Experimental Evaluation of Nano-Enhanced Phase Change Materials in a Finned Storage Unit

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Abstract—**The intermittent nature of renewable energy sources such as solar and wind necessitates integration with energy-storage units to enable realistic applications. In this study, thermal performance enhancement of the finned Cylindrical Thermal Energy Storage (C-TES) with nano-enhanced Phase Change Material (PCM) integrated with the water heating system under Storage, Charging and Discharging (SCD) conditions were investigated experimentally. The effects of the addition of copper oxide (CuO) and aluminum oxide (Al_2O_3) nanoparticles in PCM on thermal conductivity, specific heat, and on charging and discharging performance rates were theoretically and experimentally investigated and studied in detail. The experimental apparatus utilized paraffin wax as PCM, which was filled in Finned C-TES to conduct the experiments. The experimental results showed a positive improvement compared with the non-nano additive PCM. The significance and originality of this project lies within the evaluation and identification of preferable metal-oxides with higher potential for improving thermal performance.**

Keywords-phase change material; thermal energy storage; latent heat; energy efficiency

I. INTRODUCTION

The ongoing increase in world population and industrial infrastructures is accompanied by major energy consumption. On the other hand, the decreasing sources of conventional fossil fuels and the environmental issues linked with their use have created a series of issues and concerns such as energy security and global climate change. To overcome these issues, exploitation of renewable energies (e.g. solar energy, geothermal energy, wind energy, etc.) has been significantly considered by energy suppliers. However, due to the fluctuations and inability to control the renewable energy sources, it is more efficient for these systems to be used with energy storage systems. The finned Cylindrical Thermal Storage Unit (C-TES) with phase change materials (PCMs) has been found to be a very efficient energy storage application for this purpose. However, the low thermal conductivity of PCMs used makes them unable to give the desired response for storage and recovery. Various techniques like the application of fins, metal foams, etc. have been explored to solve the problem and focus has been mainly given on energy storage and recovery separately, but in real life the systems operate mostly through simultaneous storage and recovery or Charging and Discharging (SCD).

PCMs are materials that undertake a liquid-solid phase transformation (known as the fusion-solidification period) at a temperature within the limits of a chosen thermal application. The latent heat absorbed during the melting process is indicative of the latent heat of fusion. This is distinguished from the other type of latent heat – vaporization – which is characterized by a change in phase from a liquid to a gas. The heat of the material acts to raise the energy of the constituent molecules, and as a result their vibrational state increase. At melting temperature, the atomic bonds loosen and the material changes from solid to liquid. The inverse of this process is solidification, during which the material transmits energy to the area around it. Latent heat storage is accomplished by changing a material's physical state whereas sensible heat storage is accomplished by increasing a material's temperature. Materials that act as latent heat stores are termed as phase change materials. Significantly less energy is required to change a material's temperature than is required to change a material's physical state, consequently latent heat storage can offer higher storage capacities and hence space savings over sensible heat storage.

Due to the effective use of PCMs in improving Latent Heat Thermal Energy Storage (LHTES) systems, more impetus has been provided by researchers to develop LHTES systems with PCMs. Utilizing PCMs in LHTES systems has provided the advantages of high energy density and an almost constant

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Corresponding author: Nidhal Ben Khedher operating temperature. In these systems, thermal energy is stored during the melting process and released during the solidification process. A wide range of PCMs with various melting temperatures including paraffin waxes, organic and non-organic compounds, and hydrated salts are available for use in LHTES systems. To select a proper PCM, different parameters including phase change temperature, stability, amount of latent heat, and thermal conductivity should be considered

