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Research paper

Effect of water based Al_2O_3 nanoparticle PCM on cool storage performance

Ahmed A. Altohamy, M.F. Abd Rabbo, R.Y. Sakr, Ahmed A.A. Attia*

Mechanical Engineering Department, Benha University, Shoubra Faculty of Engineering, 108 Shoubra Street, Cairo, Egypt

HIGHLIGHTS

- A water based nanofluid (50 nm Al_2O_3) PCM in charge process was experimentally studied.
- Experiments were conducted with NFPCM volumes fractions 0.5%, 1%, 1.5%, and 2%.
- Charge time reduction at HTF temperature −10 °C was 32, 28, 22, 17 at flow rates of 12, 10, 8, 6 lpm.

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ABSTRACT

A spherical capsule with water based Nanofluid (50 nm Al_2O_3) phase change material during charging process was studied experimentally. The experiments were conducted with pure water and the NFPCM with volumes fractions 0.5%, 1%, 1.5%, and 2%. The results show that there is a significant effect of Nanoparticle concentration on thermal properties of PCM which sequentially reduces complete charging time for all HTF volume flow rates and also at different HTF inlet temperature. The percentage of reduction in complete charging time at HTF inlet temperature −12 °C attained approximately 32%, 28%, 18%, 12% at HTF volume flow rate of 12, 10, 8, 6 lpm respectively.

1. Introduction

The main function of thermal storage systems remove or add heat to a storage medium to be used at another time. The Cool thermal energy storage plays a vital role in central air-conditioning in the large buildings, high powered electronic cooling applications, and various industrial process cooling applications where the cooling requirement is highly intermittent Ref. [1–3]. Cool storage systems always consist of chilled water tanks and ice systems. The basic concept of the encapsulated thermal storage air-conditioning system is utilizing the characteristics of phase change material (PCM) packed inside capsules stored in tank. this capsules released or absorbed a great amount of latent heat during phase change process. Cool storage system always used to the goal of shifting peak power consumption. The performance of thermal storage system have been studied by many researcher to achieve highest performance at short charging time, great amount of energy stored and fast discharging time.

A significant influence of super cooling phenomenon during the charging process and a faster cool storage found at lower inlet coolant temperature combined with large coolant flow rate during a series of experiments performed by Bédécarrats et al. [4], to investigate the parameters that affect on storage system consists of a spherical capsules filled with water and a nucleation agent as a Phase Change Material (PCM).

Also the increasing HTF volume flow rate and lowering inlet temperature of HTF reduces the complete charging time, and increases solidified mass fraction. Employing metallic capsule and smaller capsule sizes has the same effect on the charging time and solidified mass fraction. This is declared by Reda I. El Ghnam et al. [5] during their experimental work to study the performance of heat transfer during a processes of charging and discharging for a storage system uses pure water inside a spherical capsule as PCM.

The allowance to calculate the mass of (solidified − melted) of ice at any time during the freezing or melting processes within a

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* Corresponding author. Tel.: +20 2 22050175x4111; fax: +20 2 2202336.
E-mail addresses: Ahmed_attia72@yahoo.comor, Ahmed.attia@feng.bu.edu.eg (A.A. Altohamy).

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Nomenclature

C_i	specific heat of ice, kJ/kg K
C_w	specific heat of water, kJ/kg K
L.H.	latent heat of fusion of water, kJ/kg K
m_o	mass of PCM encapsulated inside the spherical capsule, kg
m_s	solidified mass, kg
m_s/m_o	solidified mass fraction
$\dot{Q}_{ch}$	charging rate, kW
Q_{st}	accumulative energy stored, kJ
$r_{avg_{h,v}}$	average radius of solid–liquid interface in test capsule, m
r_h	horizontal radius of solid–liquid interface in test capsule, m
r_{in}	inside radius of test capsule, m
r_v	vertical radius of solid–liquid interface in test capsule, m
H	vertical distance, measured from the centre of the spherical capsule to the free surface of the encapsulated PCM, m
T_l	liquid phase temperature of PCM, °C
T_o	initial temperature of PCM (distilled water), °C
T_{pc}	phase change temperature, °C
T_s	solid phase temperature of PCM, °C
T	time, min
Δt	time difference, s
V_s	solidified volume, m^3
V_{PCM}	spherical shell volume, m^3
$V_{capsule}$	internal volume of the capsule m^3
V	actual volume flow rate, pm

Greek symbols

ρ_w	water density, kg/m^3
ρ_i	ice density, kg/m^3
ρ	volume correction factor

Abbreviations

PCM	phase change material
HTF	heat transfer fluid
NFPCM	nano fluid phase change material
CTES	cool thermal energy storage
MWCNT	multi wall carbon nanotubes
DI	de-ionized water
LDPE	low density polyethylene
Al_2O_3	aluminium oxide
LPM	litre per min

sphere is achieved with semi-empirical equations. A novel method was used to measure the water–ice interface position during the freezing process a combined with quantitative data on the movement of the solid–liquid interface position with time. This was performed theoretically and experimentally, and checked by Eames and Adref [6] and an agreement with experiments results was found. These results are also matched with the results of Ref. [4,5], for the effect of inlet HTF volume flow rate and inlet temperature.

