Study the Performance of Nano-Enhanced Phase Change Material NEPCM in Packed Bed Thermal Energy Storage System

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Abstract *The present work deals with an experimental investigation of charging and discharging processes in thermal storage system using a Nano-Enhanced phase change material (NEPCM). Paraffin wax was used as the phase change material, and nanoparticles of Cu and TiO2 used with (1%, 2%, 3%, and 5%) additive by weight that were added to melt paraffin wax and mixed with shear mixer to avoid the formation of aggregation and to form suitable NEPCM. Then, it was put in spherical capsules and packed in a cylindrical packed column which acted as an energy storage system. Air was used as the heat transfer fluid (HTF) in thermal storage unit. The effect of HTF flow rate and nanoparticles concentration on the time of charging and discharging process and on temperature hysteresis were studied. The results showed that the faster storage of thermal energy can be made by high flow rate of heat transfer fluid (HTF) and high concentration of nanoparticles. But it was found that at 65°C HTF inlet temperature, the melting and solidification processes higher accelerated at 3% weight fraction of nanoparticles than that at 1% concentration. Also, when the flow rate was increased from 9 to 24 L/s. the temperature hysteresis increases, but when the concentration of nanoparticles increase; the temperature hysteresis decrease.*

Keywords *Nano-enhanced phase change material NEPCM; paraffin wax; TiO2; Cu; heat transfer fluid HTF; thermal energy storage TES..*

I. INTRODUCTION

Energy demands in the commercial, industrial, and utility sectors vary on daily, weekly, and seasonal bases. These demands can be matched with the help of thermal energy storage (TES) systems that operate synergistically. The use of TES for thermal applications such as space and water heating, cooling, air-conditioning, and so on has recently received much attention. TES deals with the storage of energy by cooling, heating, melting, and solidifying material; the thermal energy becomes available when the process is reversed. Storage by

causing a material to raise or lower in temperature is called sensible heat storage; its effectiveness depends on the specific heat of the storage material and, if volume is important, on its density. Storage by phase change (the transition from solid to liquid with no change in temperature) is a mode of (TES) known as latent heat storage. This process made the PCM enables to storage thermal energy about 5-14 times more than that SHS like water, and rock ([1]-[3]). Paraffin wax was considered as an important material capable of storing energy through phase change. PW have the advantage of very high stability over repeated cycles of latent TES operation without degradation. So, PW were considered as good PCM candidates [4, 5]. Paraffin wax have desirable properties, it is safe, non-interacting, and congruous with all materials that consist of containers, high latent heat, low or no supper cooling, chemically stable, and different phase change temperature. This leads to make paraffin wax widespread in latent heat thermal energy storage (LHTES) ([6] - [8]) But there was a main drawback of using PW in TES it was represented by the low thermal conductivity that lead to limited heat transfer rate. The low thermal conductivity of PCM is linked to the lower heat transfer rates during melting/freezing processes which result in increasing charging/discharging times. So, for PCM application the thermal conductivity enhancement (TCE) is necessary to improve heat transfer characteristics [9]. The approach of enhancement the thermal conductivity of base material entails utilization of free-form highly-conductive powders/beads/particles ranging from fine particles to nano-particles]. The difference between nano-particles and traditional particles (millimeter or micro-scale), was that nano-particles suspended in the fluid and lowering the ability of sedimentation occur [10]. There are numerical or theoretical and experimental investigations for nano-enhanced phase change materials (NEPCM). Reference [11] developed a model of 1-D Stefan problem for the Nano-enhanced phase change materials (NEPCM) that contains water and cyclohexane as the base PCM and alumina, copper, copper oxide and titanium oxide as nano-

