# EXPERIMENTAL INVESTIGATION ON THE INFLUENCE OF NANOFLUIDS USED AS HEAT TRANSFER FLUID IN PHASE CHANGE MATERIAL BASED THERMAL ENERGY STORAGE SYSTEM

by

***Krishna Reddy KONDAKRINDI[a,c*], Meenakshi Reddy REDDIGARI[b], and Durga Prasad B.[a]***

[a] Department of Mechanical Engineering, JNTUA, Anantapuramu, A. P., India
[b] Department of Mechanical Engineering, G. Pulla Reddy Engineering College, Kurnool, A. P., India
[c] Department of Mechanical Engineering, BITS, Kurnool, A. P., India

Original scientific paper
https://doi.org/10.2298/TSCI191004060R

*The present study investigated the enhancement of energy conservation under the principles of pure substances that exercise phase change throughout charging and discharging processes. This work primarily focused on the thermal energy storage system, where the working medium charges the PCM namely (paraffin wax and stearic acid) that is normally encapsulated in spherical balls. The potentiality in charging of working medium was examined upon blending heat transfer fluid with four nanoparticles ($Al_2O_3$, CuO, $TiO_2$, and MgO). Several volume concentration levels (0.2%, 0.5%, and 0.8%) were considered for afore mentioned nanoparticles under the influence of assumed flow rates (2, 4, and 6 L per minute). The experiments were carried out with various nanofluids used as heat transfer fluid for different flow rates and volume concentrations. The results showed that there is a considerable amount of reduction in charging time, in case of 6 L per minute, 0.8% volume concentration and PCM as paraffin wax, around 27.22% for $TiO_2$ nanofluid, 36.66% for $Al_2O_3$ nanofluid, 40.90% for CuO nanofluid, and 63.63% for MgO nanofluid, and PCM used as stearic acid, around 26.31% for $TiO_2$ nanofluid, 42.10% for $Al_2O_3$ nanofluid, 47.36% for CuO nanofluid, and 68.42% for MgO nanofluid, when compared with water as the conventional heat transfer fluid. From the results, it was observed that the effect of particle concentration played an important role in the heat transfer process. During the discharging process, 210 L of hot water withdrawn with paraffin wax used as PCM and 198 L of hot water withdrawn with stearic acid used as PCM.*

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

## Introduction

Thermal energy storage (TES) is a key technology for an effective utilization of energy. The applications of PCM for TES have been the focus of extensive research in recent decades. The use of PCM can reduce the size and cost of the system since it offers higher thermal storage capacity, isothermal behavior, and the ability to be used as a thermal management tool. The nanoparticles used in water plays an important role in enhancing the thermal conductivity of heat transfer fluid (HTF). Nanofluids are suspensions of nanoparticles in base fluid, water. Nanofluids

* Corresponding author, e-mail: kkreddy642014@gmail.com

are promising fluids for heat transfer applications. Low stability and high viscosity are the two important drawbacks for practical applications of nanofluids. The aggregation and sedimentation of nanoparticles are related to the colloidal structure of nanofluids, which directly affects the stability and viscosity. To overcome this problem, an ultrasonic homogenizer used to break the aggregation of particles. The present work deals with the experimental investigation on the influence of nanofluids used as heat transfer fluid in PCM based TES system.

Naveen Kumar *et al.* [1] experimentally measured the thermophysical properties of $TiO_2$-water and $CeO_2$-water nanofluids for different volume concentrations. They observed that nanofluids with low concentration showed good stability. Nagappan *et al.* [2] studied the heat transfer at different temperature limits and its performance on the improvement of heat transfer characteristics with the use of different PCM. They observed that the highest heat transfer in the use of copper balls for encapsulation of PCM with the attachment of annular fin inside the balls. Sankar *et al.* [3] studied the thermal conductivity of PCM and observed an improvement of 5% with the addition of NiO nanoparticles when compared to pure paraffin wax. Lokesh *et al.* [4] investigated the melting and solidification characteristics of nanoparticles enhanced phase change material (NEPCM) and observed the solidification and melting time of 42% and 29% was achieved in the case of NEPCM with 0.9% and 0.3%, respectively. Prakasam *et al.* [5] investigated the performance of solar flat plate collector with $Al_2O_3$-water nanofluid as working fluid for lower volume concentration of 0.01% and by varying flow rate from 1 to 3 L per minute. They observed the collector efficiency increased by 14.3% when compared with distilled water as working medium with flow rate of 2 L per minute. Abdollahzadeh Jamalabadi *et al.* [6] analyzed the enhancement of thermal conductivity, low heat capacity and low latent heat for mixed nanofluid PCM and nanoparticles when compared with base fluid. Brownian motion of nanoparticles enhances the convective heat transfer much more than the conductive transfer. Yang and Yuhan [7] summarized that particle loading has exhibited a positive correlation with thermal conductivity of nanofluids. The $TiO_2$ nanofluids have shown good applications in many energy-related fields. Yang *et al.* [8] carried out experimental investigation on paraffin-copper foam composite and resulted the melting of PCM in composite takes 1/3 time less than that of pure paraffin.