Nanoparticle and their effect on enhancing thermal properties of the PCM are newly consider increasing the performance of thermal storage system. Many of researchers have to investigate their effect on cool storage application.

Dispersing copper oxide nanoparticles and a nucleating agent in the base PCM (phase change material) as a NFPCM through solidification process exhibited a significant reduction about 35% in solidification time due to heat transport enhancement which can result to operate the evaporator of the chillier at high temperature, which have result in energy saving. This is experimentally investigated were conducted at different bath temperatures (−2 °C, −6 °C) by V. Kumaresan et al. [7].

Kumaresan et al. [8] used Multi Wall Carbon Nanotubes (MWCNT) with volume fractions of 0.15%, 0.3%, 0.45%, and 0.6% in de-ionized water (DI) as a base for phase change material to enhance the solidification process in a spherical capsule. The result shows a significant reduction by 14% and 20.1% when the HTF temperature was the -9 °C and −12 °C respectively. This reduction is due to that the presence of MWCNT acted as nucleating agent that caused appreciable reduction in sub cooling which may achieve energy saving potential approximately from 6% to 9% in the CTES using the NFPCMs.

Wu et al. [9] found that the addition of Al_2O_3 (0.2 wt%) nanoparticles remarkably decreases the super cooling degree of water, which advances the beginning freezing time and consequentially reduces the total freezing time with water as base PCM. Also an infrared imaging to visually observe the freezing process was performed. Which suggest that the freezing time reduced by 20.5% for NPCM which also yield to energy saving in chillier unit.

A comparison of various six PCMs embedded with alumina and aluminium nanoparticles in pure as a PCM on solidification time reduction were experimentally investigate by S. Kalaiselvam et al. [10]. The experiments shows that the density of the nanoparticles that was employed have been in the same range as that of the PCM with which it was used hence the adverse effects related to the convection losses were prevented. However, the rate of melting was improved significantly for the PCMs embedded with the dispersed nanoparticles than the pure PCMs; the analytical solutions suggest that the complete solidification time depends on the Stefan number, heat generation parameter, HTF temperature and size of the spherical capsule. The dispersion of nanoparticles has greatly reduced the complete solidification time.

Through the following work a study will perform to experimentally investigate the effect of HTF temperature, the volume flow rate of HTF, and effect of additive quantity of aluminium oxide (Al_2O_3) Nano particle on the time of complete charging processes, the solidified mass fraction, the percentage of energy stored, and the charging rate.

2. Experimental setup

The schematic of the experimental test rig is shown in Fig. 1. The experiment consists of two loops, one for refrigerant and the other for ethylene glycol solution which is considered as the heat transfer fluid, which is responsible about adding or removing heat from the phase change material that is contained in the spherical capsule (test section). The heat transfer fluid is a mixture of water and Ethylene glycol with a concentration of 30% by weight. The freezing point of it is −15 °C.

A two cylindrical tank with end top and bottom caps having dimensions of 200 * 900 mm were used as charging and discharging space. The tanks were insulated by a 50 mm thickness thermal insulation to reduce the heat gain with surrounding. Each tank is filled with approximately 0.027 m^3 of the HTF. The two tanks are provided with inlet and outlet pipes including manual gate valves for the HTF circulation.

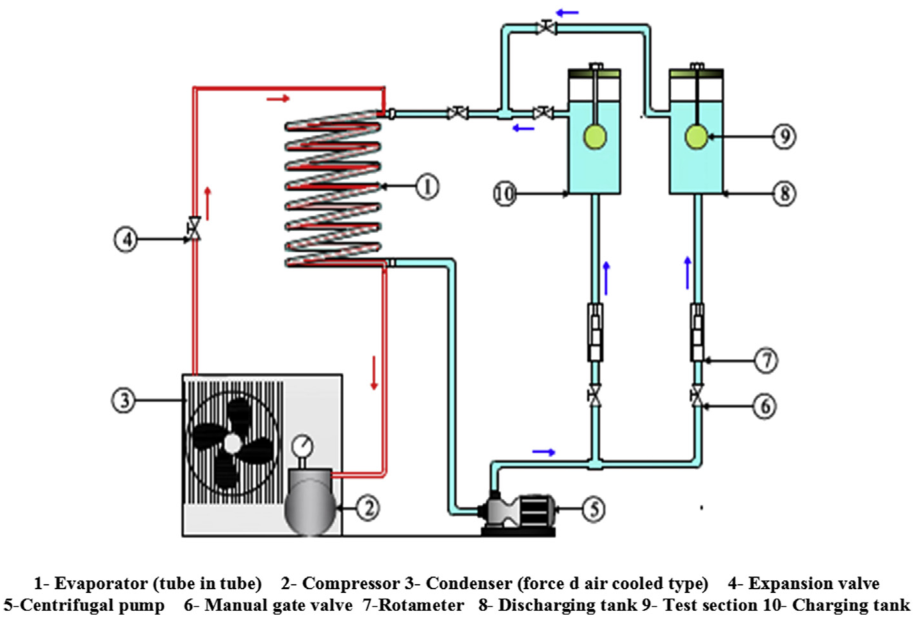

Fig. 1. The schematic of the experimental test rig.