particles additives. From the results it was found that the increasing in volume fraction causes increase in thermal conductivity of nanofluid and a decrease in the freezing time. Regardless the kind of nano-particles, the freezing time decreased by 11.36% for water and 6.91% for cyclohexane when adding 10% of nano-particles. Reference [12] studied the enhancement of thermal conductivity for the paraffin wax, when adding to its four various additives that have high thermal conductivity. Graphite powder (GP), copper particles (CP), aluminum oxide particles (AP) and copper network (CN) represent the enhancers that used in this work. Also, this work includes choosing four various types of pure waxes to test and compare their thermophysical with each other. From the results it was found that the additive concentration of 6% by weight represents the most suitable enhancement effect. The little effect on charging/discharging processes and little enhancement in thermal conductivity of waxes it was observed when used the AP composite. Also, it was found that when the mass fraction of CN additives increment from 3%, 6% and 9% by weight this led to increase the thermal conductivity of Grade B pure wax by 105.14%, 257.47% and 274.76% respectively. Reference [13] studied experimentally the enhancement of thermal conductivity of paraffin wax (PW) by adding titanium dioxide (TiO_2) nanoparticles with 20nm diameter. Thermal analysis was made in different temperatures and mass fractions. From the results, it was found that the thermal conductivity of composite material PW/TiO_2 have higher value than that of base PW material. Also, it was noticed that the thermal conductivity depends on the mass fraction of nanoparticles and increased with increasing mass fraction in PW up to 3% after which this tendency decreases, and the thermal conductivity decreased with increasing temperature. Reference [14] designed thermal energy storage system to investigate experimentally the thermal performance of NEPCM inside the spherical capsules that packed in cylindrical tube. Paraffin wax with melting temperature range of 62-68 °C used as PCM and air used as HTF. TiO2 nanoparticles with size of 10nm were added to the PCM with different mass concentrations (1wt%, 3wt%, and 5wt %). From the experimental results it was found that the thermal conductivity of composite PCM increased by a factor of 10% with increasing nanoparticles added at 5wt% mass fraction and 15°C but it reduced with increasing temperature to about 0.17%. Also, it was observed that with adding TiO2 nanoparticles, the rate of thermal storage increased to about 0.95 times with respect to PCM without nanoparticles. Also, the rate of thermal release increased to about 1.5 times correspond to the case of PCM without nanoparticles.

II. Experimental Investigation

The experimental set up used to study the thermal performance of TES system was shown in Fig.1. It consists of insulated cylindrical thermal energy storage (TES) tank of 30 cm diameter and 50 cm height, filled with spherical capsules that contain PCM. Electrical heater was used to supply heat to the HTF; a rotameter was used to measure the flow rate of HTF; refrigeration device was installed in order to cool the air. The spherical capsules that contain paraffin wax (melting point 58 of oC) were 4 cm in diameter and they were made from HDPE. PCM capsules were packed as a fixed bed with 4 layers in the cylindrical tank which was insulated with glass wool of thickness 5 cm to prevent heat losing. Four thermocouples are located in the axial direction of the cylindrical tank to record the temperature of PCM and HTF at each layer. Other thermocouples were located at the top and bottom of the storage unit to record the temperature of HTF at inlet and outlet point. A mineral tray was used between each layer of spherical capsules to provide/create uniform void spacing between capsules and layers as well. The thermo- physical properties of PCM, TiO_2, and Cu are given in Table 1, 2, & 3 respectively.

Table 1: Thermo-physical Properties of PCM

Melting Temperature °C		58
Latent heat kJ/kg		154.21
Density kg/m³		885
Specific heat kJ/m³K		2269
Thermal conductivity W/m.°C	Solid at 15 °C	0.2499
	Liquid at 60 °C	0.2397

Table 2: Thermophysical properties of TiO_2 (Nanoparticle)

