{\partial z} = k_f \in \frac{\partial^2 T_f}{\partial z^2} + h_{eff} a_p (T_p - T_f)$$

where T_f is the temperature of fluidized liquid at the node location, T_p – the PCM capsule temperature, ε – the porosity of the bed, N_b – the number of the PCM balls, H – the height of the tank, and a_p – the total surface area of PCM balls per unit volume of the tank. First term of the equation represent the rate change of the internal energy of HTF. Second term represents the energy converted through the bed. In the RHS, first term is the energy diffused through the HTF and the last term is the energy transferred to the PCM balls. An in house code was developed in MATLAB R2019a. Numerical model of TES tank as represented in fig. 2.



$$\in = \frac{N_b \frac{4}{3}\pi D_b^3}{\frac{\pi}{4} D_t^2 H}$$

Figure 2. Numerical model of TES tank

Experimental study

Experimental construction

Figure 3 represents the experimental construction layout diagram. It consists of a TES insulated tank in cylindrical shape, which contains spherical capsules encapsulated with PCM, solar flat plate collector, control valve, flow meter, and circulating pump. The photograph of the experimental construction is presented in fig. 4. The TES stainless steel tank of capacity 57 L with specification 535 mm height and diameter of 370 mm to hot water supply for a 5-6 members of a family. The tank top and bottom are layered into two chambers and uniform flow of the HTF is obtained by a flow distributor which is placed on the tank top. The 30 mm thick glass wool is insulated for the storage tank. The spherical capsule is fabricated with a 2 mm wall thickness of mild steel and inner diameter is 70 mm. The 90 spherical capsules are used in the tank. The five layers of spherical capsules are packed uniformly and each layer is supported with the help of wire mesh. The PCM used is paraffin wax, with its 61 °C melting temperature and 213 kJ/kg of the latent heat of fusion. An active solar flat plate collector is connected with the TES tank with 2 m^2 of area, and the PCM capsules are surrounded by water in the tank. Both water and nanofluids are used as HTF and SHS material. Figure 5 shows the arrangement of linked PCM capsules filled in the tank.

Preparation of nanofluids

Different volume concentrations of nanoparticles were added to water at 0.2%, 0.5%, and 0.8%. The parameter which is basic for dispersing the nanoparticles that are aggregated is sonication time. Therefore, the sonication time was selected as 180 minutes based on works of literature survey [10]. The nanofluid is sonicated continuously for varied cycle from 0-180 minutes and ultrasonic homogenizer is used to ensure that the nanoparticles are dispersed properly in water. Table 1 represents the thermo physical properties of PCM whereas tab. 2 shows the properties of nanoparticles and nanofluids-thermo physical. Figures 6 and 7 show the nanofluid SEM images at many magnifications.

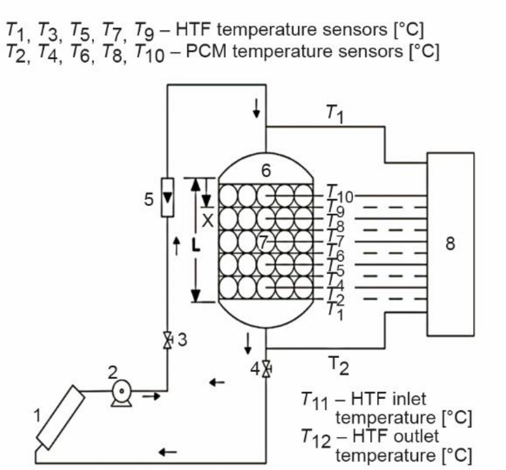


Figure 3. Experimental set-up scheme;
1 – solar flat plate collector, 2 – pump, 3, 4 – control valve, 5 – flow meter, 6 – storage tank, 7 – spherical capsules, 8 – digital temperature indicator

Figure 4. Photograph of experiment

Figure 5. Arrangement of PCM capsules in the TES tank

Table 1. The PCM properties - thermophysical

The PCM	Temperature of melting [°C]	Latent heat of fusion [$kJkg^{-1}$]	Density [kgm^{-3}]		Specific heat [$Jkg^{-1}°C^{-1}$]		Thermal conductivity [$Wm^{-1}°C^{-1}$]	
			Solid	Liquid	Solid	Liquid	Solid	Liquid
* Type-II paraffin wax	61	213	861	778	1850	2384	0.4	0.15
**(Grade-TGV-MP) stearic acid	57	198.91	960	840	1600	2300	0.3	0.172

Suppliers: *CPCL, Chennai. ** TGV SRAAC Limited, Kurnool, AP.