Cool thermal storage process is carried out using spherical capsule (test section) charged with water based Nanoparticle (Water–Al_2O_3) as PCM material. The capsule is made of low-density polyethylene (LDPE) material with an outer diameter of 84 mm and thickness of 2 mm, and filled with 80% of its inner volume with a PCM to avoid the thermal expansion during the solidification process. Nine calibrated Copper-Constantan (T-type) thermocouples were employed to measure the temperature distribution with ±0.5 °C distributed on the horizontal and vertical axes of the spherical capsule at specified locations as shown in Fig. 2. The thermocouples are located at intersection points of concentric circles with the vertical and half of horizontal axes of spherical capsule. The centre of concentrate circles is located at centre of spherical capsule where thermocouple no 3 was placed. Thermocouples no (2, 7, 4) located at intersections points of circle with diameter 20 mm thermocouples no (8, 5) is located at intersection points of circle with diameter 40 mm except thermocouple 1 little dropped to be assured that it is fully immersed in PCM. The circle with diameter 60 mm the third intersection point is located over the maximum level of PCM material so only two thermocouples no (6, 9) are located on this circle. For horizontal axis of capsule the symmetric configuration makes that available to use on side of the intersection with circles.

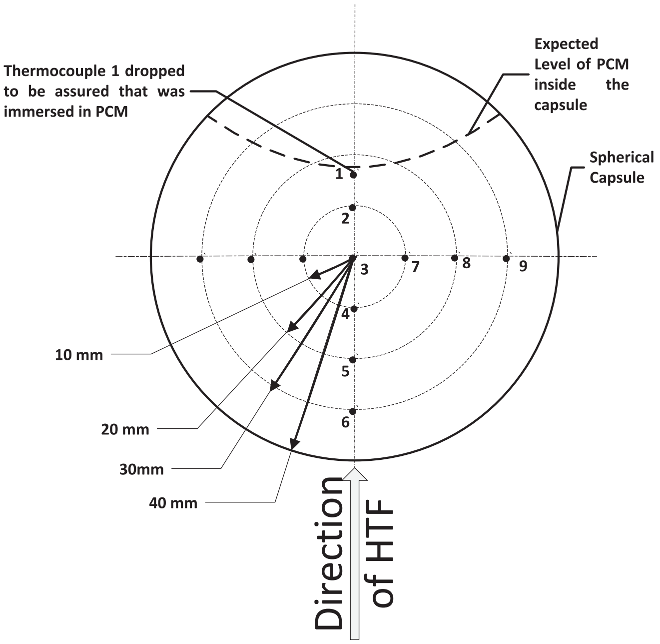

Fig. 2. Thermocouples distribution inside PCM Capsule.

To achieve the requirements HTF outlet temperature for the charging and discharging process, a simple vapour–compression cycle (refrigeration unit) operate with R-404A was installed. It includes a hermetic compressor of 3 HP; air cooled condenser (forced type), filter, drier, thermostatic expansion valve, and one ton refrigeration evaporator (tube-in-tube type). A 1 HP centrifugal pump is used to circulate the HTF through the piping system to carry out the charging and discharging process of the experiments. The piping system and the manual gate valves are arranged to enable the pump to circulate the HTF through charging and discharging loops.

A data acquisition card (National Instruments, NI USB-6210, 32-inputs, resolution of 16-bit and scanning rate of 250 kS/s) and a laptop are used to record temperatures through aforementioned thermocouples. The HTF volume flow rate is monitored by using a calibrated rota-metre. A digital temperature controller (ELIWELL IC 901, 0.5% accuracy, and 1 °C set-point differential) is used to control the required temperature inside the charging or discharging tank during the charging and discharging experiments. A series of charging experiments are performed under different operating condition. The varied parameters in the present study are listed in Table 1.

Table 1
Experiment parameters.

HTF	Temperature (during charge process): −6, −8, −10, and −12 °C Volume flow rates: 6, 8, 10, and 12 lpm
PCM	Water + nano (Al_2O_3) volume fractions (0.0%, 0.5%, 1%, 1.5% and 2%)

At charging process, the manual gate valves incorporated with the piping system are positioned for the charging mode, and the refrigeration unit operates to cool the circulating HTF (Table 2). The digital temperature controller is set at one of the four test temperatures as listed in Table 1. The PCM temperature is maintained at 22 °C as an initial temperature for all charging experiments. Once the adjusted HTF temperature reaches, the volume flow rate of the HTF is set at one of the four volume flow rates listed in Table 1. Then the capsule is immersed and suspended by long screw belt fixed at the centre of the top end cap and two nuts which adjust the position of the capsule at the centre of the tank, the measurements of the PCM temperatures inside the test capsule and the HTF temperatures around it were scanned and recorded every one second by the data acquisition system. The experiment is terminated when the temperature of the PCM inside the capsule starts to be equal to that of the HTF. This indicates that the water is completely frozen and the ice is being sensibly sub-cooled. The refrigeration unit and the pump are switched off, and the frozen test capsule is kept inside the charging tank to maintain its temperature until finishing the preparation of the discharging experiment (which will takes few minutes).