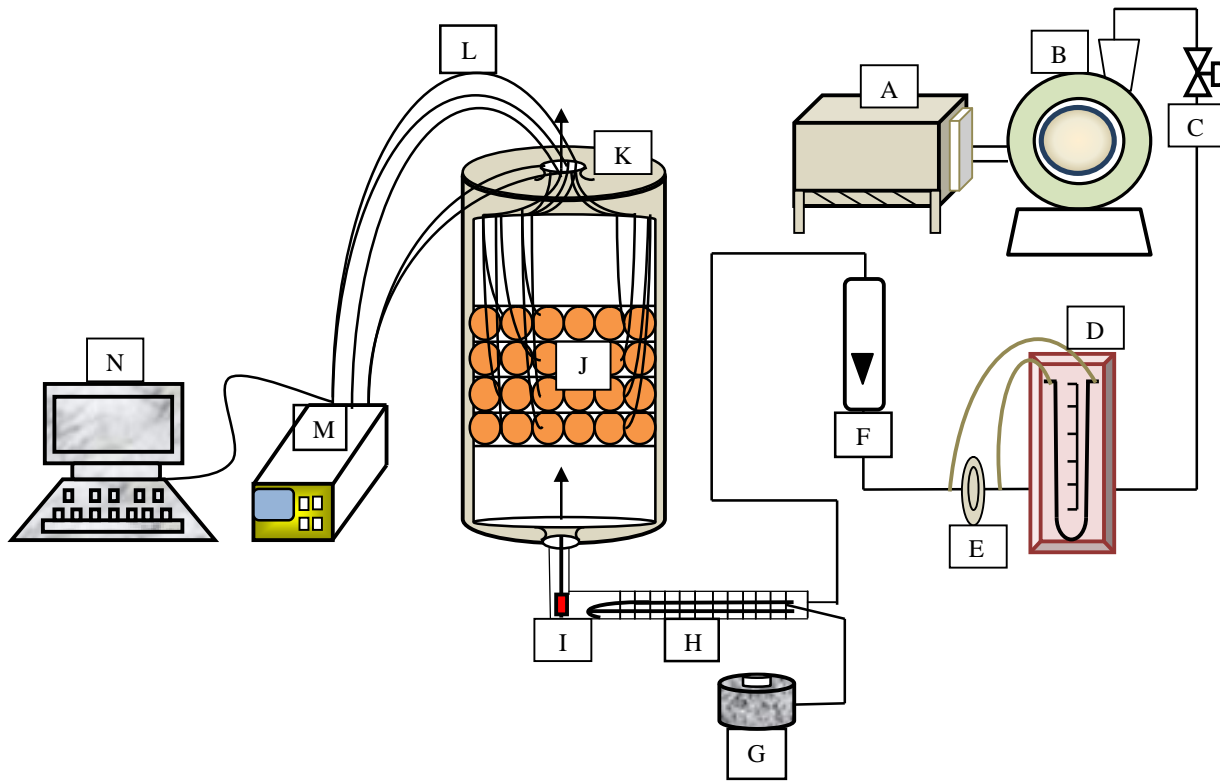| Size	40 nm
Density kg/m³	8933
Specific heat J/kg.°k	385
Thermal conductivity W/m.°C	400

Fig.1 Experimental Set up

A- Air conditioning device, B- Blower, C- Manometer, D- Orifice meter, E- Rotameter, F- electric heater, G-Rode heater, H-sensor for inlet air, I- TES tank, J- spherical capsules, K- thermocouples sensor, L- data logger, M- PC

Table 3: Thermophysical properties of Cu (Nanoparticle)

Size	30-50 nm
Density Kg/m^3	4250
Specific heat J/kg.°k	686.2
Thermal conductivity W/m.°C	8.9538

III. Results and Discussion

A. Charging and Discharging Process with PCM

Experimental work was aimed to show the temperature behavior with time for different air flow rate and inlet temperature; that is the temperature history inside the beds packed with PCM capsules. The effect of air flow rate on thermal storage and charging and discharging time was also investigated. On the other hand, because that the hysteresis is an important phenomenon which lead to a loss of energy, the hysteresis in the beds packed with PCM was also evaluated. Four capsules of PCM were selected along the axial direction in the packed each in one of the four layers of the test section inside the bed to measure the PCM axial temperatures along with the corresponding HTF temperatures. The variation in temperatures with time at both melting and solidification processes were measured and