II. LITERATURE REVIEW

The energy density of the storage medium may be greatly enhanced if a material that undergoes a phase transition from solid to liquid is employed. The storage media used by these systems are the PCMs which offer advantages such as much greater heat storage per unit volume. Thermal energy storage using the latent heat of PCSm has received considerable attention in the past 3 decades. There have been many research efforts devoted to developing such novel materials for a variety of applications, such as buildings, textiles, and space heating. PCMs are promising thermal storage materials for storing and discharging bulk amounts of latent heat throughout phase change process [1-4] with regulated time intervals associated as per energy demand. Though, the criteria for the choice of a PCM for a specific application is its melting temperature, but other properties such as the latent heat of fusion, thermal conductivity, thermal stability, density, and lower volume change, also play significant role and therefore are essential to be considered [5, 6]. Authors in [7] presented a detailed numerical investigation of a heat storage system's inclination effect on the PCM melting process in order to comprehend the natural convection mechanism inside a shell and tube Thermal Energy Storage (TES) unit. Several unit positions were examined to interpret physically the thermal demeanor of the fusion process in terms of heat transfer modes estimation, PCM melting rate, and axial and radial temperatures distribution. The results showed that the TES unit inclination according to the range angle (0°-90°) makes an imbalance of the natural convection in the PCM liquid fraction which contributes in creating an instability and diminution of heat transfer during the melting process. As the increase of the heat transfer inside the PCM space could augment the efficiency of the storage unit, the method of including extended surfaces (fins) is used to ameliorate the heat transfer interchange inside the PCM. This method was experimented in a horizontal shell and tube TES unit [8] through testing the unit thermal performance in standard configuration, then in annular space embedded by circular and longitudinal fins. The test outcome elucidated a positive response of the natural convection activity in the longitudinal fins case, which made the melting process faster due to the swiftness of the heat transfer diffusion along the fins. The integration of a combined sensible and LHTES with a solar water heating system in [9] presented a detailed review on thermal energy storage using PCM focusing on three aspects: materials, heat transfers, and applications. Authors in [10] developed a computer model based on the two-phase Schumann model for the estimation of temperature profiles of the solid and the fluid along the length of the packed bed of eutectic Al–Si PCM encapsulated spherical capsules as functions of distance along the bed and time during a series of heat storage and utilization cycles[10].

III. METHODOLOGY

A. Experimental Setup

A schematic diagram of the experimental setup and its physical model are shown in Figures 1 and 2 respectively. The setup consists of a water tank (1), the finned storage unit which goes inside the water tank, which is insulated from all sides except one for visualization, 2 electrical heaters, an 8-channel DAQ (Data Acquisition) System (2) connected to a computer (3) for data capture and processing, and thermocouples (4) connected to the DAQ system.

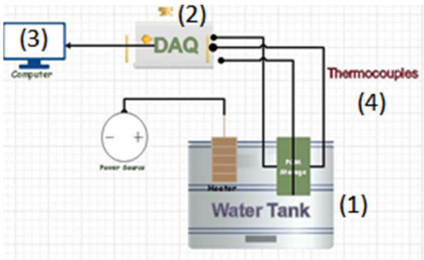

Fig. 1. Schematic diagram of the setup used in the experiment

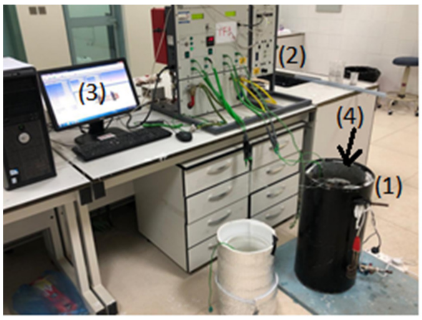

Fig. 2. The actual setup used in the experiment

Fig. 3. The physical model used in the experimental setup

Thermal conductivity was tested using KD2 Pro Thermal Property Analyzer, Hotplate Stirrer, Thermostatic Bath, Heated Ultrasonic Cleaner, and a computer for data recording and analysis.

B. Materials

PCMs have high energy density that sets them at the forefront of energy storage materials. However, their power density is low due to their low thermal conductivity, which results in a decrease in the rate of heat transfer [11]. To solve this issue, the effect of performance increase of the system and latent heat stored will be investigated by adding nanoparticles to the PCM storage unit. Paraffin wax (A51H) was chosen as a base PCM due to its average melting temperature range between 58°C-58.5°C. It provides dependable cycling, is non-corrosive and chemically inert when compared to non-paraffin organics, hydrated salts, and metallic PCMs [12]. Aluminum oxide (Al_2O_3) and copper monoxide (CuO) nanoparticles were chosen to be studied, having average particle size of 50nm (max 100nm). Before we begin to conduct the main experiment, we need to test the nanomaterial to make sure the thermal conductivity is within the acceptable range of the theoretical values. The experiment included filling test tubes with PCM and nanomaterials as shown in Table I.