The thermocouples were set in these specified places in the sphere capsule to indicate the temperature changes through the solidification process. This will make use able to specify the solidification volume of PCM inside the capsule through the test and get r_h and r_v then get $r_{avgh,v}$ and finally get the solidified volume at any time through the experiment Ref. [5].

3. Data reduction: the output of data acquisition system for each experiment for different concentration of nanoparticle are treated with the following equation to get performance parameters

$$V_s = \rho\left(\frac{\rho_w}{\rho_i}\right)(2/3)\pi\left(r_{in}^3 - r_{avg_{h,v}}^3\right) + \pi h\left(r_{in}^2 - r_{avg_{h,v}}^2\right) \quad \left(m^3\right) \tag{1}$$

$$r_{avg_{h,v}} = \frac{r_h + r_v}{2} \quad (m) \tag{2}$$

The solidified mass can calculate as $m_s = \rho_i * V_s \quad (kg/s)$ (3)

The solidified mass fraction is calculated from

$$= m_s/(\rho_w * V_{PCM}) \tag{4}$$

The PCM volume $V_{PCM} = 0.80\ V_{capsule} \quad \left(m^3\right)$ (5)

The accumulative thermal energy stored within the test capsule is derived as follows:

$$Q_{st} = \rho_w * V_o C_w (T_o - T_l) + \left(\frac{m_s}{m_o}\right) * L \cdot H + \left(\frac{m_s}{m_o}\right) C_i (T_{pc} - T_s) \quad (kJ/kg) \tag{6}$$

The percentage of energy stored calculated by

$$\%\, Q_{st} = Q_{st}/Q_{st,max} \tag{7}$$

The charging rate of thermal energy stored within the test capsule is calculated from;

$$Q_{\dot{s}t} = \frac{\Delta Q_{st}}{\Delta t} \quad (kW) \tag{8}$$

4. Nanofluid preparation

The particles used in the nanofluid experiments are gamma-alumina (γ-Al_2O_3) (50 nm average particle size with surface area >200 m^2/g). The thermo physical properties of γ-Al_2O_3 nanoparticles are revealed in Table 3.

The γ-Al_2O_3/water nanofluid was prepared in this study with four different nanoparticles volume concentrations of 0.5, 1, 1.5 and 2%. The dispersion of particles in water was done by two step the first step is put the mixture in ultra-sonication for 90 min in a water bath temperature of 30 °C. The second steps to achieve good mixing for the nanofluid the mixture was pumped in the tube coil for six hours before beginning the experiments. It was observed with naked eyes that there was no significant settlement of nanoparticles for first six days of static condition of nanofluid. Nevertheless, settlement appeared gradually from the seventh day, and the complete settlement occurred after 13 days.

5. Result and discussion

Fig. 3 illustrates the Effect of Nano fluid concentration on the complete charging time at different HTF volume flow rate for different HTF inlet temperature. It is noticed from the figure that as the Nano fluid concentration increases the total time required for complete charging decreases. Also it is observed that as the volume flow rate of the HTF increases the total charging time decreases. The same behaviour is noticed for inlet HTF temperatures vary value of −6 and −12 °C respectively. This change in charging time is due to changing in physical properties of PCM after adding nanoparticles in nanofluid PCM. The nanoparticle behave as nucleation agent helping crystallization process of ice to grow faster than pure water only increases the overall system thermal storage capacity through reduction in cycle time of charging and discharging. This reduction happened through dispersion of ice layer that traditionally formed on internal wall of capsule causing serious reduction in thermal conductivity of PCM. This reduction will increase the charging time. This doesn't allow the energy usage cycle to be matched with system storage cycle, making it working at lower system total capacity than the capacity which the system should use it.

The reduction percentage of complete charging time increases with the increase of Nano fluid concentration as illustrated in Fig. 4 for HTF temperature having values of −6 and −12 °C respectively. A reduction percentage is about 16.5% for a HTF volume flow rate of 12 lpm and Nano concentration of 2% at a HTF inlet temperature of −6 °C and about 25% for HTF inlet temperature of −12 °C. This reduction in charge time will have a contribution in reducing the running time of chiller system or its size which affect on running cost or installation cost.

Table 2
Uncertainty of the measured quantities.

Parameter	Relative uncertainty
Encapsulated volume, ($V_{o)}$	±0.332%
Solidified mass fraction (m_s)	±1.12%
Percentage of energy stored ($\%Q_{st}$)	±3.00%
Charging rate ($Q_{\dot{s}t}$)	±8.63%

Table 3
Properties of γ-Al_2O_3 nanoparticles.

