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Experimental Investigation of a packed bed Latent heat thermal energy storage system with Nanofluids as Heat transfer fluid (HTF) for Solar heating applications

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Abstract- Solar energy is one of the non-polluting, inexhaustible and clean form of renewable energy sources, which serves to be the solution for the present day "Energy crisis" and for reducing use of fossil fuels for cleaner environment. Thermal energy storage is an excellent energy strategy to manage the intermittent nature and diurnal changes in intensity of solar radiation. A TES unit is designed, constructed and integrated with solar flat plate collector. The TES unit contains paraffin as phase change material (PCM) filled in spherical capsules which are packed in an insulated cylindrical storage tank. In this paper, enhancing the thermal conductivity of water by using two high conductivity materials was studied. Alumina (Al2O3) and TiO2 nano-particles added in a volume fraction of 0.2, and 0.5% with water and tested in the recent study. The water and nano-fluids as heat transfer fluid (HTF) to transfer heat from the solar collector to the storage tank also acts as sensible heat storage material. Charging experiments were carried out at varying inlet fluid temperatures to study the effects of HTF flow rate and nano-particle volume concentrations on the storage unit performance. Discharging experiments were carried out by batch wise process to recover hot water for domestic applications.
Keywords – Thermal energy storage system (TESS), Phase change material (PCM), Paraffin wax, Solar flat plate collector, Heat transfer fluid (HTF), Nanoparticles, Nanofluid, Charging, Discharging

I. INTRODUCTION

Renewable energy supplies are steadily gaining importance in all the countries. In particular, solar energy, being non-polluting, clean, and inexhaustible, has received wide attention among scientists and engineers. Though there are many advantages, an important factor is that solar energy is a time dependent energy source with an intermittent character. Hence, some form of thermal energy storage (TES) is necessary for the most effective utilization of this energy source. A lot of researchers conducted analytical, numerical, and experimental investigation of the thermal performance of SHS systems in the past. Beasley and Clark [1] provided an excellent review of such efforts in the case of packed bed SHS systems. Dincer et al. [2] presented a detailed investigation of the availability of SHS techniques for solar thermal applications, selection criteria for SHS systems, the economics, and environmental impacts of SHS systems. Thermal performances of solar water heating systems integrated with the SHS system were investigated experimentally by many researchers, viz, Pereira et al. [3]. Nallusamy et al.[4] made a case study of PCM based packed bed storage system integrated in a building air conditioning system installed in Tidel Park, Chennai. The modes of operation, advantages of such a system for energy management, and suitability of this concept for other applications were highlighted in their paper. Cho et al. [5] investigated the thermal characteristics of paraffin in a spherical capsule during freezing and melting process. Experiments were performed with paraffin. The study has shown that the heat transfer coefficients increase with increase in inlet temperature and the Reynolds number of heat transfer fluid (HTF) flow. However, they were less affected during freezing process due to free convection effect. Nallusamy et al. [6], Mehling et al. [7] studied effective utilization of solar energy for water heating applications using combined sensible heat and latent heat storage system. Results show that adding PCM modules at the top of the water tank would give the system higher storage density and compensate heat loss in the top layer. R.M. Reddy et al.[8] developed a TES system for the use of hot water for domestic applications using combined sensible and latent heat storage concept. The present study concentrates on the development of dispersion techniques of CNT Alumina hybrid nanofluid in aqueous. Therefore, the main objective focused to determine a more acceptable way to increase dispersion characteristic of hybrid nanofluid without any surfactant. They have studied the dispersion and stabilization of as-prepared CNT/Alumina hybrid nanofluid in aqueous [9]. Nanofluids have been studied for the last decade with the huge potential to enhance the efficiency of the heat transfer characteristics [10-12]. Hong et al. [13] studied about TiO2, Al2O3 and Tungsten oxide (WO3) nanoparticles dispersed in water and ethylene glycol and reported high increase in thermal conductivity compared to base fluids. They suggested primary factor in determining the thermal conductivity of nanofluids was the high surface to volume ratio of nanoparticle. Murshed et al. [14] conducted both experimental and theoretical study on thermal conductivity and viscosity of nanofluids. They reported strong dependence of temperature on thermal conductivity and viscosity increase and also the effect of volume fraction. They predicted thermal conductivity of nanofluids having spherical and cylindrical nanoparticles proposed to be the two static mechanisms based models, considering particle size, interfacial layer and volume fraction. The results show good agreement with experimental data. Mahbubu et al. [15] analysed the effect of sonication time on properties of 0.5 vol. % of Al2O3–water nanofluid dispersion. They sonicated the nanofluid for different periods from 0 h to 5 h with help of horn type sonicator. Particle size and distribution analysis showed decrease in cluster size with the increase in sonication time. The increase in sonication time resulted in better particle dispersion, lower aggregate size, and higher zeta potential increase. In addition, thermo physical properties showed thermal conductivity increase with the rise of temperature and sonication time. Goudarzi et al. [16] investigated the CuO-H2O and Al2O3–H2O nanofluids connected to cylindrical solar collector with helical tube. They analysed the effect of pH on nanofluids. The results implied that thermal efficiency enhancement of the solar collector is achieved by higher differences between the pH and iso-electric point produce. Al2O3 aqueous nanofluids were proved for their enhanced thermal conductivity, enabling them in several thermal applications [17]. Likewise, the critical thermal properties of TiO2 nanoparticles- chemical compatibility & physical interaction- enabled such heat transfer fluids in harvesting solar energy for domestic applications [18]. Materials such as solid particles, sand, alumina, find their applicability in sensible heat storage - PCMs, - their applicability in latent heat storage. Energy storage transpires in PCM when it undergoes solid-liquid transformation. Here, not only the choice of PCM's is crucial-Phisico-chemical thermal properties, but also their selection was found to be influenced by the context of application [19]. A detailed investigation has done a on heat transfer attributes of nano fluids involving numerical and experimental studies. Likewise, they covered the effects of various critical parameters such as heat transfer performance, thermo physical properties and applications [20].