Procedure of the experiment

Charging process

The HTF inlet temperature is varied during the charging experiments, according to the radiation of solar effects, and it is continuously circulated through all the levels of the tank. The thermal energy transfer is done by the HTF to the capsules of PCM. Before the process of charging, the PCM temperature inside the packed bed capsules is less than the temperature of melting which is 35 °C. Initially, the stored energy is as sensible heat in the capsules till the PCM obtains the temperature of melting. When the process of charging continues, storage of energy is obtained during PCM melting at a constant temperature. As a result of continuation, the PCM gets superheated and the energy is stored in liquid PCM as SHS. Temperatures of the PCM and HTF at various locations in the tank, as illustrated in fig. 3, which is noted at gap of 15 minutes duration. The process of charging is preceded till the temperature of PCM obtains 70 °C. The experimental step is duplicated for HTF as TiO_2 and CuO nanofluids.

Table 2. Nanoparticles and nanofluids - thermophysical properties

Property	Nanoparticles		TiO_2 nanofluid [vol.%]			CuO nanofluid [vol.%]		
	TiO_2	CuO	0.2	0.5	0.8	0.2	0.5	0.8
Density	4000 kg/m^3	6500 kg/m^3	1600	2500	3400	2100	3750	5400
Thermal conductivity	11.8 W/m°C	33 W/m°C	0.97	1.954	4.5783	1.0158	2.2096	6.2098
Specific heat	0.697 kJ/kg°C	0.525 kJ/kg°C	2.4385	1.3936	0.8953	1.9173	1.0123	0.6603
Average particle size	30-50 nm	30-50 nm	–	–	–	–	–	–

Suppliers: PNPL, Kachwach, Mahagama, Jharkhand.

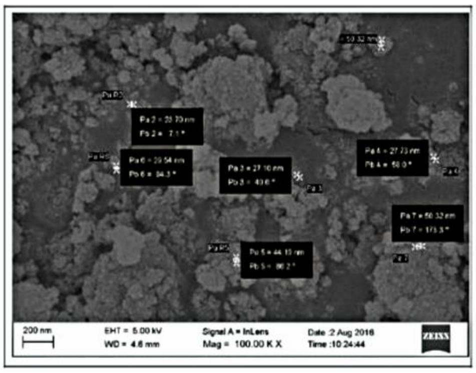


Figure 6. Crystal structures of TiO_2 nanoparticles

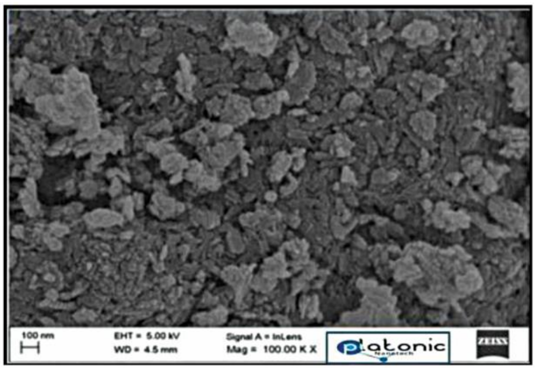


Figure 7. Crystal structures of CuO nanoparticles for analysis of SEM

Discharging process

The batch-wise method was carried out for discharging experiments. Full extraction of heat is obtained by this discharge method from the TES tank. Each batch of 20 L quantity of hot water was removed from the tank and was again filled with the equal quantity of cold water into the tank. The hot water withdrawn was collected into a drum with insulation and the temperature was monitored and as a result, after the required batches are collected, the average hot water temperature was calculated. The water collection is varied at 2.0, 4.0, and 6.0 Lpm. The inlet flow to the tank was maintained 2.0 Lpm constantly. Period of 20 minutes was allowed in between batches as an optimum retention. The hot water collection in batches was preceded till the outlet temperature reaches to 45 °C.