Thermal conductivity (W/m °C)	Density (kg/m^3)	Specific heat (J/kg °C)
36	3600	773

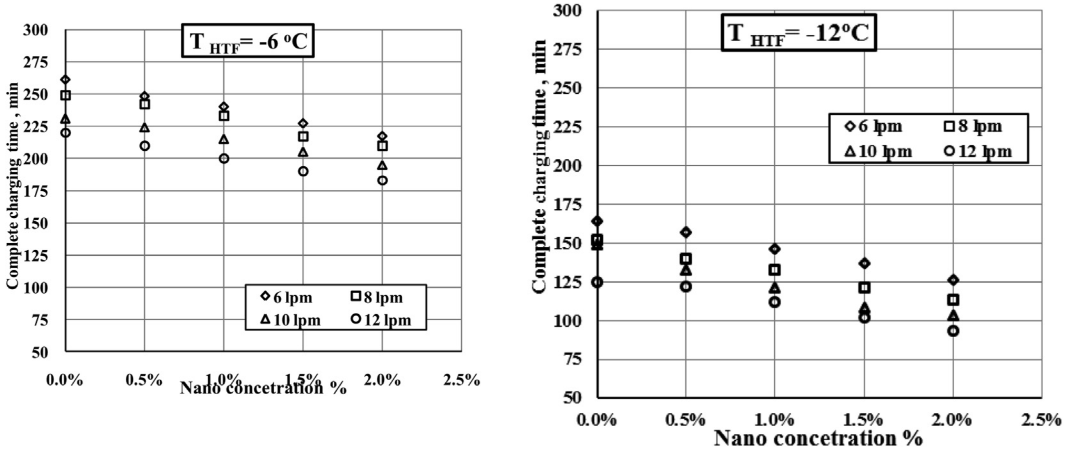

Fig. 3. Effect of Nano fluid concentration on the complete charging time at different HTF volume flow rate for different HTF inlet temperature.

Effect of Nano fluid concentration on the solidified mass fraction through the charging process at different HTF volume flow rate for different HTF inlet temperature is shown in Fig. 5. It is observed from the figure that for all cases of the different HTF volume flow rate the solidification mass fraction increases with the time proceeds and it is clear that for a certain time the solidified mass fraction increases with the increase of the Nano concentration due to the enhancement of thermal properties of the PCM Ref. [11–15] which increases the heat transfer rate. The solidified mass fraction express about the rate of growing ice crystals which is greatly affect by exciting metal particles (nanoparticle).

Fig. 6 shows the effect of Nano fluid concentration on the energy stored percentage for different volume flow rate (6 and 12 lpm) of HTF at inlet HTF temperature −12 °C, it is clear from figure that the energy stored increases with the increase of Nano fluid concentration for all times during the charging process, which also happen due to the improvement of the thermal properties of the water based Nano fluid PCM.

Fig. 7 Effect of Nano fluid concentration on charging rate through the charging process at different HTF volume flow rate for different HTF inlet temperature is illustrated. It is observed from the figure that for all cases of the different HTF volume flow rate the charging rate decrease with the time proceeds. Also significant effect of the Nano fluid concentration at early time and as the time progress the effect of concentration becomes insignificant.

Fig. 8 illustrate the time wise variation of solidified mass fraction for different Nano fluid concentration, different HTF inlet temperature −6 and −12 °C at HTF volume flow rate of 10 lpm, it clear from the figure that the increase of the Nano concentration increase the solidified mass fraction for all time through the charging process and that the high mass solidified fraction occur at the lowest HTF inlet temperature. The variation of percentage of energy stored for different concentration at HTF volume flow rate of 10 lpm and different HTF inlet temperature of −6 and −12 °C is showed in Fig. 9a,b, it is depicted from the figure tend as the Nano fluid concentration increase the energy stored increase at any time less than 95% of the total charging time, at later stage of the charging process the effect of Nano concentration is insignificant.

The time wise variation of charging rate for different concentration at HTF volume flow rate of 10 lpm and different HTF inlet temperature of −6 and −12 °C is showed in Fig. 10a,b, it is noticed that as the energy charging process proceeds the rate of energy charging decreases. Also the more the Nano fluid concentration increases the more the charging rate increase.

6. Conclusion

A charging (solidification) process of water based Nano fluid with different volume concentration up to 2% in a spherical capsule LHTES system are experimentally investigated. From this study it can be concluded the following:

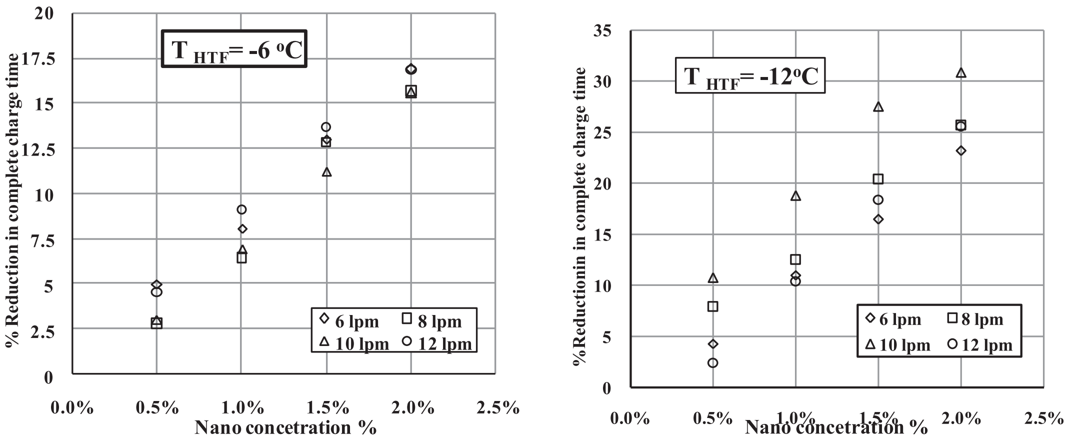

Fig. 4. Effect of Nano fluid concentration on the percentage of reduction in complete charging time at different HTF volume flow rate for different HTF inlet temperature.