Reddigari *et al.* [9] experimentally investigated that performance of TES system for different PCM (paraffin and stearic acid) by varying HTF flow rates and for various sizes of spherical capsules. They observed that the stearic acid was obtained maximum temperature equal to HTF inlet temperature and 12% more than paraffin wax. The charging time decreased with increased mass flow rate of HTF. Kumaresan and Velraj [10] experimentally measured the thermophysical properties of water-ethylene glycol (EG) mixture based CNT nanofluids at various temperatures. The maximum thermal conductivity enhancement of 19.75% observed for the nanofluid containing 0.45% volume of MWCNT at 40 °C. Mahbubul *et al.* [11] analyzed the effect of sonication time on properties of 0.5 vol.% of $Al_2O_3$-water nanofluid dispersion. They sonicated the nanofluid for different periods from 0 to 180 minutes with the help of ultrasonic homogenizer. The increase in sonication time resulted in better particle dispersion; higher thermal conductivity, density, and lower viscosity were observed. They concluded that 2 hours of ultrasonication was needed for better performance of the nanofluid. Abdul Hamid *et al.* [12] studied thermal conductivity enhancement of $TiO_2$ nanoparticles dispersed in mixture of water and EG. They observed that enhancement in thermal conductivity compared to their base fluid of a water/EG mixture in 60:40 ratio. Kailash Nemade *et al.* [13] analyzed the effect of ZnO nanoparticles concentration on thermal conductivity of nanofluid. Harikrishnan *et al.* [14] analyzed on TES behavior moreover, the work accentuates on typical thermal properties of $TiO_2$ nanofluids. The authors worked on the enhancement of PCM based latent heat storage system and their study concerns numerical modeling of solidification of nanoenhanced PCM inside an enclosure with two wavy walls. Their work pointed out the typical nature of $Al_2O_3$-water nanofluids [15]. Anderson *et al.* [16] worked on building models to predict fluid and solid temperatures in a packed bed of TES system involving alumina particles. Al-Azawii *et al.* [17] focused on materials such as solid particles, sand, alumina; find their applicability in sensible heat and latent heat storage. Energy storage transpires in PCM when it undergoes solid-liquid transformation. Minea *et al.* [18] investigated the thermal behavior of TES system with HTF as nanofluids and concluded that the studies on such HTF are gaining much research attention.

Obaid *et al.* [19] investigated on MgO nanoparticles (0.1, 0.2, 0.4, and 0.5 wt.%) when added to pure water which considered as working fluid in the building heating system by solar energy. They observed that addition of 0.1, 0.2 wt.% gave low temperature gradient than the pure water and 0.4, 0.5 wt.% gave greater temperature gradient than pure water which is the requirement for using any nanofluid. Valan *et al.* [20] investigated the performance enhancement of paraffin wax with nanoalumina ($Al_2O_3$) particles in comparison with simple paraffin wax in a concentric double pipe heat exchanger and observed the charge-discharge rates enhanced using nanoPCM. Menlik *et al.* [21] investigated the effect of nanofluid (MgO) on the performance of a two-phase closed thermo-siphon heat pipe and observed the effectiveness of heat pipe improved by 26%. Rashid *et al.* [22] analyzed MgO nanofluids used in TES in a heating/cooling systems of buildings to prevent the bacterial and fungal presence in water. They observed the time of melting and solidification are decreased with increase of the MgO nanoparticles concentrations. Khan *et al.* [23] analyzed the nanoparticles, their types' synthesis, characterizations, physiochemical properties and applications. Gupta *et al.* [24] investigated on $Al_2O_3$-water nanofluids and their flow rates on the efficiency of conventional solar collectors and enhanced efficiencies of more than 8% in comparison to pure water. Cobanoglu *et al.* [25] studied on the utilization of nanofluids in solar thermal applications. They concluded that by the utilization of the carbon-based nanofluids enhanced the efficiency of the system. Turkyilmazoglu [26] analyzed the enhancement of performance of a direct absorption solar collector based on $Al_2O_3$-water nanofluid. The author observed that enhancement of thermal efficiency is 85.63% compared to water. Muthoka *et al.* [27] investigated the super cooling and thermal properties of water based barium chloride dehydrate with two types of nanoparticles as MgO and MWCNT. The MgO nanofillers have the greatest thermal conductivity enhancement up to 17%. Addad *et al.* [28] studied thermal effects of nanofluid as HTF in a thermocline-type packed-bed energy storage tank filled with spherical PCM capsules. The results showed that using a nanofluid with a 5% nanoparticles concentration as HFT reduced the charging/discharging period by 20%. Prasanth *et al.* [29] analyzed blending of the Al and Zn metal nanoparticles with the PCM as paraffin and observed that the latent heat capacity increased when the loading level is below 1.0 wt.%.The maximum value was observed to be 0.7 wt%. Grosu *et al.* [30] studied the effect of nanoparticles on thermophysical properties of molten salts and focused on preparation, characterization and stability of nanofluids based on molten salts.

