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Nexus approach: Valorising underrated lignocellulosic waste biomass through conjugated magnetic nanoparticles for thermal energy storage facilities

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Abstract: Converting waste to a value-added material is a fortune. At the meantime highlighting the utilization of renewable solar energy as an inconsumable energy cradle is a future prospect to overcome the energy shortage and crisis. In this regard, storing the solar energy for the use at the off-sun periods is essential. Introducing sawdust waste for thermal energy storage system is a ecological chance. Treated sawdust was mixed with the environmentally benign magnetite to be a composite and mixed with technical grade paraffin base PCM. The composite was characterized through X-ray diffractometer (XRD), Transmission electron microscopy, TEM analysis and Scanning Electron Microscope, SEM (augmented with Dispersive X-Ray Analysis, EDX). Micrographs and Fourier transform infrared (FTIR) exhibited that the prepared composite substance is well prepared. The sawdust is subjected to the PCM system in various mass % ranged from 0.5 to 4%. Subsequently, the thermal system outline is presented and compared. The experimental data revealed that the addition of 2.0 weight percentage of the PCM of composite material showed the superior system performance. The system is achieved a heat gained reached to 82 kJ/min in comparison to 7 kJ/min for the 2.0% WCM-PCM and pristine PCM, respectively. Thereby, the current investigation is introducing the waste sawdust as an energy storage enhancement system that could be applied in heating application systems.

Keywords: Thermal heating facility; Phase change materials (PCM); Energy storage; Waste sawdust; magnetite-nanoparticles.

1. Introduction

Energy crisis is one of the problems that modern societies are suffering from since the industrialization and current lifestyle. This regard is leading to a massive utilization of conventional fossil fuels [1, 2]. Thus, the role of scientists and academia is to motive a real solution for resolving such challenges and safe the environment in a sustainable energy alternative solution [3-5]. The converting to solar energy use is an appropriate opportunity, but the intermitted solar energy periods through the daytime is still an obstacle [6, 7]. In this regard, searching for an energy storage system is a research topic. Phase change materials (PCMs) are suitable candidates since they could soar thermal energy through changing their physical state and then release the stored heat in the form of latent heat [6, 8-10]. Then, the solar stored energy could be applied in various uses such as domestic building heating, hot water uses, drying purpose as well as industrial



applications. Also, recently it could be applied in thermodynamic solar plants [11]. Such process could conduct via melting/freezing cycles. Among the phase change materials, the solid phase composite materials possess a vital role. New trends in phase change materials are using composite materials embedded the PCMs to improve their performances. Such modified PCM could be an amorphous or crystalline phase composite [12, 13]. Hence, the research articles conducted on the PCM and their modifications are gaining the researchers' attention. Whereas, latent heat energy storage (LHS) has wide operating temperature ranges, is not applied so far as sensible heat energy storage. Recently, the utilization of economic PCM as a cost-efficient energy storage material is essential [14, 15]. Thus, numerous numbers of experimental studies are available to introduce various heat storage media. Although water as a heat storage media is extensively applied as a sensible heat storage substance, the shortcomings are still limiting its real applications such as small storage density and the essential need of high insulation. Therefore, novel materials are introduced to design energy storage PCM as less sophisticated and economic systems [16, 17]. But, the gaining advantages of nanoparticles or inorganic materials embedded PCM are suitable candidate for effective their thermo-physical characteristics. Also, the unique physical as well as chemical properties are suggesting such substances as appropriate PCMs. Such PCMs substances might support further latent heat store facility. Therefore, future further research work is essential to improve such inserted PCM systems.

The principal deficiency of the conventional pure phase change materials is linked to the low thermal conductivity such materials possess that lies in the range of (0.2-0.7 W/mK). Thus, such conventional systems are signified as poor systems and are required to be enhanced. Thermal conductivity of nanomaterials shows an important role in improving the PCM' conductivity [18]. Also, the presence of embedded nanomaterials in the PCM change various characteristics linked to the thermophysical characteristics of the pristine PCM [19, 20]. Such properties are including the temperatures of the melting and solidification cycles, phase change material duration, the density and viscosity of the PCM material, latent heat capacity, latent heat of fusion and subcooling [6]. Consequently, a controllable nanoparticles dispersion in the pristine PCM is a suggested opportunity. This research work is introducing and aiming to deliver an improvement in the thermal conductivity of commercial Paraffin-AP25 through the addition of modified waste material from woodchips (W) with magnetic (M) material as a hybrid composite to enhance the thermal conductivity of Paraffin based PCM. The dispersed particles into the PCM are so-called P-AP25/WM. The material characteristics are illustrated and the application for such P-AP25/WM composite is investigated through melting and solidification cycles.

2. Experimental section

2.1 Materials

Technical grade of Paraffin-AP25 is supplied by Aramis, Co. (USA) is used as the base phase change material. The melting point of Paraffin-AP25 is ranged from 48 to 53°C, whereas the latent heat of fusion is recorded at 190 KJ/kg. Also, the other thermo-physical characterization including 930 kg/m³ of solid density, while the liquid density is 830 kg/m³ with a thermal conductivity of 0.21kJ/kg°C and the Solid Specific is 2.1 kJ/kg°C.