II. EXPERIMENTAL INVESTIGATION

2.1 Experimental Setup

A schematic diagram of the experimental setup is shown in Figure1.It consists of an insulated cylindrical TES tank, which contains PCM encapsulated spherical capsules, solar flat plate collector, control valve, flow meter, and circulating pump. Figure 2 shows the photographic view of the experimental setup. The stainless steel TES tank has a capacity of 57 liters (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 spherical 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 wax is used as the PCM, which has a melting temperature of 61°C and the latent heat of fusion of 213 kJ/kg. The TES tank is connected with an active solar flat plate collector with an area of 2 m2, and the PCM capsules in the TES tank are surrounded by water. Water and nanofluids are used, both as SHS material and HTF.

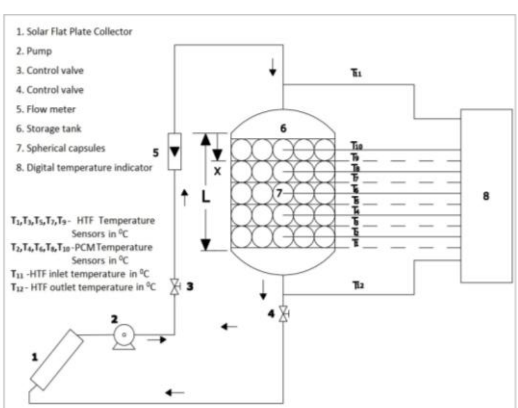

Figure 1.Schematic diagram of experimental setup

Figure 2.Photographic view of experimental setup

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2.2 Preparation of nano-fluids

The nano-particles in the form of dry powder dispersed into a base fluid (water) and mixed with the help of ultrasonic probe sonicator. The sonication time is an important parameter for dispersing the aggregated nano-particles. Therefore, based on works of literature the time of sonication was selected as 30 min. The mixture is continuously sonicated for 30 min using an ultrasonic bath to ensure the proper dispersion of the nanoparticles in water. Nano-particles added to water for different volume concentrations as 0.2% and 0.5% .Table 1 indicates the properties of nanoparticles purchased from the supplier. The SEM images of the nano-particles at different magnification are shown in Fig. 4 to 7.

Table 1. Properties of Nano-Particles

S.No.	Property	Nano-particles	
		Al2O3	TiO2
1	Density	3970 kg/m3	4000 kg/m3
2	Thermal conductivity	30 W/m K	11.8 W/m K
3	Specific heat	0.955 kJ/kg K	0.697 kJ/kg K
4	Avg Particle size	30 to 50 nm	30 to 50 nm