Results and discussion

Numerical results

Temperature histories

The repositioning of PCM temperatures at five segmentations of the storage tank, such as x/L = 0.2, 0.4, 0.6, 0.8, and 1.0, are shown in fig. 8. During the charging process, water is used as HTF at a flow-rate of 2 Lpm. It may be noted from the above figure the PCM based temperature along the axial direction of TES tank raises speedily till the phase transition temperatures of PCM is progressed. The temperature of the PCM in the extreme layers is found to be very high than the other layers at any given time. It is seen from the figure the PCM temperature steps up in gradual way at the commencing of the period of charging and left nearly same while melting process happens and increases quickly while heating of liquid PCM. The top most layers of PCM attain the phase transition temperature early on and the phase change also is accomplished sooner than the other layers. The total charging time is 312 minutes for HTF flow-rate of 2 Lpm when PCM fully charged at 70 °C temperature.

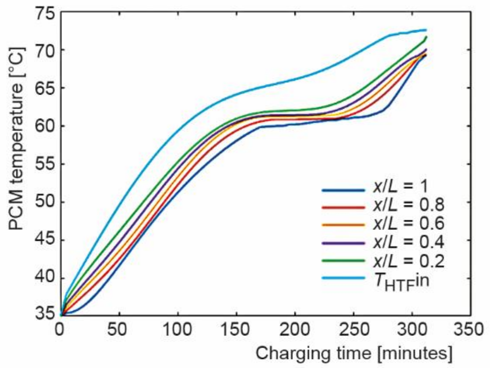


Figure 8. Repositioning of PCM temperatures during charging process for water as HTF and flow-rate of 2.0 Lpm

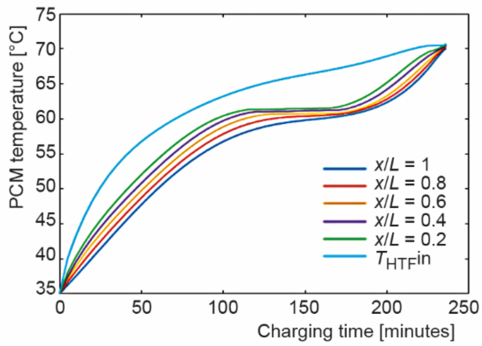


Figure 9. Shifting of PCM temperatures during charging period for TiO_2 nanofluid as HTF at 0.2% volume concentration and flow-rate of 6 Lpm

Effect of nanoparticles volume concentration

The variation of PCM temperatures at five parts of the TES tank, such as x/L = 0.2, 0.4, 0.6, 0.8, and 1.0, are shown in fig. 9. During the charging process, TiO_2 nanofluid is used as HTF at volumetrically related concentrations of 0.2%, with HTF flow-rate of 6 Lpm. It is observed from the figure that the PCM temperature stepping up bit by bit at the initial stages of the charge time and stays nearly unchanged all the way through melting process and increases rapidly while heating up of liquid PCM. The total time commanded for charging of PCM is 236 minutes.

Experiments for charging

History of temperatures

The PCM temperatures are varied at five segmentations of TES based tank, at x/L = 0.2, 0.4, 0.6, 0.8, and 1.0, are graphically represented in fig. 10. During the process of charging a rate of flow of 2 Lpm is maintained as water is used as HTF and it is observed from the graph that, the PCM temperature along the direction of axial to the tank raises gradually till the phase transition PCM temperature is reached. It is also observed that, the temperature of the PCM in the top most layers are more likely higher than the other layers at any period of time. Initial stages of the charging, the PCM temperature slowly increases and remains unchanged during melting process and enhanced suddenly during liquid PCM heating. The PCM in the upper most layers reached the phase transition temperature in the beginning and completed the phase change earlier than the other layers. The total charging time taken is 330 minutes for a flow-rate of 2 Lpm for the PCM to completely charge at 70 °C temperature.