From the cited literature, it was observed that effect of flow rate in connection with nanofluids was not much investigated. Hence, the objective of the present work is to investigate the effect of nanoparticles $Al_2O_3$, CuO, $TiO_2$, and MgO in water – on the melting time of two different PCM-paraffin wax and stearic acid in spherical encapsulation used in TES system. Nanofluids were employed at different volume concentrations (0.2%, 0.5%, and 0.8%) for enhancing heat transfer. The study transpired on nanofluids for flow rates of 2, 4, and 6 L per minute to envisage the heat transfer enhancement and the effects of these fluids on the melting time of the PCM were carried out, which is novelty of this work. The main aim is to investigate the heat recovery of the TES system during discharging process and compare with conventional storage system.

## Experimental set-up

A schematic diagram of the experimental set-up is shown in fig. 1. This consists of an insulated cylindrical TES tank, which contains PCM encapsulated spherical capsules, a control valve, a flow meter, and circulating pumps. The photographic view of the experimental set-up is shown in figs. 2 and 3, represening the spherical capsules arrangement in the TES tank. The stainless steel TES tank has a capacity of 57 L (370 mm in diameter and 535 mm in height) to supply hot water for a family of 5-6 persons. There are two plenum chambers on the top and the bottom of the tank, and a flow distributor is provided on the top of the tank to make a uniform flow of the HTF. The storage tank is insulated with glass wool that is 30 mm thick. The inner diameter of the spherical capsule is 70 mm, and it is made of mild steel with a wall thickness of 2 mm. The total number of capsules used in the TES tank is 90. The spherical capsules are uniformly packed in five rows, and each row is supported by a wire mesh. In the analysis, each row of spherical capsules is considered as one layer. Paraffin and stearic acid being used as the PCM, which has a melting temperature of 61 °C and 57 °C and the latent heat of fusion of 213 kJ/kg and 198 kJ/kg, respectively. Water and nanofluid are used as sensible heat storage material and HTF.

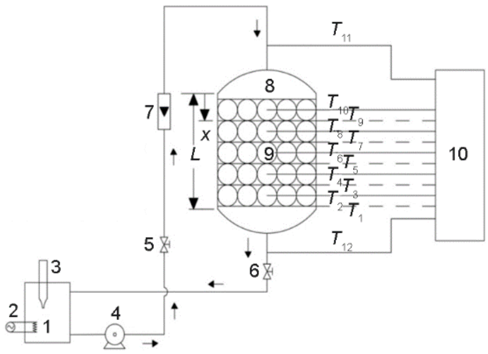


**Figure 1. Schematic of experimental set-up;**
*1 – constant heat source, 2 – thermostatic heater, 3 – ultrasonic probe sonicator, 4 – pump, 5, 6 – control valve, 7 – flow meter, 8 – storage tank, 9 – spherical capsules, 10 – digital temperature indicator, $T_1$, $T_3$, $T_5$, $T_7$, $T_9$ [°C] – HTF temperature sensors, $T_2$, $T_4$, $T_6$, $T_8$, $T_{10}$ [°C] – PCM temperature sensors, $T_{11}$ [°C] – HTF inlet temperature, $T_{12}$ [°C] – HTF outlet temperature*

**Figure 2. Photographic view of experimental set-up**

### *Preparation of nanofluids*

Nanoparticles were added to water at different volume concentrations of 0.2%, 0.5%, and 0.8%. The sonication time is an important parameter for dispersing the aggregated nano-particles. Therefore, based on [11] the time of sonication was selected as 180 minutes. The nanofluid is continuously sonicated for different periods from 0 to 180 minutes with help of ultrasonic homogenizer to ensure the proper dispersion of the nanoparticles in water.