TABLE I. MASS FRACTION [%] OF THE TESTED TUBES

Test tube number	Contents		
	PCM (%)	Nano particle type	Nano particle (%)
1	100	-	-
2	99	Al_2O_3	1
3	98	Al_2O_3	2
4	97	Al_2O_3	3
5	99	CuO	1
6	98	CuO	2
7	97	CuO	3

C. Volumetric fraction

The volume fraction which is necessary to calculate the theoretical thermal conductivity and specific heat is:

$$\Phi = \frac{\frac{m_{np}}{\rho_{np}}}{\frac{m_{np}}{\rho_{np}}+\frac{m_{pcm}}{\rho_{pcm}}} * 100 \quad (1)$$

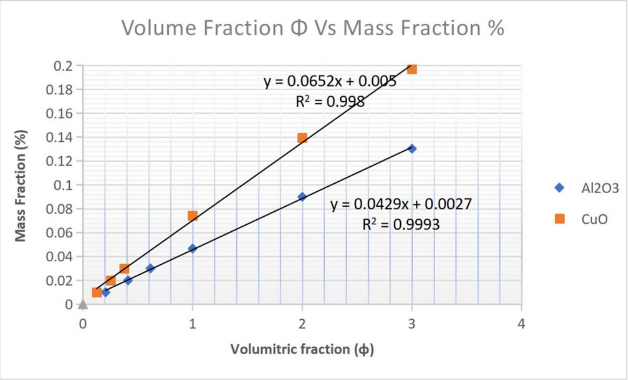

Fig. 4. Volume fraction versus mass fraction

The equation of the line for volume fraction vs mass fraction can be applied to obtain any volume fraction value using mass fraction. From that equation, we determine the graph in Figure 4. The line equation for PCM with Al_2O_3 nano-composites is:

$$y = 0.0652x + 0.005, \text{ with } R^2 \text{ of } 0.998 \quad (2)$$

The same can be said for PCM with CuO nano-composites:

$$y = 0.0429x + 0.0027, \text{ with } R^2 \text{of } 0.9993 \quad (3)$$

The line equation can be used to obtain any volume fraction value using mass fraction. The specific heat and thermal conductivity are calculated by (4) and (5) respectively:

$$c_{p.nano\ pcm} = \frac{(1-\Phi)(\rho_{pcm} * C_{p.pcm}) + \Phi(\rho_p * c_{Nano})}{(1-\Phi)\rho_{pcm} + \Phi\ \rho_p} \quad (4)$$

$$k_o = k_{pcm} \frac{k_g + 2k_{pcm} - 2\varphi(k_{pcm} - k_g)}{k_g + 2k_{pcm} - \varphi(k_{pcm} - k_g)} + \frac{\rho_{np}\varphi C_p}{2k_{pcm}} \sqrt{\frac{2B_oT}{3\pi d_{np}\mu_f}} \quad (5)$$

The thermal conductivity due to the addition of nanoparticles (k_o) was determined by the model of Maxwell, however, it was modified in [13] and (5) was obtained.

D. Procedure

The experiment consists of two parts:

1) Charging Phase

During the charging process, the PCM storage unit is initially at ambient temperature of 20°C and is injected inside the hot water tank (70°C) and it starts melting once its temperature reaches the melting temperature (58°C). The duration of the charging/discharge process is an important factor considered in the design of latent TES systems. It reveals how the storage material is effective in responding with time for the energy storage/retrieval. This phase stops when the temperature of the water tank and TES system reaches thermal equilibrium. We repeat the charging procedure for all our experiments.

2) Discharging Phase

In the discharging phase, the PCM storage unit is dropped inside a white cold-water tank (with ambient temperature of 21°C) while the data acquisition system records data. This phase stops when the temperature of the water tank and TES system reaches thermal equilibrium.