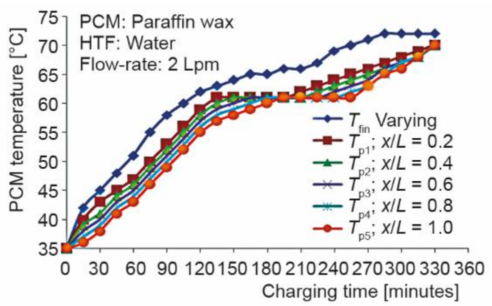


Figure 10. Variations in PCM temperatures during charging process and rate of flow of 2.0 Lpm for water as HTF

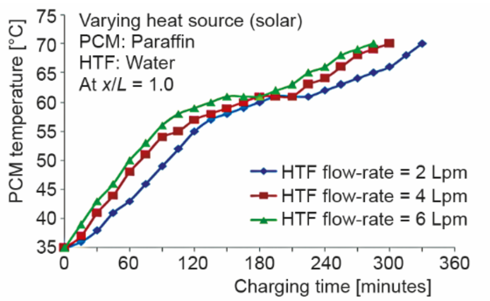


Figure 11. The HTF flow-rate effect on the time required for the process of charging (at x/L = 1.0)

The HTF flow-rate effect

Figure 11 indicates about the graphical variation of PCM temperatures during charging when water is used as HTF at varied mass flowing rate ranging as 2.0, 4.0, and 6.0 Lpm. From the figure it can be known basically that the rate of uplift in PCM temperature is high initially at all flow-rate of mass, because of high temperature changes between HTF and PCM. The PCM temperature remains neutral during the process of melting and while the heating of PCM at liquid state, it increases abruptly. The total charging time obtained is 330 minutes, 300 minutes, and 285 minutes for flow-rate of 2.0 Lpm, 4.0 Lpm, and 6.0 Lpm, respectively. Higher flow-rate is preferred as the results proved that the percentage of charging time decreased by 9.09% and 13.63% for flow-rate amplified certainly from 2.0 Lpm to 4.0 Lpm and 2.0 Lpm to 6.0 Lpm, respectively.

Effect of nanoparticles volume concentration

The different graphical variations of PCM temperatures at five various sections of the TES tank such as x/L = 0.2, 0.4, 0.6, 0.8, and 1.0, are effectively represented in fig. 12. During the charging process, 0.2% volume concentration of TiO_2 nanofluid is used as HTF with flow-rate of 6 Lpm. It was noted that the temperature of PCM rises at the initial stage of the process of charging and remains constant at the time of process of melting and then further increases in rapidity through heating of PCM in liquid state. Eventually, the PCM in the top most segments attains the temperature of phase change very fast and the phase change is also completed earlier compared to other segments. The total charging time taken is 255 minutes for a flow-rate of 6.0 Lpm for the PCM to charge completely at 70 °C temperature.

Figure 13 represents the various indications of PCM temperatures during charging process for volumetric concentrations of 0.2%, 0.5%, and 0.8% TiO_2 nanofluid is used as HTF. From the figure it could be observed further that, PCM temperature has been increased to be high enough initially at all volume concentrations because of greater temperature gaps between HTF and the PCM. The PCM temperature remains incessant during process of melting and rises rapidly through heating of liquid PCM. The total charging time taken is 255 minutess, 240 minutes, and 225 minutes for volume fractions of 0.2 vol.%, 0.5 vol.%, and 0.8 vol.%, respectively. The outcomes showed that the percentage of charging time is decreased by 5.88% and 11.76% for volume concentration which increased from 0.2% to 0.5% and 0.2% to 0.8%, respectively. From the result oriented graphical representations, it is observed that, the effect of nanoparticles and their volumetric based concentrations play a significant role in completing heat transfer processes.

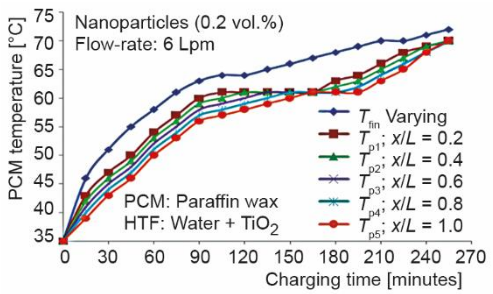


Figure 12. Variations in PCM temperatures during charging period for 0.2% volume concentration of TiO_2 nanofluid as HTF and rate of flow of 6.0 Lpm

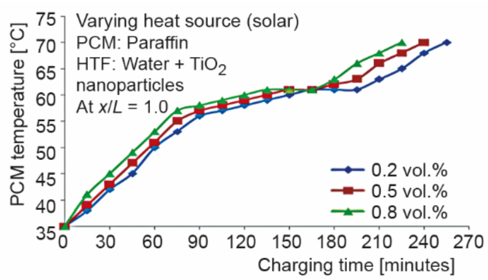


Figure 13. Variations of PCM temperatures during charging period for at various volume percentages of TiO_2 nanofluid as HTF and flow-rate of 6 Lpm

The results of temperatures of PCM at five sections of TES tank such as at x/L = 0.2, 0.4, 0.6, 0.8, and 1.0, are cited in fig. 14. During the charging process, 0.8% volume concentration of CuO nanofluid is used as HTF at flow-rate of 6 Lpm. It is observed from the figure that the PCM based temperature enhanced gradually at the initial period of charging and remains nearly unaltered during the stage of melting and augmentation through heating of PCM at liquid form. It is followed that, the total charging time for CuO nanofluid is 180 minutes.