shown in Figs. 2 to 5. In the case of pure PCM, it is noted that the PCM in the first layer (at the bottom of TES tank) melt and solidified faster than the PCMs in the region far away (toward upper sections). This is because of the high temperature difference (driving force) between the PCM and HTF temperatures. At the start of charging process, the temperature of PCM increases gradually and the rising of temperature decreased at around 56-57 °C, which is due to the energy absorbed as latent heat which is used to change the phase from the solid to the liquid. After this period, the temperature of PCM increased rapidly due to rapid heating the liquid of PCM as shown in Fig.2. On the other hand, it was noticed that the temperature of HTF at all the layers increased rapidly rather than PCM. This is due to that more quantity of heat is absorbed by the air than the amount of heat it gives to the PCM which can be attributed to the higher solid PCM thermal resistance for heat flow. It can be observed in the fourth layer (CH4) of the bed that when the flow rate was increased, the time needed to reach melting point of the PCM decreased. The time needed to reach 65°C decreased by 5%, 8.97% and 14% for the volumetric flow rates of 14, 19 and 24 L/s respectively as shown in Figs. 2 to 5. This is because the increase in the heat transfer coefficient with the increase of air velocity which led to higher rate of heat transfer.
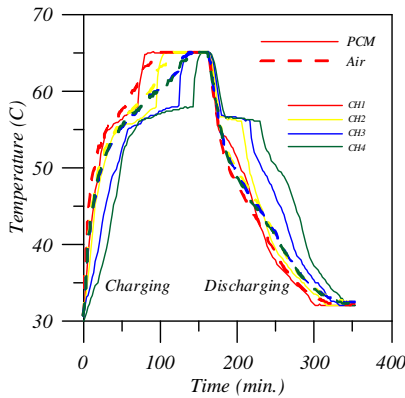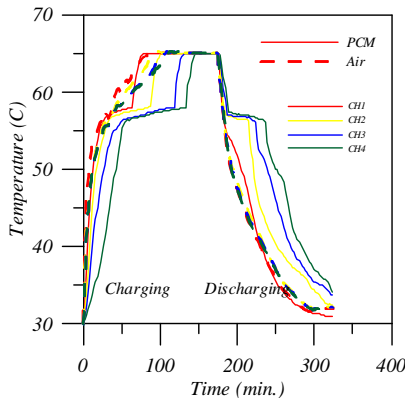

Fig.3 Charging and Discharging of PCM with T65& Flow Rate = 14 L/s

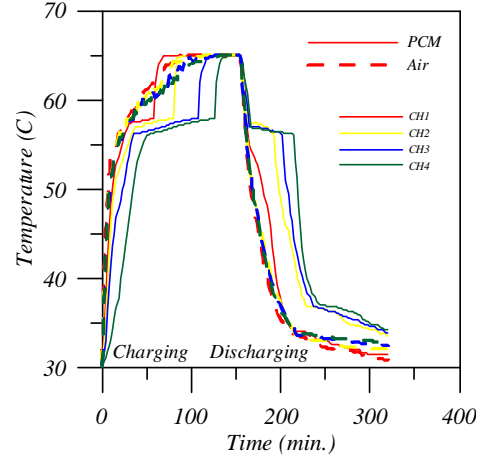Fig.4 Charging and Discharging of PCM with T65& Flow Rate = 19L/s

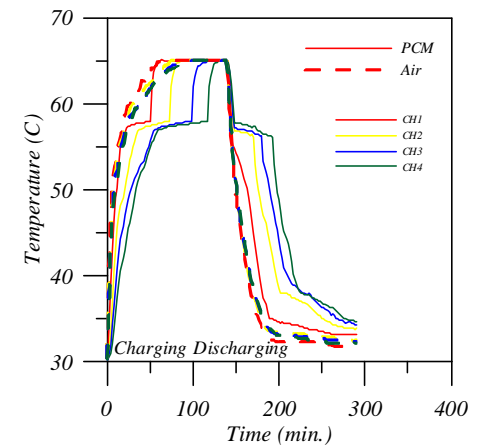Fig.5 Charging and Discharging of PCM with T65& Flow Rate = 24 L/s

Fig.2 charging and discharging of PCM with T65& flow rate = 9 L/s

In the discharging side, it was noticed that there are three stages; cooling the liquid PCM, phase change, and solid sub-cooling. The temperature decreased rapidly, as a result of the high temperature difference between the PCM and HTF until reaching the range 57-56°C at which the temperature approximately constant with the time. After the phase change, the temperature decreased gradually; due to the solid cooling until reaching the temperature 35°C as shown in Figs. 2 to 5. It was found that the capsule in the first layer solidified faster than that in the other layers due to high temperature difference. The temperature of the HTF (air) decreased rapidly, due to the absence of thermal resistance to heat flow. When the volumetric flow rate was raised from 9 to 24 L/s, the discharging time required to reach 35°C decreased in all layers as in CH4 with inlet temperature of 65°C. The percent decreased in time was 5.2%, 9.1%, and 15.6% for the change of flow rate from 9 to 14, 19, and 24 L/s respectively.