The thermophysical properties of PCM are given in tab. 1. The thermophysical properties of nanoparticles are given in tab. 2. The SEM images of the nanofluids at different magnification are shown in figs. 4-7.

**Figure 3. Spherical capsules filled with PCM**

## *Experimental procedure*

### *Charging process*

During the charging process, the HTF (water) was circulated through the TES tank continuously. Initially, the temperature of the PCM capsule was 35 °C. The HTF exchanges its heat energy to PCM; the PCM gets heated up to melting temperature of 61 °C and 57 °C for paraffin and stearic acid, respectively (storing the energy as sensible heat). Later, heat is stored as latent heat once the PCM melts and becomes liquid. The energy is then stored as sensible heat in liquid PCM. The temperature of the PCM and HTF were recorded at intervals of 5 minutes. The charging process is continued until the PCM temperature reaches 70 °C. The same procedure repeated for HTF used as $Al_2O_3$, CuO, $TiO_2$, and MgO nanofluids.

**Table 1. Thermophysical properties of PCM**

| PCM* | Melting temperature [°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 |
| Paraffin wax Type-II | 61 | 213 | 861 | 778 | 1850 | 2384 | 0.4 | 0.15 |
| Stearic acid | 57 | 198.91 | 960 | 840 | 1600 | 2300 | 0.3 | 0.172 |

* Manufactures: Sree Rayalaseema Alkalies and Allied Chemicals Ltd., Kurnool, AP, India

**Table 2. Thermophysical properties of nanoparticles**

| Property* | Nanoparticles | | | |
|---|---|---|---|---|
| | $Al_2O_3$ | CuO | $TiO_2$ | MgO |
| Density | 3970 kg/m$^3$ | 6500 kg/m$^3$ | 4000 kg/m$^3$ | 3580 kg/m$^3$ |
| Thermal conductivity | 30 W/m°C | 33 W/m°C | 11.8 W/m°C | 60 W/m°C |
| Specific heat | 0.955 kJ/kg°C | 0.525 kJ/kg°C | 0.697 kJ/kg°C | 1.03 kJ/kg°C |
| Average particle size | 30-50 nm | 30-50 nm | 30-50 nm | 30-50 nm |

* Manufactures: Platonic Nanotech Private Limited Mahagama, Godda, Jharkhand

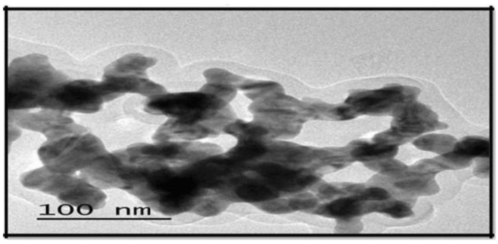


**Figure 4. Crystal orientations of $Al_2O_3$ nanoparticles in SEM analysis**

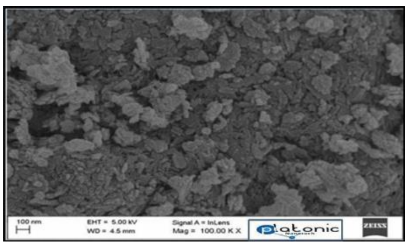

**Figure 5. Magnified view of CuO in SEM analysis**

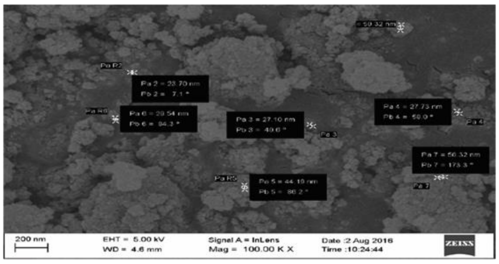

**Figure 6. Crystal structure of $TiO_2$ in SEM analysis**

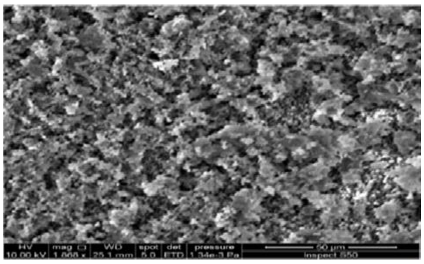

**Figure 7. Magnified view of MgO in SEM analysis**

*Discharging process*

The discharging experiments were carried out by batch-wise method. This method of discharge permits the full extraction of heat from the storage tank. A quantity of 20 L of hot water for each batch was withdrawn from the storage tank and the same amount of cold water was again filled into the storage tank. Withdrawn hot water was collected into an insulated drum and the temperature was noted and finally, after collecting all the batches the average temperature of hot water was measured. The collection of water is made at 2, 4, and 6 L per minute. However, the inlet to the TES tank was kept constant at 2 L per minute only. An optimum retention period of 20 minutes between batches was allowed. The withdrawing of hot water in batches was continued till the outlet temperature reaches to 45 °C. Uncertainty analysis was carried out by using the method proposed by Moffat and Robert [31]. The uncertainties associated with various measured parameters are presented in tab. 3.