IV. RESULTS AND DISCUSSION

The performance enhancement of the TES with nano-enhanced PCM under SCD conditions was investigated experimentally. Before we start with the main experiment, the correlation between thermal conductivity and temperature was determined experimentally for both PCMs with CuO and Al_2O_3 as shown in Figures 6 and 7.

A. Specific Heat and Charging Time Improvement

The results shown in Figure 5 represent the relation between specific heat and thermal conductivity before and after adding nanoparticles to pure PCM. Figure 5 shows that the specific heat of the nano-enhanced PCM decreases due to the lower specific heat capacity (C_p) of both Al_2O_3 and CuO nanoparticles associated with an increase in thermal conductivity (K). Lower specific heat capacity ensures faster addition and release of energy which is desired in thermal storage applications. Higher thermal conductivity is also desired because it guarantees faster heat conduction from the surrounding tank.

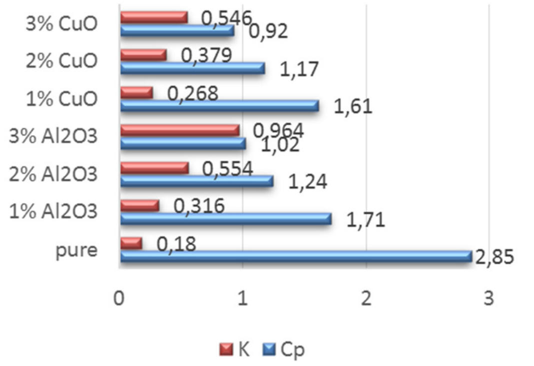

Fig. 5. The theoretical specific heat and thermal conductivity of PCM with and without nanoparticles