B. Charging and discharging process with NEPCM

To enhance the thermal performance of PCM in TES system, nanoparticles of Cu with purity of 99.9% and TiO$_2$ with purity of 99.8% were used as additives melted paraffin wax. The solution was mixed by ultrasonic mixer to avoid the formation of agglomeration. The resulted nanofluid was used to fill small spherical containers that were used to pack the TES system. The present study aimed to investigate the effect of two varying the nanoparticles concentrations (1, and 3 wt %) with HTF inlet temperature 65°C and different flow rate 14 L/s) in charging and discharging conditions as shown in fighres 6 to 9.

Generally, the addition of Cu nanoparticles to the pure PCM enhances the heat transfer processes, by reducing the time needed to completely melting and solidifying of the PCM. This is because that the heat transfer rate between the HTF and the NEPCM is higher than that in the case of pure PCM. On the other hand, it was found generally that the use of copper NEPCM had more effect in reducing time of complete melting and solidification than that when using TiO$_2$ nanoparticles.

Considering the long term operation for the LHTES system, the mass fraction of 3% additives by weight is suggested as the most suitable concentration used to mix with the wax to form the composite PCM for two reasons. Firstly, it reduces the deposition of the additives (powder) after long time and frequent melting/solidification cycles. Secondly, it was found that the increase to 5% additives by weight shows no or a little reduction in the time for melting and solidification processes than that of 3% additives. This is due to the fact that the heat transfer rate doesn't increase linearly with increasing nanoparticles concentration. Also the NEPCM nanofluid with 5% concentration became dense and showed strong instability, which causes sedimentation to occur. This is in agreement with [15].
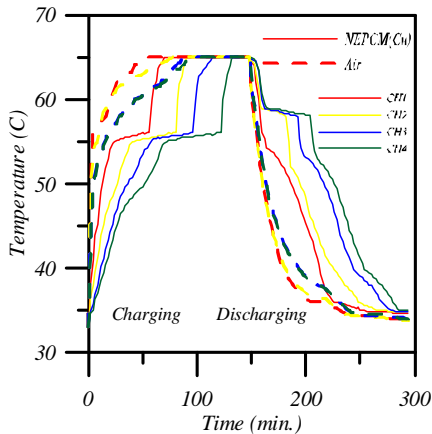
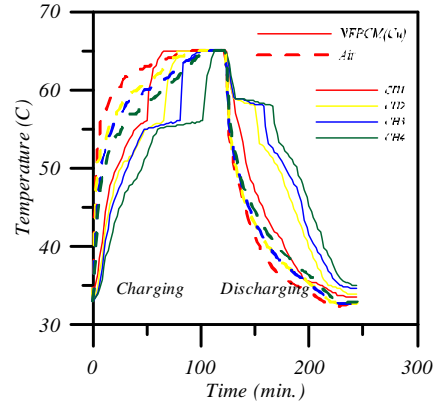Fig.6 Charging and Discharging of NEPCM (1% wt. Cu) with Flow Rate = 14 L/s

Fig.7 Charging and Discharging of NEPCM (3% Cu, Flow Rate =14L/s)

Titanium dioxide nanoparticles were also used as additives to the paraffin wax PCM. The thermal performance of NEPCM with TiO$_2$ for complete melting and solidification processes with 1% and 3% by weight concentration and flow rates of 14 L/s was investigated.
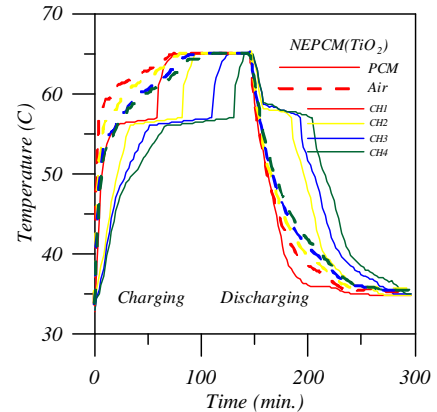