**Table 3. Summary of estimated uncertainties**

| Parameters | Uncertainty [%] |
|---|---|
| Temperature | 0.47 |
| Length | 0.1 |
| Diameter | 0.052 |
| Time | 0.33 |
| Flow rate | 0.83 |

## Results and discussions

### *Charging experiments*

The experiments were conducted for various HTF with different flow rates (2, 4, and 6 L per minute) and different volume concentrations of nanoparticles (0.2%, 0.5%, and 0.8%).

*Effect of nanofluid*

Figure 8 indicates that the temperatures of PCM gradually increases in the beginning and remains constant during the phase change period and further increases. Charging time is 110 minutes for HTF used as pure water, 80 minutes for HTF used as $TiO_2$ nanofluid, 70 minutes for HTF used as $Al_2O_3$ nanofluid, 65 minutes for HTF used as CuO nanofluid, and 40 minutes for HTF used as MgO nanofluid. The results show that there is considerable amount of reduction in charging time, in case of 6 L per minute and 0.8% volume concentration, around 27.22% for $TiO_2$ nanofluid, 36.66% for $Al_2O_3$ nanofluid, 40.90% for CuO nanofluid and 63.63% for MgO nanofluid, when compared with water as the conventional HTF. From the results, it is observed that the effect of nanofluid plays an important role in the heat transfer process.

Figure 9 indicates that the temperatures of PCM gradually increases in the beginning and remains constant during the phase change period and further increases. Charging time is 95 minutes for HTF used as pure water and 70 minutes for HTF used as $TiO_2$ nanofluid, 55 minutes for HTF used as $Al_2O_3$ nanofluid, 50 minutes for HTF used as CuO nanofluid and 30 minutes for HTF used as MgO nanofluid. The results show that there is considerable amount of reduction in charging time, in case of 6 L per minute and 0.8% volume concentration, around 26.31% for $TiO_2$ nanofluid, 42.10% for $Al_2O_3$ nanofluid, 47.36% for CuO nanofluid, and 68.42% for MgO nanofluid, when compared with water as the conventional HTF.

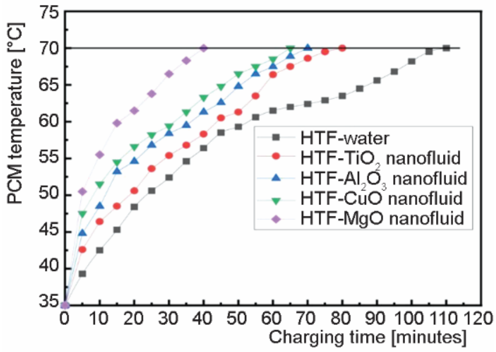


**Figure 8. Variation of PCM temperature with charging time for PCM as paraffin, HTF flow rate as 6 L per minute and 0.8% volume concentration of nanoparticles**

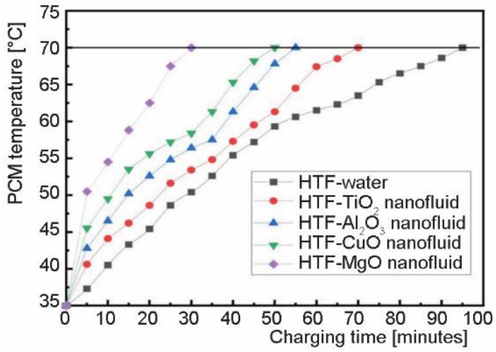


**Figure 9. Variation of PCM temperature with charging time for PCM as stearic acid, HTF flow rate as 6 L per minute and 0.8% volume concentration of nanoparticles**

*Effect of nanofluid volume concentration*

Figure 10 indicates that the Charging time is 60 minutes for 0.2% volume concentration, 50 minutes for 0.5% volume concentration and 40 minutes for 0.8% volume concentration with HTF used as MgO nanofluid and PCM used as paraffin wax. From the results, it is observed that the effect of nanofluid volume concentration plays an important role in the heat transfer process.