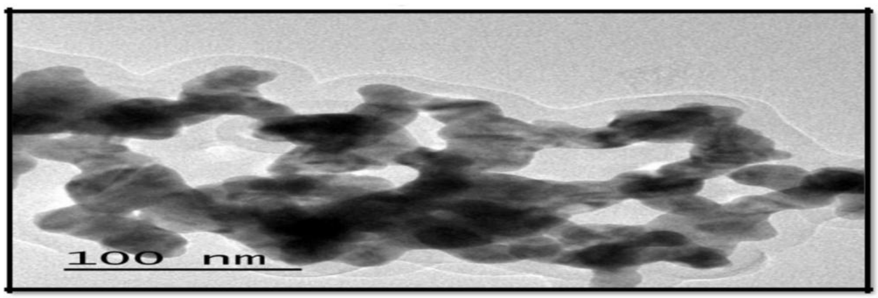

Figure 3. Crystal orientation of Al2O3 nanoparticles in SEM analysis

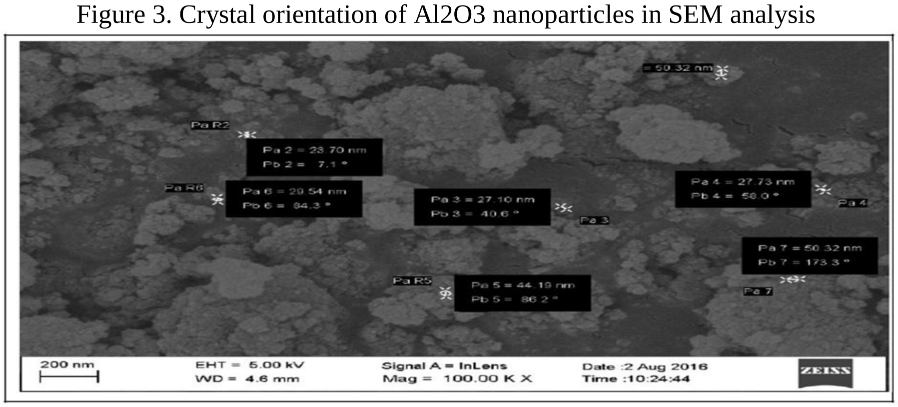

Figure 4. Crystal structure of TiO2 in SEM analysis

2.3 Experimental Procedure

2.3.1 Charging Process

During the charging experiments, the HTF inlet temperature varies in accordance with the solar radiation, and it is circulated through the TES tank continuously. The HTF exchanges its energy to PCM capsules. In the beginning of the charging process, the temperature of the PCM inside the packed bed capsules is 35°C, which is lower than the melting temperature. Initially, the energy is stored inside the capsules as sensible heat until the PCM reaches its melting temperature. As the charging process proceeds, energy storage is achieved by melting the PCM at a constant temperature. Finally, the PCM becomes superheated. The energy is then stored as sensible heat in liquid PCM. Temperatures of the PCM and HTF at different locations of the TES tank, as shown in Figure1, are recorded at an interval of 15min. The charging process is continued until the PCM temperature reaches the value of 70°C.The same procedure repeated for HTF as Al2O3 and TiO2 nano-fluids.

2.3.2 Discharging Process

The discharging experiments are carried out by batch-wise method. This method of discharge permits the full extraction of heat from the storage tank. A quantity (20 liters) of hot water is withdrawn from the storage tank and the same amount of cold water is filled into the storage tank. Withdrawn hot water is collected into an insulated drum and the temperature is noted and finally, after collecting all the batches the average temperature of hot water is measured. Collection of water is made at 2 and 4 lit/min. However, the inlet to the TES tank is kept constant at 2 lit/min only. An optimum retention period of 20 minutes between batches is allowed. The batches of withdrawing hot water are continued till the outlet temperature reaches 45°C.

III. RESULTS AND DISCUSSIONS

3.1 Charging Experiments

The experiments are conducted for various HTFs with different flow rates (2 and 4 lit/min) and different volume concentrations of nano-particles (0.2% and 0.5%).

3.1.1 Effect of nano-fluid

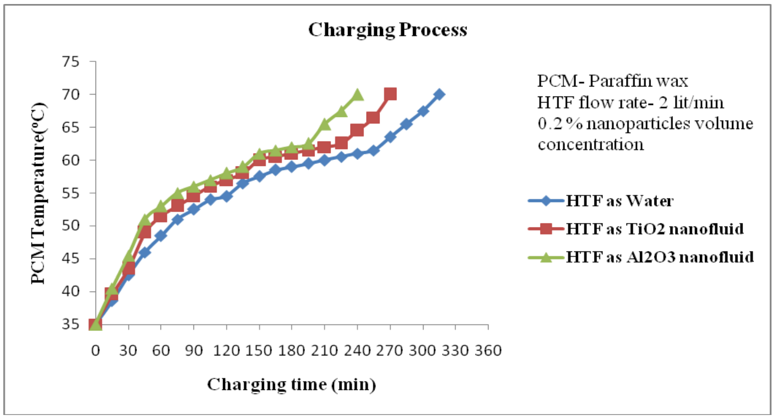

Figure 5. Variation of PCM temperature with charging time (with and without nano-fluid)