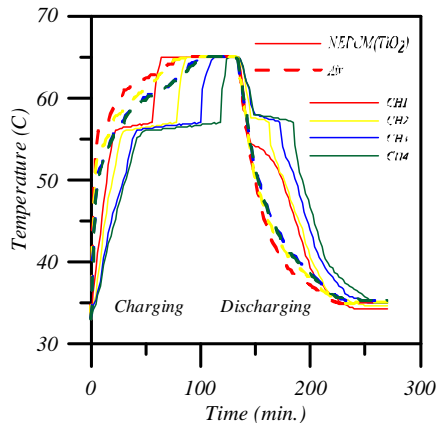Fig.8 Charging and Discharging of NEPCM (1% TiO$_2$, Flow Rate =14L/s)

Fig.9 Charging and Discharging of NEPCM (3% TiO_2, Flow Rate =14L/s)

Therefore, for CH4 at 1% and 3% TiO_2 concentration with flow 14L/s, the time needed for charging was decreased by 5.4% & 14.86 % less, respectively when compared to pure PCM.

At the discharging side, at flow rate 14L/s, the time required at CH4 was decreased by 6.7% &16% less with respect to pure PCM.

C. Hysteresis in Packed bed with PCM

Hysteresis can be defined as phenomenon in which the melting and solidification of PCM occur in various range of temperatures. The kinetic and chemical properties of material also the flow rate of HTF have great effect on this phenomenon. As well, the phenomenon of hysteresis in TES applications is defined as the delay in PCM solidification [1]. For complete process of PCM melting and solidification at low flow rate (9 L/s) took more time to complete process than other flow rates. The hysteresis area between two curves (charging & discharging) appears as the smallest as shown in Figs. 10 and 11. The temperature hysteresis increases with increasing the HTF flow rate as shown in Fig. 11. It can be seen that whenthe flow rate was increased from 9 to 24 L/s at HTF inlet temperatures 65°C, the temperature hysteresis increased rapidly by 19%, This is because that the time required for charging and discharging processes decreases with increasing flow rate and temperature
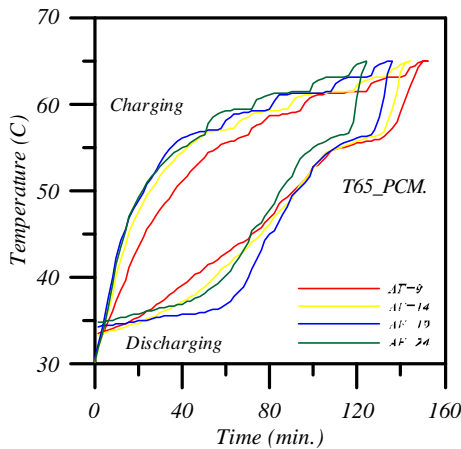

Fig.10 Thermal hysteresis cycles in thermal storage system packed with PCM for different air flow rates
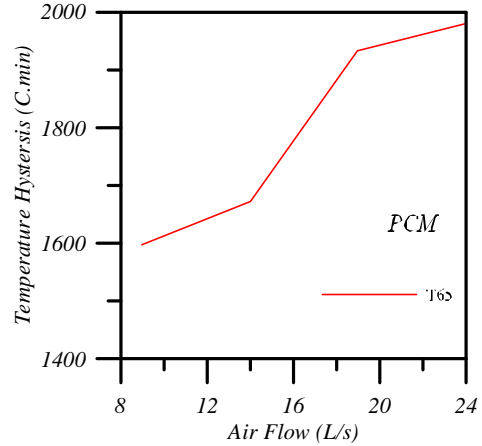