Figure 11 indicates that the charging time is 50 minutes for 0.2% volume concentration, 40 minutes for 0.5% volume concentration and 30 minutes for 0.8% volume concentration with HTF used as MgO nanofluid and PCM used as stearic acid.

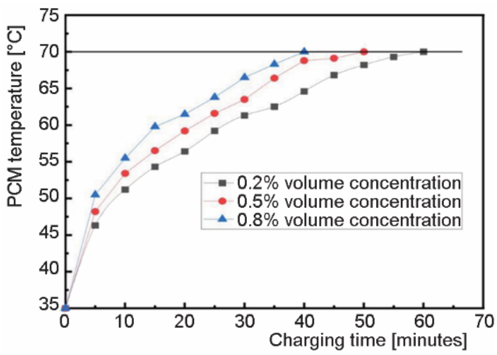


**Figure 10. Variation of PCM temperature with charging time for PCM as paraffin and HTF as MgO nanofluid**

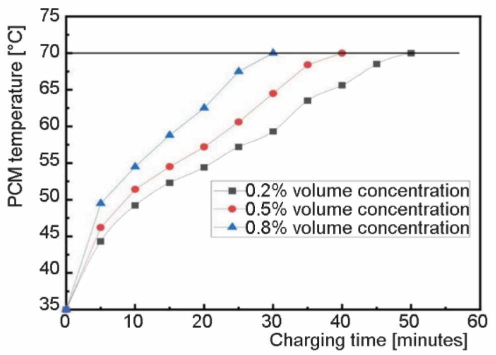


**Figure 11. Variation of PCM temperature with charging time for PCM as stearic acid and HTF as MgO nanofluid**

*Effect of flow rate*

Figure 12 indicates that the charging time is 70 minutes for 2 L per minute flow rate, 55 minutes for 4 L per minute flow rate and 40 minutes for 6 L per minute flow rate with HTF used as MgO nanofluid and PCM used as paraffin wax. From the results, it is observed that the effect of nanofluid flow rate plays an important role in the heat transfer process.

Figure 13 indicates that the Charging time is 60 minutes for 2 L per minute flow rate, 45 minutes for 4 L per minute flow rate and 30 minutes for 6 l/min flow rate with HTF used as MgO nanofluid and PCM used as stearic acid.

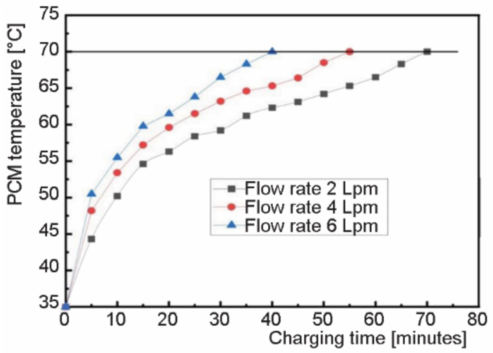


**Figure 12. Variation of PCM temperature with charging time for PCM as paraffin and HTF as MgO nanofluid**

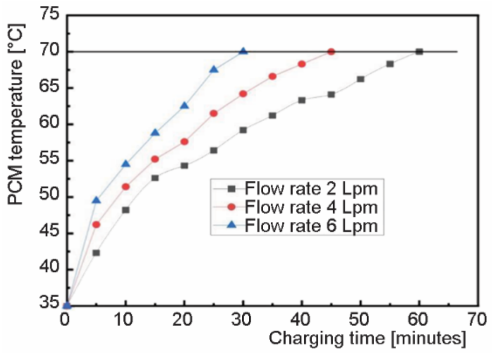


**Figure 13. Variation of PCM temperature with charging time for PCM as stearic acid and HTF as MgO nanofluid**

## *Discharging experiments*

Discharging experiments are conducted to study the heat recovery behavior of the TES system.

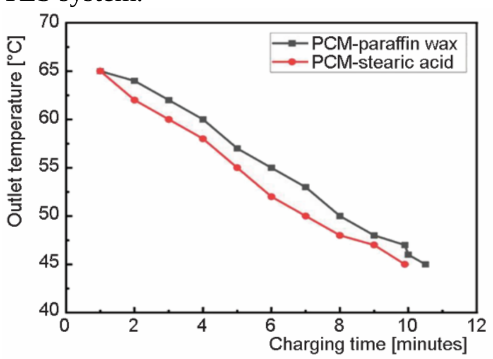


**Figure 14. Batches of water withdrawn *vs.* outlet water temperature**

Figure 14 indicates that the temperature of each batch of water withdrawn from the TES tank is slightly higher with paraffin wax as PCM when compared with stearic acid as PCM. Hence, the total amount of hot water that could be withdrawn also is more with paraffin wax as PCM (210 L as compared to 198 L with stearic acid as PCM). Similar results were observed by Reddigari *et al.* [9] in their study.