Figure 5 indicates that the temperatures of PCM gradually increases in the beginning & remains constant during the phase change period and further increases. Charging time is 315 min for HTF as pure water and 270 min for HTF as TiO2 nano-fluid, and 240 min for HTF as Al2O3 nano-fluid. The results show that there is considerable amount of reduction in charging time, in case of 2 lit/min and 0.2% volume concentration, around 14.28 % for TiO2 nano-fluid, and 23.80% for Al2O3 nano-fluid, when compared with the conventional HTF, water. From the results, it is observed that the effect of nano-fluid plays an important role in the heat transfer process.

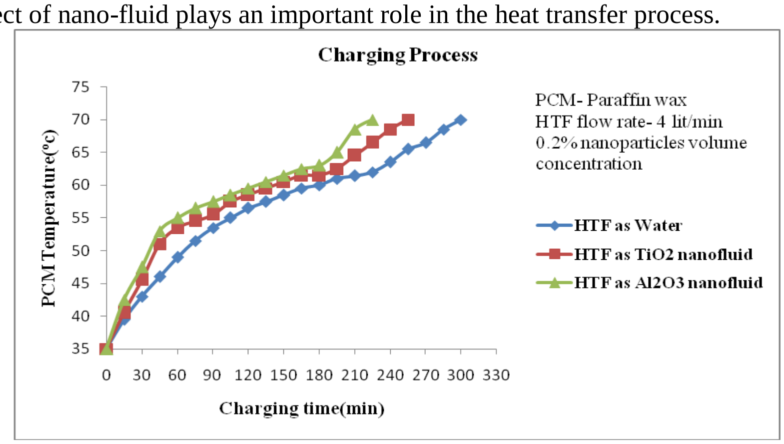

Figure 6. Variation of PCM temperature with charging time (with and without nano-fluid)

Figure 6 indicates that the temperatures of PCM gradually increases in the beginning & remains constant during the phase change period and further increases. Charging time is 315 min for HTF as pure water and 255 min for HTF as TiO2 nano-fluid, and 225 min for HTF as Al2O3 nano-fluid. The results show that there is considerable amount of reduction in charging time, in case of 4 lit/min and 0.2% volume concentration, around 19.04 % for TiO2 nano-fluid, and 28.57% for Al2O3 nano-fluid, when compared with the conventional HTF, water. From the results, it is observed that the effect of nano-fluid plays an important role in the heat transfer process.

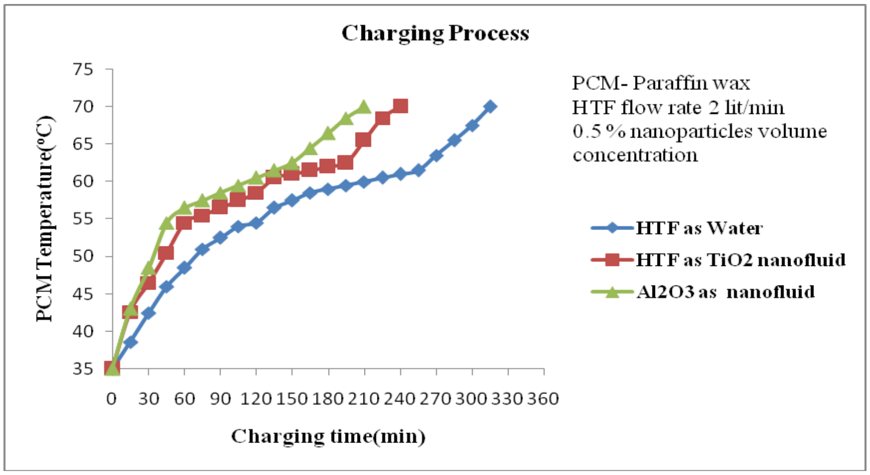

Figure 7. Variation of PCM temperature with charging time (with and without nano-fluid)

Figure 7 indicates that the temperatures of PCM gradually increases in the beginning & remains constant during the phase change period and further increases. Charging time is 315 min for HTF as pure water and 240 min for HTF as TiO2 nano-fluid, and 210 min for HTF as Al2O3 nano-fluid. The results show that there is considerable amount of reduction in charging time, in case of 2 lit/min and 0.5% volume concentration, around 23.80 % for TiO2 nano-fluid, and 33.33% for Al2O3 nano-fluid, when compared with the conventional HTF, water. From the results, it is observed that the effect of nano-fluid plays an important role in the heat transfer process.