Fig.11 Temperature hysteresis of PCM with air flow rate

D. Hysteresis in Packed bed with NEPCM

A material with thermal hysteresis will exhibit a melting temperature that is different from the solidification temperature. The phase change material is one of these materials who suffered from hysteresis. The present study focused on how to model this hysteresis rather than to concern with the exact physical mechanisms by which thermal hysteresis happens. Figs. 12 and 13show the thermal hysteresis as a function to airflow rate for 1%Cu and 3% Cu and figs. 14 and 15 for 1%TiO_2 and 3% TiO_2 nanoparticles respectively. It is clear that the area between the charging and discharging curves which represents the hysteresis cycle is proportional to the increase in air flow rate and inversely proportional to the increase in nanoparticles concentration for composite PCM. The hysteresis cycle areas were calculated by integration using a computer program. The calculated area was plotted against air flow rate for different nanoparticle concentrations as shown in Fig. 16 for Cu and Fig. 17 for TiO_2 nanoparticles. It is clear that the air flow rate and nanoparticles concentration have significant effect on the thermal hysteresis. The increase of thermal hysteresis cycle area with air flow rate can be attributed to the increase in heat transfer rate which mean an increase in the rate of heat gain and release. On the other hand, thermal hysteresis was inversely proportional to the nanoparticles concentration; which can be referred to the thermophysical properties of nanofluid formed by the addition of nanparticles such as density and thermal conductivity.
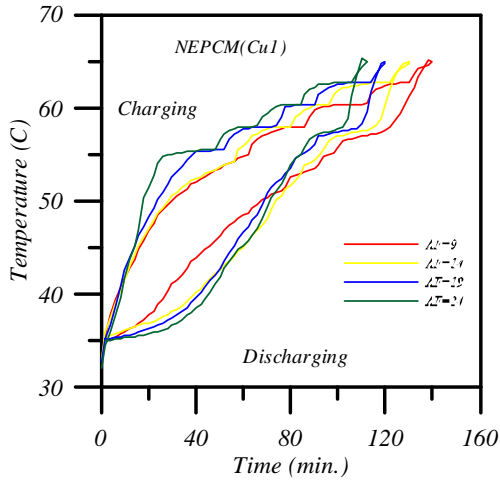
Fig.12 Thermal hysteresis cycles in thermal storage system packed with 1% Cu NEPCM for different air flow rates
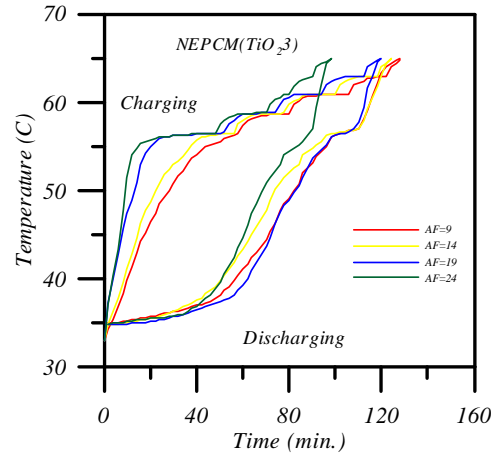

Fig.13 Thermal hysteresis cycles in thermal storage system packed with 3% Cu NEPCM for different air flow rates

Fig.14 Thermal hysteresis cycles in thermal storage system packed with 1% TiO$_2$ NEPCM for different air flow rates

Fig.15 Thermal hysteresis cycles in thermal storage system packed with 3% TiO$_2$ NEPCM for different air flow rates
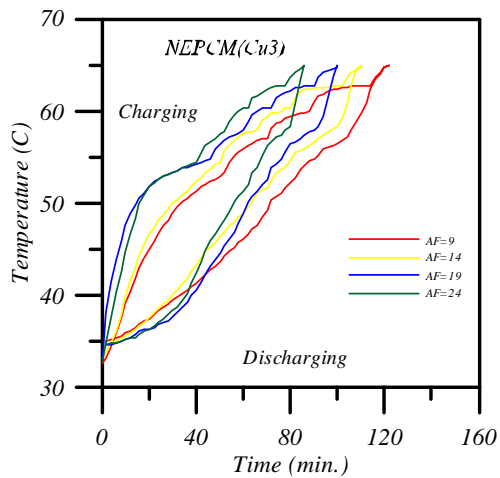