Figure 15 depicts that the PCM temperatures slowly rising in the starting stage and nearly remains unchanged between the stage of phase transition and further rises up suddenly through heating of liquid PCM. It is noted that the time of charging is 285 minutes for water, 225 minutes for TiO_2 nanofluid, and 180 minutes for CuO nanofluid when used as HTF. The results cited that, when compared in relation with the existing HTF, water there is significant rate of simplification in the time of charging, in case of flow-rate of 6.0 Lpm and 0.8% volumetric based percentages of nanoparticles, around 21.05% for TiO_2 nanofluid and 36.84% for CuO nanofluid. From the outcomes, it is noted that the result of nanofluid plays a dominant character in the method of heat transfer.

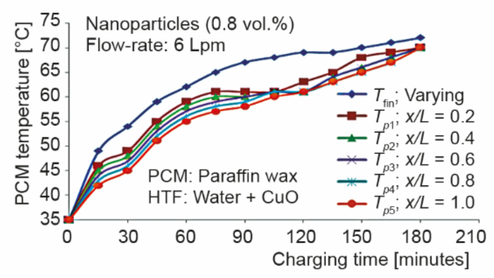


Figure 14. Variation of PCM temperatures during process of charging for 0.8 vol.% CuO nanofluid as HTF and flow-rate of 6 Lpm

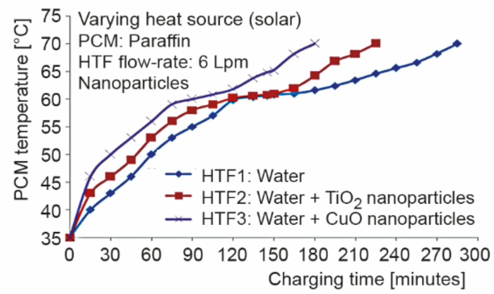


Figure 15. Variation of PCM temperatures during charging period for 0.8 vol.% of nanoparticles and paraffin as PCM, flow-rate of 6 Lpm

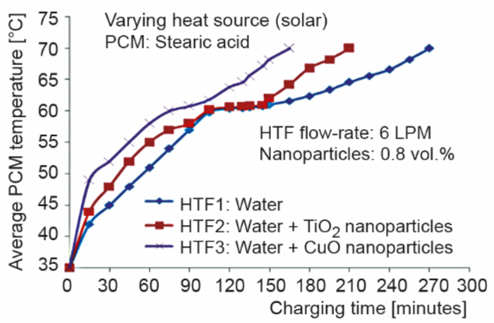


Figure 16. Variations of PCM temperatures during charging process for 0.8 vol.% of nanoparticles and stearic acid as PCM, flow-rate of 6 Lpm

Figure 16 represents graphically that, the temperature of PCM slowly enhances at the initial stage and remains unaltered during the period of phase transition and further increases quickly in liquid PCM heating. It is observed from the graph that the time taken for charging is 270 minutes for water when used as HTF, and 210 minutes for TiO_2 nanofluid and 165 minutes for CuO nanofluid used as HTF. The results showed that when compared in relation with the existing HTF, water there is certain percentage of downfall in charge cycle times, but in case of flow-rate of 6.0 Lpm and 0.8 vol.% of nanoparticles, around 22.22% for TiO_2 nanofluid, and 38.88% for CuO nanofluid. From the outcomes, it is observed further that, the impact of nanofluid plays a major purpose in heat transferral process.