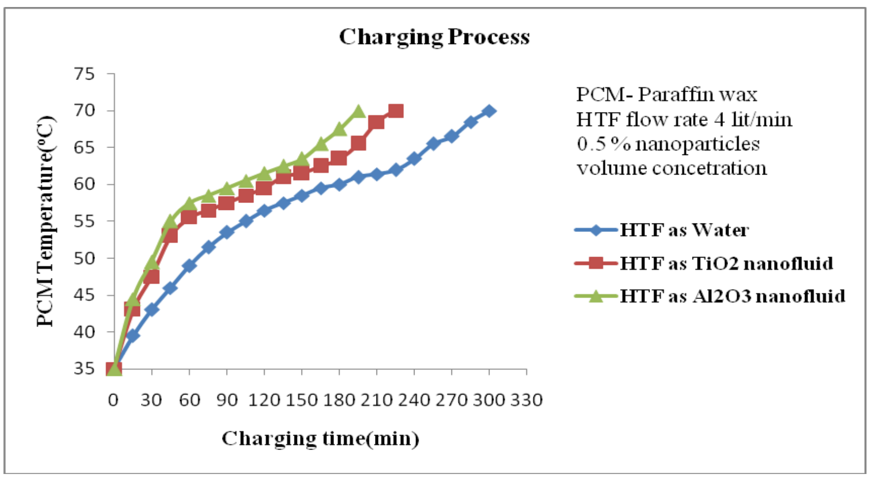

Figure 8. Variation of PCM temperature with charging time (with and without nano-fluid)

Figure 8 indicates that the temperatures of PCM gradually increases in the beginning & remains constant during the phase change period and further increases. Charging time is 315 min for HTF as pure water and 225 min for HTF used as TiO2 nano-fluid, and 195 min for HTF as Al2O3 nano-fluid. The results show that there is considerable amount of reduction in charging time, in case of 4 lit/min and 0.5% volume concentration, around 28.57 % for TiO2 nano-fluid, and 38.09% for Al2O3 nano-fluid, when compared with the conventional HTF, water. From the results, it is observed that the effect of nano-fluid plays an important role in the heat transfer process.

3.1.2 Effect of flow rate

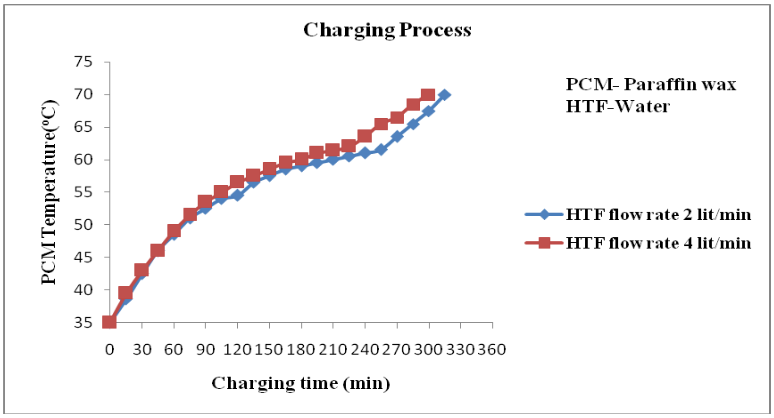

Figure 9. Variation of PCM temperature with charging time for HTF as water

Figure 9 indicates that the Charging time is 315 min for 2lit/min flow rate, 300 min for 4 lit/min flow rate with HTF as water and PCM used as paraffin wax. From the results, it is observed that the effect of HTF flow rate plays an important role in the heat transfer process.