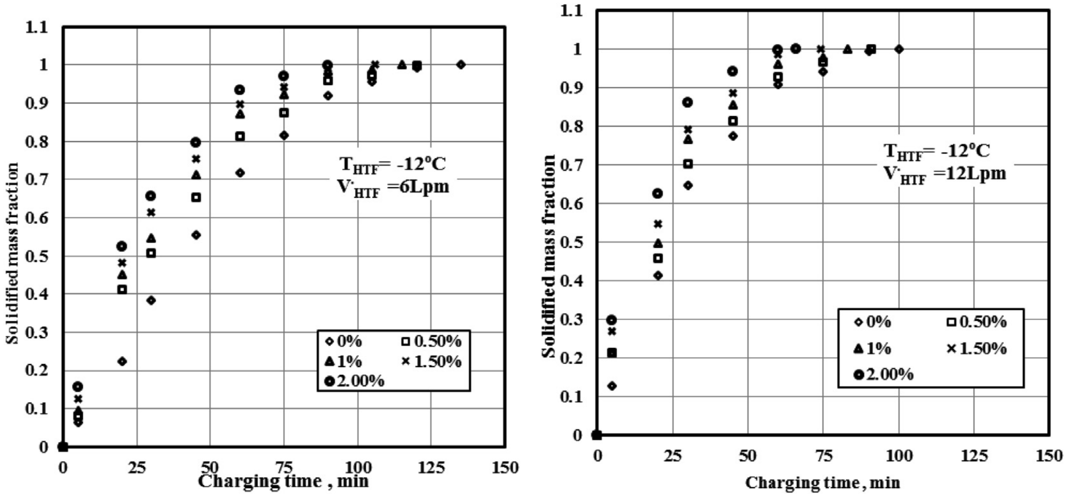

Fig. 5. Variation of the solidified mass fraction with charging time using different HTF volume flow rate at different nano fluid concentration for HTF temperature of −12 °C.

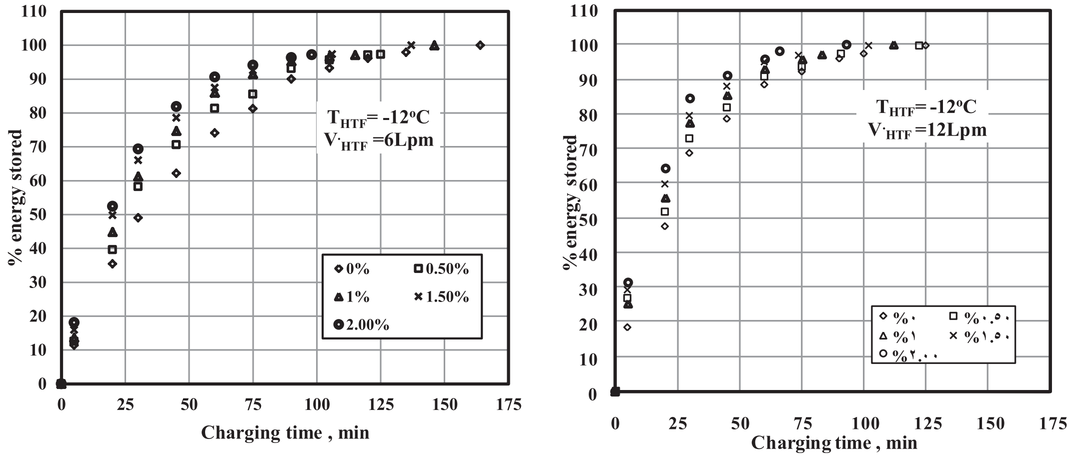

Fig. 6. Variation of the percentage of energy stored with the charging time using different HTF volume flow rate at different Nano fluid concentration for HTF temperature of −12 °C.

- The addition of Al_2O_3 nanoparticle on the water (PCM) has a significant effect on the solidified mass fraction, charging rate and percentage of energy stored specially at high volume concentration.
- The charging time significantly decreases with Al_2O_3 nanoparticle volume concentration increase, this due to the enhancement in thermal properties(thermal conductivity) of PCM due to the existence of metal particle which enhance contact surfaces and creating points to build the solidified nucleate which increase the growing rate of grows layer. The reduction in charging time may reach to be about 30% at nanoparticle concentration 2% (by volume) compared with