Figure 17 shows the instant rate of accumulated heat in the tank while the charge related process takes place for a flow-rate of 6.0 Lpm with water, TiO_2 nanofluid, and CuO nanofluid used as HTF. This is predicted by the means of instant temperatures of the HTF inlet and outlet. It is seen that in the initial stage of charging, the instant heat stored in PCM at that time is high, and then it falls because of downfall in temperature changes between the HTF and the TES tank. Since the charging process continues further, the PCM starts the melting process, and the quantity of stored heat remains almost same due to the incessant temperature differences between the HTF and the tank.

Figure 18 indicates the accumulative stored heat for the total system in the tank that facilitates the storage option, through the process of charging for a flow-rate of 6.0 Lpm with water, TiO_2 nanofluid, and CuO nanofluid when used as HTF. It is depicted from figure that the quantity of heat stored is higher for 0.8 vol.% of nanofluid HTF of at a certain time when equated to water. The fact is due to that, the higher heat transporting capacity of nanofluids. The amount of cumulative stored heat for total system when the PCM temperature to reach 70 °C is 10400 kJ.

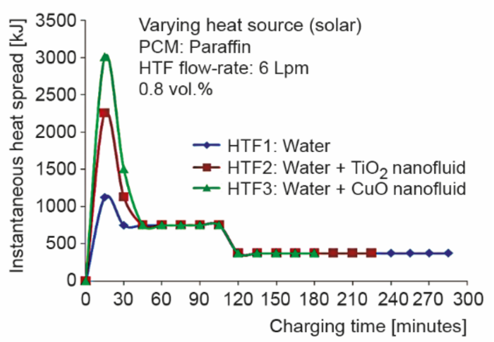


Figure 17. Variation of instantaneous heat stored in the charging process for various HTF; varying heat source

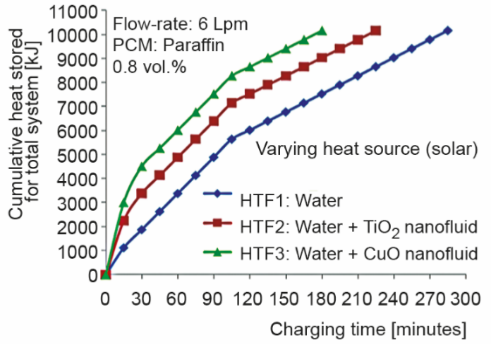


Figure 18. Variation of cumulative stored heat for total system at charging period for various HTF; varying heat source

System efficiency is defined as ratio of quantity of energy laid in storage tank and the heat energy existing from solar radiation.

$$\eta_{\text{sys}} = \frac{mCp\ T_{\text{in}} - T_{\text{out}})}{\lambda A}$$

where λ [Wm^{-2}] is the solar insolation and A [m^2] – the solar collector area. The measurement of solar radiation is with an accuracy of ±2.5%. Initially the system efficiency is high due to thermal inertia as in case of instantaneous energy.

Figure 19 represents the storage tank system efficiency of the during charging when accomplishing a flow-rate of 6.0 Lpm with different HTF. This is approximated based on the ratio of energy quantity that has been stacked in the tank and the thermal energy harvested from sun's radiation. As the time passes, the system efficiency scales down and remains nearly same through the transition period of phase and further falls down on sensible heating of PCM in liquid form. This is because as the charging process yields further, the temperature divergence between the HTF and the PCM minimizes. When compared to water as HTF, an increment in system efficiency of 6.02% for TiO_2 nanofluid and 24.23% for CuO nanofluid at 0.8 vol.% is noticed.

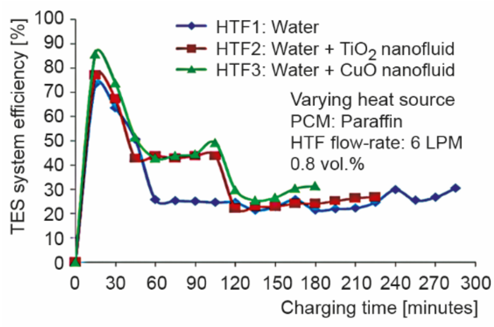


Figure 19. Variation of TES System efficiency during charging process for different HTF

Table 3 represents the comparison of numerical results and experimental results. Observed that percentage difference between numerical result and experimental result is below 10%.