## Conclusions

In the present work, experimental investigations were conducted on four different selected nanofluids to study their effects on melting time of PCM under different percentages of volume concentrations and flow rates of HTF.

- From the study, the main conclusion drawn is the positive influence of nanoparticles added to water.

  - For 6 L per minute flow rate, 0.8% volume concentration and paraffin wax as PCM, the considerable reduction in charging time compared to water was observed with different nanofluids as explained below.
  - The 27.22% for $TiO_2$ nanofluid, 36.66% for $Al_2O_3$ nanofluid, 40.90% for CuO nanofluid and 63.63% for MgO nanofluid. The maximum reduction was noticed for MgO nanofluid.
  - For the same conditions previously explained but with stearic acid as PCM, again highest reduction in charging time was noticed as 68.42% for MgO nanofluid.
  - Reductions for other nanofluids are 26.31% for $TiO_2$ nanofluid, 42.10% for $Al_2O_3$ nanofluid, and 47.36% for CuO nanofluid.
- The MgO nanofluid have played a remarkable role in decreasing melting time due to low density, high thermal conductivity, Brownian motion, agglomeration and micro-convection.
- This result suggests the applicability of MgO as nanofluid for faster charging of PCM in discharging process, 210 and 198 L of hot water were withdrawn by using pomestic heating of water, dying cloths, cooking purposes, *etc.*
- During tharaffin wax and stearic acid as PCM, respectively.

## Limitation of the present study

In the present study, the volume concentrations of nanoparticles used are 0.2%, 0.5%, and 0.8% for enhancing heat transfer. Literature review and the experiments reveal that higher the concentration higher the viscosity and lower the specific heat capacity of the HTF. Hence, the volume concentration of nanoparticles is limited within 1%.

## References

[1] Naveen Kumar, G., Subrata Kumar, G., Thermophysical Properties of Nanofluids, *International Journal of Innovative Technology and Exploring Engineering*, *8* (2019), 11, pp. 1616-1620
[2] Nagappan, B., *et al.,* Heat Transfer Enhancement of a Cascaded Thermal Energy Storage System with Various Encapsulation Arrangements, *Thermal Science, 23* (2019), 2A, pp. 823-833
[3] Sankar, P., *et al.*, Performance Analysis of PCM Based Thermal Energy Storage System Containing Nanoparticles, *International Research Journal of Engineering and Technology, 5* (2018), 4, pp. 285-290
[4] Lokesh, S., *et al.,* Melting/Solidification Characteristics of Paraffin Based Nanocomposite for Thermal Energy Storage Applications, *Thermal Science, 21* (2017), 6, pp. 2517-2524
[5] Prakasam., M. J. S., *et al.*, An Experimental Study of the Mass Flow Rates Effect on Flat Plate Solar Water Heater Performance using $Al_2O_3$/Water nanofluid, *Thermal Science, 21* (2017), Supp. 2, pp. S379-S388
[6] Abdollahzadeh Jamalabadi, M. Y., Jae Hyun, P., Effects of Brownian Motion on Freezing of PCM Containing Nanoparticles, *Thermal Science, 20* (2016), 5, pp. 1533-1541
[7] Yang, Liu, Yuhan Hu., Toward $TiO_2$ Nanofluids – Part 2: Applications and Challenges, *Nanoscale Research Letters, 12* (2017), 1, 446
[8] Yang, J., *et al.,* Experimental Study on Enhancement of Thermal Energy Storage with Phase Change Material, *Applied Energy*, *169* (2016), May, pp. 164-176
[9] Reddigari, M. R., *et al.*, Thermal Energy Storage System Using Phase Change Materials: Constant Heat Source, *Thermal science, 16* (2012), 4, pp. 1097-1104
[10] Kumaresan, V., Velraj, R., Experimental Investigation of the Thermo-Physical Properties of Water-Ethylene Glycol Mixture Based CNT Nanofluids, *Thermochimica Acta, 545* (2012), Oct., pp. 180-186
[11] Mahbubul, I. M., *et al.,* Experimental Investigation on Effect of Ultrasonication Duration on Colloidal Dispersion and Thermophysical Properties of Alumina-Water Nanofluid, *International Journal of Heat and Mass Transfer, 88* (2015), Sept., pp. 73-81
[12] Abdul Hamid, K., *et al.,* Thermal Conductivity Enhancement of $TiO_2$ Nanofluid in Water and Ethylene Glycol (EG) Mixture, *Indian Journal of Pure & Applied Physics, 54* (2016), 10, pp. 651-655