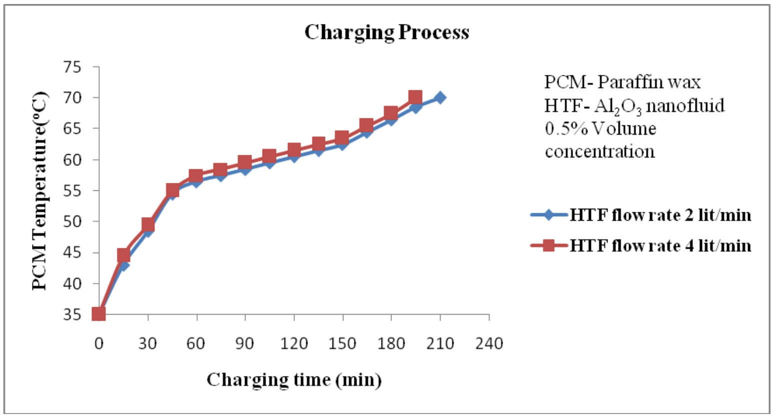

Figure 10. Variation of PCM temperature with charging time for HTF as water

Figure 10 indicates that the Charging time is 210 min for 2 lit/min flow rate, and 195 min for 4 lit/min flow rate with HTF as Al2O3 nano-fluid and PCM as paraffin wax. From the results, it is observed that the effect of nano-fluid flow rate plays an important role in the heat transfer process.

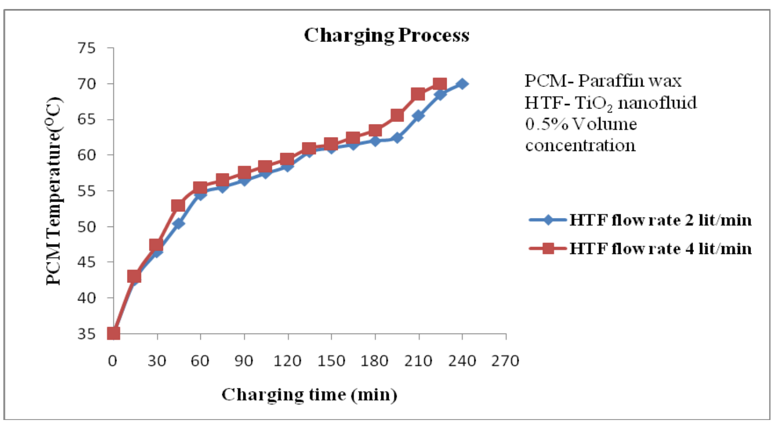

Figure 11. Variation of PCM temperature with charging time for HTF as water

Figure 11 indicates that the Charging time is 240 min for 2 lit/min flow rate, and 225 min for 4 lit/min flow rate with HTF as TiO2 nano-fluid and PCM as paraffin wax. From the results, it is observed that the effect of nano-fluid flow rate plays an important role in the heat transfer process.

3.2 Discharging Experiments

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

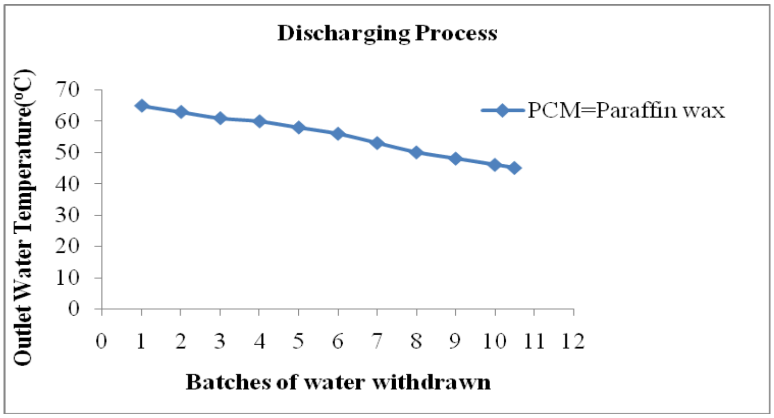

Figure 12. Batches of water withdrawn vs Outlet water temperature

Figure 12 indicates that the amount of hot water withdrawn is 210 liters with paraffin wax as PCM.

IV. CONCLUSIONS

In this work, experimental investigations were conducted on selected two nanofluids to study their effects on the melting time of PCM under different percentages of volumetric concentrations of nano-particles and HTF flow rates.
The results show that there is considerable amount of reduction in charging time, in case of 2 lit/min flow rate, 0.2% volume concentration and Paraffin is used as the PCM, around 14.28 % for TiO2 nano-fluid, 23.80% for Al2O3 nano-fluid, when compared with the conventional HTF, water. From the results, it is observed that the effect of nano-fluid plays an important role in the heat transfer process.
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Due to low density, high thermal conductivity, and Brownian motion, agglomeration, micro convection of Al2O3 have played a remarkable role in decreasing melting time.
Because of the foregoing, the inference is that Al2O3 nanofluid has a remarkable break-through for domestic thermal energy storage applications.
During the discharging process, 210 liters of hot water withdrawn with paraffin wax is used as the PCM.

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