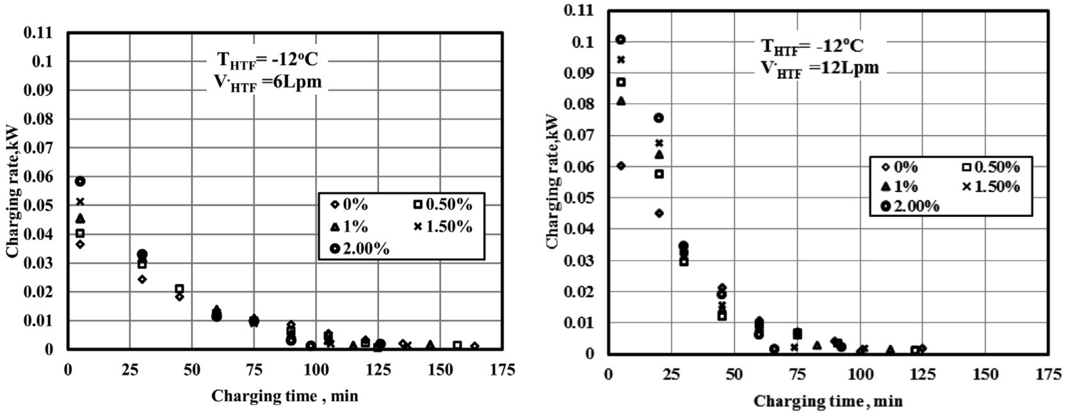

Fig. 7. Variation of the charging rate with the charging time using different HTF volume flow rate at different Nano fluid concentration for HTF temperature of −12 °C.

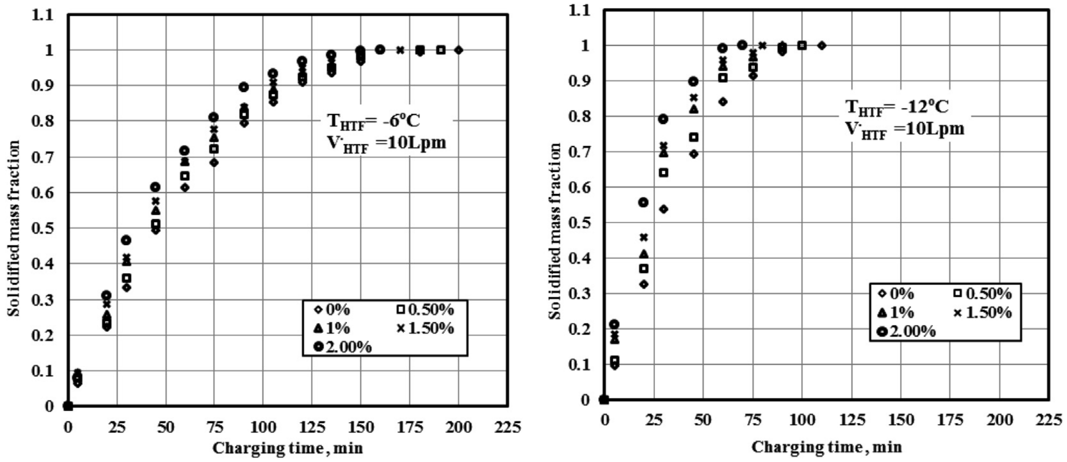

Fig. 8. Variation of the solidified mass fraction with the charging time using different HTF temperature at different Nano fluid concentration for HTF volume flow rate of 10 lpm.

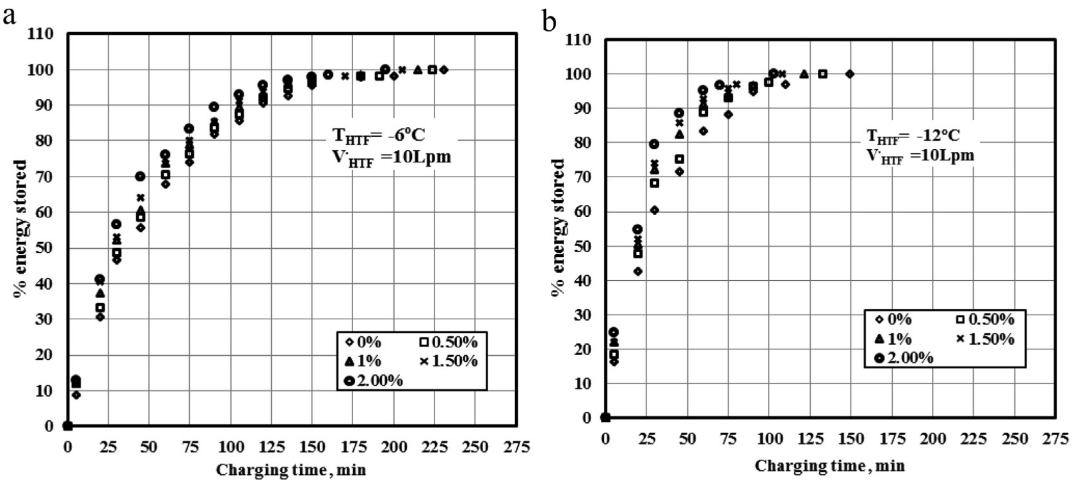

Fig. 9. Variation of the percentage of energy stored with the charging time using different HTF temperature at different Nano fluid concentration for HTF volume flow rate of 10 lpm.

pure water. The percentage of charging time reduction with average value of 20% in different HTF volume flow rate with 2% volume fraction (0.08% by weight) which previously expected by Ref. [9].

- The most of nanoparticle submersed to the bottom of the sphere specially (by naturally settling) with charging processing. This allowing good contact between PCM and internal metal surface of the capsule. This will increase the heat transfer coefficient rate.