B. *Correlation Between Thermal Conductivity and Temperature*

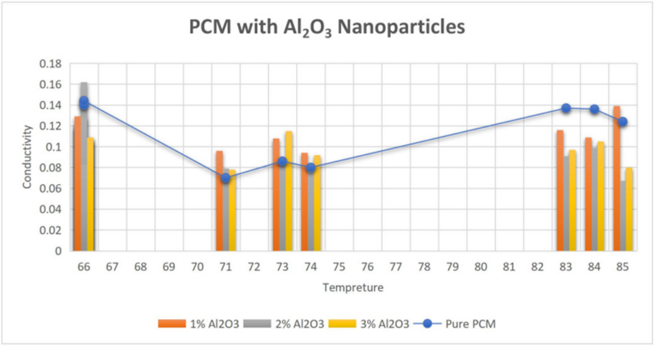

Fig. 6. Thermal conductivity of PCM with Al_2O_3

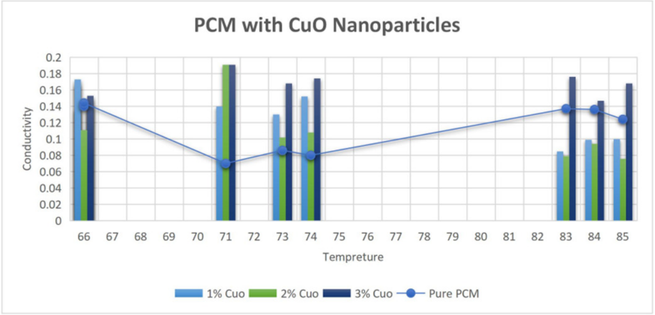

Fig. 7. Thermal conductivity of PCM with CuO

C. *Duration of the Charging/Discharging Process*

The duration of the charging/discharging process is an important factor considered in the design of latent TES systems. It reveals how the storage material is effective in responding with time for energy storage/retrieval. For the present experiment, the results are shown in Figures 7-8. These Figures show that at the beginning of the solidification period the temperature of the PCM decreased rapidly by transferring the sensible heat stored to the cooling water. During this period, the temperature of the PCM is high, and the PCM is in liquid state. This is mainly because the heat transfer inside the molten PCM is conducted by natural convection and the temperature gap between PCM storage and the cooling water is large. Then the PCM begins to freeze and discharge its latent heat. It was found that the PCM releases its sensible heat very rapidly while a longer time is needed to transfer the latent heat during the phase change. The experimental results show clearly that the charging duration was decreased with the addition of nanoparticles. The charging and discharging rates of base PCM were significantly enhanced with the inclusion of nanoparticles. The experimental results indicate that using Al_2O_3 with 3% volumetric fraction ensures a rapid charging and discharging processes compared to CuO and pure PCM. Moreover, it is clearly noticed that higher mass fractions engender short charging and discharging periods. But at the same time, the latent heat will slightly decrease. The percentage enhancement in charging rates of Al_2O_3 based nano-PCM samples with 1%, 2% were 29.4% for both cases, and 41.04% for the Al_2O_3 3% case. Likewise, the discharging rates are improved by 21.09%, 29.45% and 30.08%. However, an increase in volume concentration reduces natural convection and overall thermal enthalpy and increases the total cost of the nano-PCM.

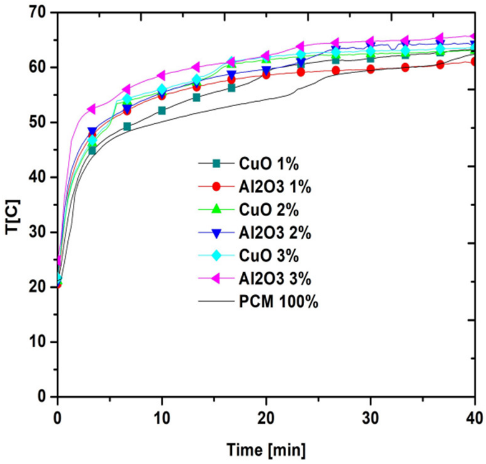

Fig. 8. Charging times for all cases

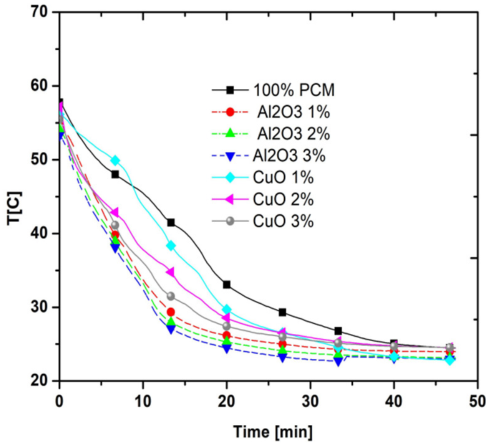

Fig. 9. Discharging times for all cases

V. CONCLUSION

This study focused on the experimental analysis of Al_2O_3 and CuO metal oxides-based nano-PCMs of different concentrations to establish an approach for selecting nano additives for optimal thermal enhancement. Charging and discharging processes, heat transfer, and energy storage characteristics of nano-PCMs in a finned tube storage system were numerically and experimentally investigated. The finned TES system is either filled with Al_2O_3 or CuO nanoparticles dispersed in A58H paraffin at different mass fractions of nanoparticles (1%, 2%, and 3%). The thermal conductivity of each nanofluid solution was measured by varying temperature from 60°C to 83°C. The obtained results demonstrate that the thermal conductivity of nanofluids increase with the increase of volume fraction. Aluminum Oxide showed the best results of charging and discharging times enhancement which are directly linked with the increase of thermal conductivity. The presented experimental investigation conclusions are:

- The addition of metal-oxide nanoparticles significantly enhances the effective thermal conductivity and surface area for heat transfer.
- In general, Al_2O_3 nanoparticles exhibit by far greater enhancement of thermal conductivity in comparison to CuO. The enhancement in charging rates of Al_2O_3 based nano-PCM with 3% was 30%.

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NOMENCLATURE

Φ = volumetric fraction (%)

m = mass (kg)

ρ = density (kg/m^3)

c_p = specific heat (J/kg K)

k_g = thermal conductivity of nano-particles (W/m.K)

B_o = Boltzmann's constant = 1.381 $*10^{-23}$ J/K

μ_f = dynamic viscosity (Pa.s)

np = nano particles

T = temperature (K)

d = particle diameter (m)

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