Table 3. Compared numerical and experimental result (PCM: Paraffin wax)

S. No.	Heat transfer fluid	Charging time (numerical result)		Charging time (experimental result)		Difference between numerical and experimental result [%]
1	Water	268 minutes	Charging time percentage decreased by14.10% for flow-rate increased from 2 Lpm to 6 Lpm	285 minutes	Charging time percentage decreased by 13.63% for flow-rate increased from 2 Lpm to 6 Lpm	5.96%
2	TiO_2 nanofluid (0.8 vol.%, flow-rate 6.0 Lpm)	208 minutes	Charging time percentage decreased by 22.38% compared with water used as HTF	225 minutes	Charging time percentage decreased by 21.05% compared to HTF used as water	7.55%
3	CuO nanofluid (0.8 vol.%, flow-rate 6.0 Lpm)	165 minutes	Charging time percentage decreased by 38.43% compared with water used as HTF	180 minutes	Charging time percentage decreased by 36.84% compared to HTF used as water	8.33%

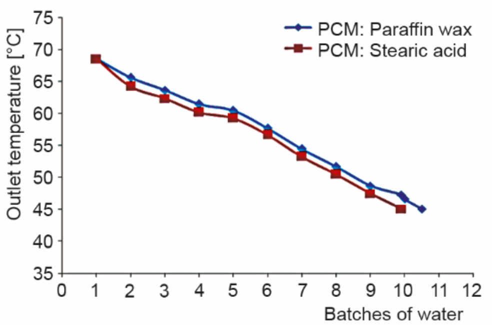


Figure 20. Batches of withdrawn water *vs.* outlet temperature of water

Discharging experiments

Figure 20 represents that the batches of water temperature collected from the tank is more in small degree with PCM of paraffin wax, when actually obtained with PCM of stearic acid. Thus, concludes that the hot water quantity that has to be taken out is more with PCM of paraffin wax is 210 L as compared with 198 L along with stearic acid as PCM.

Conclusions

This experimental research study shows HTF mass flow-rates effects and the volume percentage of nanoparticles mixed in water. The study is done on two materials such as TiO_2 and CuO with the effect on PCM melting time.

- When water is used as HTF, the total charging time is 330 minutes, 300 minutes, and 285 minutes for flow-rate of 2.0 Lpm, 4.0 Lpm, and 6.0 Lpm, respectively.
- The results proved that the percentage of charging time decreased by 9.09% and 13.63% for flow-rate which amplified certainly from 2.0 Lpm to 4.0 Lpm and 2.0 Lpm to 6.0 Lpm, respectively. Hence higher flow-rates are preferred.

- When TiO_2 nanofluid is used as HTF, the total charging time is 255 minutes, 240 minutes, and 225 minutes for volume fractions of 0.2 vol.%, 0.5 vol.%, and 0.8 vol.%, respectively.
- The outcomes show that the percentage of charging time decreased by 5.88% and 11.76% for volume concentration increased from 0.2% to 0.5% and 0.2% to 0.8%, respectively.
- From the result oriented graphical representations, it is seen that, the effect of nanoparticles and their volumetric based concentrations play a significant function in complete heat transfer processes.
- When compared in relation with the existing HTF, water, there is significant rate of simplification in the charging period, in case of flow-rate of 6 Lpm and 0.8% volumetric based percentages of nanoparticles, around 21.05% for TiO_2 nanofluid and 36.84% for CuO nanofluid.
- The amount of cumulative stored heat for total system when the temperature of PCM reaches 70 °C is 10400 kJ.
- When compared to water as HTF, an increment in the efficiency of the system of 6.02% for TiO_2 nanofluid and 24.23% for CuO nanofluid at 0.8 vol.% is noticed.
- Nanofluid of CuO has given a remarkable state in melting time reduction due to higher thermal conductivity, Brownian motion, low density, agglomeration, and micro convection.
- Domestic applications like heating of water, drying clothes, cooking purposes, *etc.* are suggested as the results shown are faster when CuO nanofluid is used as HTF.
- Hot water quantity of 210 L and 198 L were collected during the discharging process when the paraffin wax and the stearic acid are used as PCM, respectively.

The present study limitation

In the nanofluids, when the nanoparticles percentage of volume concentration is increased more than 1%, the HTF specific heat capacity gets decreased. Hence, the nanoparticles percentage of volume concentrations used for enhancing heat transfer are 0.2%, 0.5%, and 0.8%

Nomenclature

HTF – heat transfer fluid
SHS – sensible heat storage
TESS – thermal energy storage system
TES – thermal energy storage

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