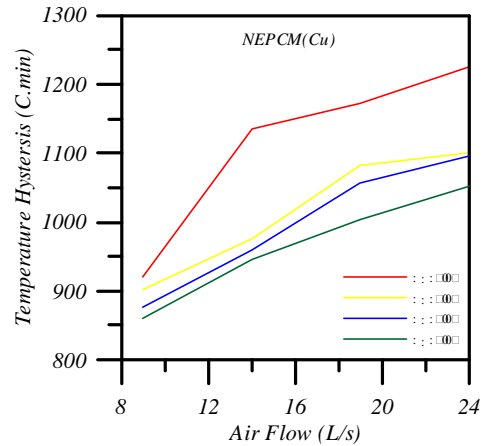Fig.16 Thermal hysteresis area vs. air flow rate for different concentrations of Cu nanoparticles in the NEPCM packed beds
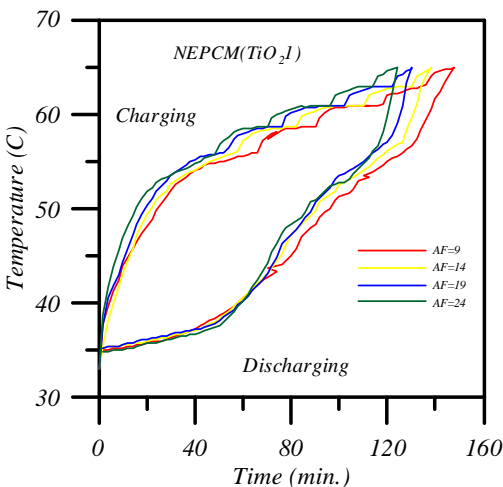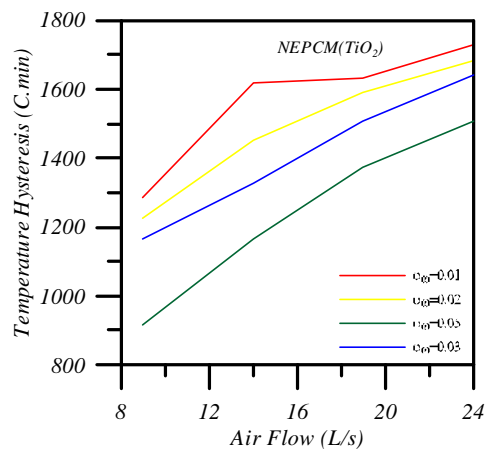

Fig.17 Thermal hysteresis area vs. air flow rate for different concentrations of TiO$_2$ nanoparticles in the NEPCM packed beds

IV. Conclusions

Thermal energy storage system was studied with storage sensible and latent heat in PCM with the air used as working fluid. It is concluded that the volumetric flow rate has significant effect on the heat extraction rate from the air and heat recovered to the air which in turn affects the rate of charging and discharging of the TES tank.

Initially, Tp was increased rapidly until reaching the phase change temperature at which it approximately remained constant until the phase change finished and then increased until reaching the inlet HTF temperature.

In discharging, Tp initially decreased rapidly until it reached the phase change region at which Tp remained approximately constant and then it continuously decreased until it reached 35°C.

Charging and discharging time decreased with increase volumetric flow rate Q from (9 to 24) lit/s by 27.9% and 57.14% respectively. Therefore, the high rate and efficient process of charging and discharging can achieve with high flow rate of HTF. Compared to the results of pure PCM, the thermal response of all composite PCM is enhanced by embedding additives into it. It has been found that the selection of 3% additives by weight has been found to provide the most suitable enhancement effect.

The developed Cu + PCM composite, that using combined sensible and latent heats storage concept is found to produce the best thermal response due to its good homogeneity with wax and its high conductivity.

The NEPCM with TiO_2 is found to exert well effect on melting/solidification processes but smaller than the NEPCM with Cu nanoparticles

Thermal analysis indicates that the charge and discharge rates of LHTES are greatly enhanced using composite. It's found that for paraffin wax/Cu composite with 3% additives, the charging and discharging times decreased by 33% and 35% respectively than that of pure wax.

The temperature hysteresis increase with increasing flow rate, and decreased with increasing HTF inlet temperature and increasing nanoparticles concentration in composite PCM.

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