[13] Kailash, N., *et al.*, Thermal Conductivity Enhancement in Zinc Oxide –Water Based Nanofluid System, *Research Journal of Chemical Sciences*, *6* (2016), 8, pp. 43-45
[14] Harikrishnan, S., *et al.*, Preparation and Thermal Energy Storage Behaviour of Stearic Acid-$TiO_2$ Nanofluids as a Phase Change Material for Solar Heating Systems, *Thermochimica Acta, 565* (2013), Aug., pp. 137-145
[15] Abdollahzadeh, M., Esmaeilpour, M., Enhancement of Phase Change Material (PCM) Based Latent Heat Storage System with Nanofluid And Wavy Surface, *International journal of heat and mass transfer, 80* (2015), Jan., pp. 376-385
[16] Anderson, R., *et al.*, Experimental Results and Modelling of Energy Storage and Recovery in a Packed Bed of Alumina Particles, *Applied Energy, 119* (2014), Apr., pp. 521-529
[17] Al-Azawii, M. M. S., *et al.*, Experimental Study on the Cyclic Behavior of Thermal Energy Storage in an Air-Alumina Packed Bed, *Journal of Energy Storage*, *18* (2018), Aug., pp. 239-249
[18] Minea, A. A., Moldoveanu, M. G., Studies on $Al_2O_3$, CuO, and $TiO_2$ Water-Based Nanofluids: A Comparative Approach in Laminar and Turbulent Flow, *Journal of engineering thermophysics, 26* (2017), 2, pp. 291-301
[19] Obaid, H. N., *et al.*, Thermal Energy Storage by Nanofluids, *Journal of Engineering and Applied Sciences, 8* (2013), 5, pp. 143-145
[20] Valan, A. A., *et al.*, Numerical Performance Study of Paraffin Wax Dispersed with Alumina in a Concentric Pipe Latent Heat Storage System, *Thermal science, 17* (2013), 2, pp. 419-430
[21] Menlik, T., *et al.*, Heat Transfer Enhancement Using MgO/Water Nanofluid in Heat Pipe, *Journal of the Energy Institute*, *88* (2015), 3, pp. 247-257
[22] Rashid, F. L., *et al.*, Novel Phase Change Materials, MgO Nanoparticles, and Water Based Nanofluids for Thermal Energy Storage and Biomedical Applications, *International Journal of Pharmaceutical and Phytopharmacological Research, 8* (2018), 1, pp .46-56
[23] Khan, I., *et al.*, Nanoparticles: Properties, Applications and Toxicities, *Arabian Journal of Chemistry, 12* (2019), 7,pp. 908-931
[24] Gupta, H. K., *et al.*, Investigations for Effect of $Al_2O_3$-$H_2O$ Nanofluid Flow Rate on the Efficiency of Direct Absorption Solar Collector, *Case Studies in Thermal Engineering, 5* (2015), Mar., pp. 70-78
[25] Cobanoglu, N., *et al.*, Carbon-Based Nanofluid Applications in Solar Thermal Energy, *E3S Web of Conferences, 111* (2019), ID 01056
[26] Turkyilmazoglu, M., Performance of Direct Absorption Solar Collector with Nanofluid Mixture, *Energy Conversion and Management, 114* (2016), Apr., pp. 1-10
[27] Muthoka, M. J., *et al.*, Study on Thermophysical Properties of Nanofluid Based Composite Phase Change Material for Low Temperature Application, *Energy Procedia, 142* (2017), Dec., pp. 3313-3319
[28] Addad, Y., *et al.*, Effects of Nanofluids on the Performance of a PCM-Based Thermal Energy Storage System, *Journal of Energy Engineering, 143* (2017), 4, 04017006
[29] Prasanth, B., *et al.*, Experimental Study of Latent Heat Thermal Storage System Using Mixed Nano Particles with PCM, *International Journal of Engineering, Science and Mathematics, 7* (2018), 4, pp. 455-469
[30] Grosu, *et al.*, Preparation and Characterization of Nanofluids Based on Molten Salts with Enhanced Thermophysical Properties for Thermal Energy Storage at Concentrate Solar Power, *In AIP Conference Proceedings*, *2126* (2019), 1, ID 200021
[31] Moffat, R. J., Using Uncertainty Analysis in the Planning of an Experiment, *Jour. of Fluids Engineering, 107* (1985), 2, pp. 173-178

Paper submitted: October 4, 2019
Paper revised: January 10, 2020
Paper accepted: January 20, 2020