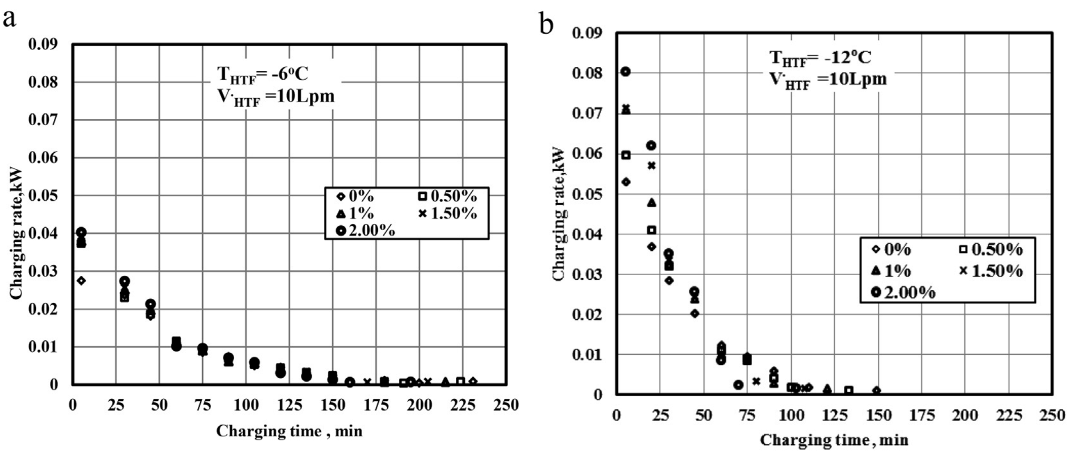

Fig. 10. Variation of the charging rate with the charging time using different HTF temperature at different Nano fluid concentration for HTF volume flow rate of 10 lpm.

References

[1] G. Li, Y. Hwang, Radermacher, Review of cold storage materials for air conditioning application, Int. J. Refrig. 35 (8) (2012) 2053–2077.

[2] G. Li, Y. Hwang, R. Radermacher, Chun, Review of cold storage materials for subzero applications, Energy 51 (2013) 1–17.

[3] Y.D. Liu, Y.G. Zhou, M.W. Tong, X.S. Zhou, Experimental study of thermal conductivity and phase change performance of nanofluids PCMs, Microfluid Nanofluid 4 (2009) 579–584.

[4] J.P. Bédécarrats, J. Castaing-Lasvignottes, F. Strub, J.P. Dumas, Study of a phase change energy storage using spherical capsules. Part I: experimental results, Energy Convers. Manag. (2009) 2527–2536.

[5] Reda I. ElGhnam, Ramdan A. Abdelaziz, Mohamed H. Sakr, Hany E. Abdelrhman, An experimental study of freezing and melting of water inside spherical capsules used in thermal energy storage systems, Ain Shams Eng. J. 3 (2012) 33–48.

[6] Ian W. Eames, Kamel T. Adref, Freezing and melting of water in spherical enclosures of the type used in thermal (ice) storage systems, Appl. Therm. Eng. 22 (2002) 733–745.

[7] P. Chandrasekaran, M. Cheralathan, V. Kumaresan, R. Velraj, Enhanced heat transfer characteristics of water based copper oxide nanofluid PCM (phase change material) in a spherical capsule during solidification for energy efficient cool thermal storage system, Energy 72 (2014) 636–642.

[8] V. Kumaresan, P. Chandrasekaran, Maitreyee Nanda, A.K. Maini, R. Velraj, Role of PCM based nanofluids for energy efficient cool thermal storage system, Int. J. Refrig. 36 (2013) 1641–1647.

[9] Shuying Wu, Dongsheng Zhu, Xinfang Li, Hua Li, Junxi Lei, Thermal energy storage behavior of Al_2O_3–H_2O nanofluids, Thermochim. Acta 483 (2009) 73–77.

[10] S. Kalaiselvama, R. Parameshwarana, S. Harikrishnanb, Analytical and experimental investigations of nanoparticles embedded phase change materials for cooling application in modern buildings, Renew. Energy 39 (2012) 375–387.

[11] H. Masuda, A. Ebata, K. Teramae, N. Hishinuma, Alteration of thermal conductivity and viscosity of liquid by dispersing ultrafine particles (dispersion of c-Al_2O_3, SiO_2, and TiO_2 ultra-fine particles), Netsu Bussei 4 (4) (1993) 227–233.

[12] S. Lee, S.U.S. Choi, S. Li, J.A. Eastman, Measuring thermal conductivity of fluids containing oxide nanoparticles, J. Heat. Transf. 121 (1999) 280–289.

[13] H. Xie, J. Wang, T. Xi, Y. Liu, F. Ai, Q. Wu, Thermal conductivity enhancement of suspensions containing nanosized alumina particles, J. Appl. Phys. 91 (7) (2002) 4568–4572.

[14] C.H. Li, G.P. Peterson, Experimental investigation of temperature and volume fraction variations on the effective thermal conductivity of nanoparticle suspensions (nanofluids), J. Appl. Phys. 99 (8) (2006) 1–8.

[15] V. Barbes, R. Paramo, E. Blanco, M.J. Pastoriza-Gallego, M.M. Pineiro, J.L. Legido, C. Casanova, Thermal conductivity and specific heat capacity measurements of Al_2O_3 nanofluids, J. Therm. Anal. Calorim. 111 (2013) 1615–1625.