2.2 P-AP25/WM composite PCM preparation

Primarily, facile co-precipitation method is applied for Fe₃O₄ (magnetite) nanoparticles preparation. The method is based on the mixing of stoichiometric ratios of (2 mol) Fe₂(SO₄)₃ and (1 mol) Fe(SO₄) that are dissolved in distilled water. Afterwards, NaOH is added in a drop wise manner to elevate the pH to about 11.0 value which is linked to the magnetite precipitation. The preparation is conducted under a continuous stirring under 80°C heating. Then a successive washing is accompanied to reach to distilled water to reach pH 7.0 for removing excess of sodium hydroxide and Na₂SO₄, the resultant material is then left to settle and filtered and then exposed to oven drying (60°C) and manually grounded [17].

Initially, woodchips waste is subjected for treatment to obtain fine powder cellulose particles. A successive distilled water washing is first subjected to remove any impurities attached with the material then it is subjected for chemical treatment through hydrolysis and washed then dried. While, magnetite nanoparticles is prepared via simple co-precipitation route. Then, the mixture of cellulose and magnetite is mixed through hydrothermal technique in a weight percent of 4 to 1 of cellulose and magnetite and the sample is labeled as WM-(4:1). Subsequently, the 15 gm of Paraffin-AP25 is melted at 62°C and then mixed with the composite WM-(4:1) and dispersed through ultrasonic cavitation. The WM-(4:1) is added at different weight proportion of 0, 0.5, 1, 2 and 4%.

2.3 Experimental methodology

The heat transfer fluid introduced is water, which is transferred onto the heat exchanger of the type of (shell-and-tube) heat exchanger type in its shell to provide two cycles of melting, and solidification that is so-called

charging and discharging PCM cycles. Further, the hot water storage tank is highly insulated to prevent the heat losses of the hot water from the discharging cycle. All the convectors are in parallel via rubber piping tubes and the heat transfer fluid flows in a specific flow rate of 0.13 kg/s. Graphical overview of the system describing the process is exhibited in Fig. 1.

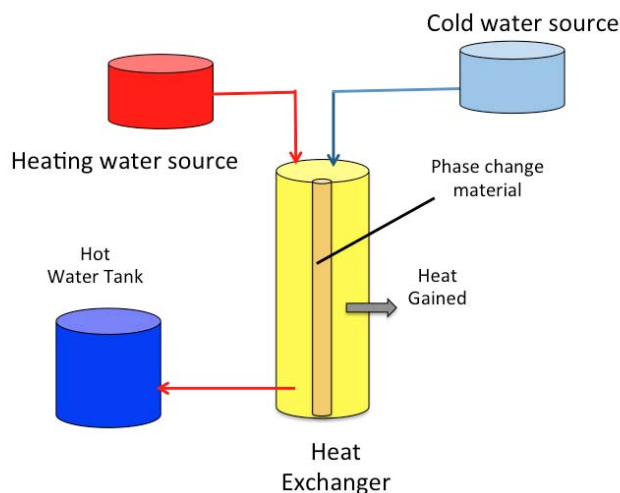


Figure 1. Illustration of the PCM storing system description steps

3. Results and Discussions

3.1. Composite characterization

3.1.1 Morphological characterization and EDX analysis: SEM micrographs of pristine cellulose, magnetite nanoparticles, cellulose/magnetite composite and PCM (AP25/WM-(4:1) composite) is applied to describe their micromorphology through Scanning Electron Microscope manufacturing using FE-SEM (model type of Quanta FEG 250). According to Fig. 2 (a) and (b) illustrates the pristine cellulose and magnetite nanoparticles, respectively. Also, the composite of WM-(4:1) is displayed in Fig. 4(c) verifies the existence of magnetite nanosized particles on the surface of cellulose fiber. These observations have been confirmed by the EDX Elemental Analysis for the distribution of various elements (in Fig. 2(e)). Fig. 2 (d) verifies that the WM-(4:1) layers that are distributed in the AP25 in various paths and spots. The WM-(4:1) created a skeleton, which provides and supports the heat transfer. Furthermore, the deposits of the WM-(4:1) layers were totally and regularly covered by paraffin, where the AP25 and WM-(4:1) were significantly integrated.

3.1.2. TEM analysis: The isolated cellulosic fibers, magnetite nanoparticles as well as the WM-(4:1) composite material were investigated under transmission microscope type Tecnai G20, FEI. The corresponding micrographs are displayed in Fig. 3 (a, b, and c), respectively. Results from Fig. 3 (a) signified a sheet-like micrograph of cellulose fiber. Moreover, the Fig. 3(b) displays the TEM micrograph of the pristine magnetite nanoparticles, which reflects a spherical like shape. Fig. 3(c) confirms the sheet-like morphology of the cellulose that are sheltered with condensed aggregates of spherical like particles which reflects the magnetite nanoparticles covered the cellulose sheet. Furthermore, the samples recorded average particle size of 12 nm (Fig. 3(d)).

3.1.3. FTIR analysis: Fourier Transforms Infrared Spectroscopy (FTIR) analyses were conducted to categorize the related functional groups of the prepared material WM-(4:1) composite and the results displayed in Fig. 4. Cellulose conjugated with magnetite nanoparticles exhibited the characteristic peaks at the wavenumber of (3370, 2906.2 and 1732.73 cm^{-1}) that are apportioned to O-H symmetric, aliphatic C-H stretching and C=O vibration, respectively. Also, C-H scissoring, C-C bending and C-O stretching are reflected at 1375, 895.77 and 1375 cm^{-1} , respectively. All of such peaks representing cellulose fiber. However, magnetite in the composite was detected by the 431.97 and 555.39 cm^{-1} verifies the stretching band Fe-O.

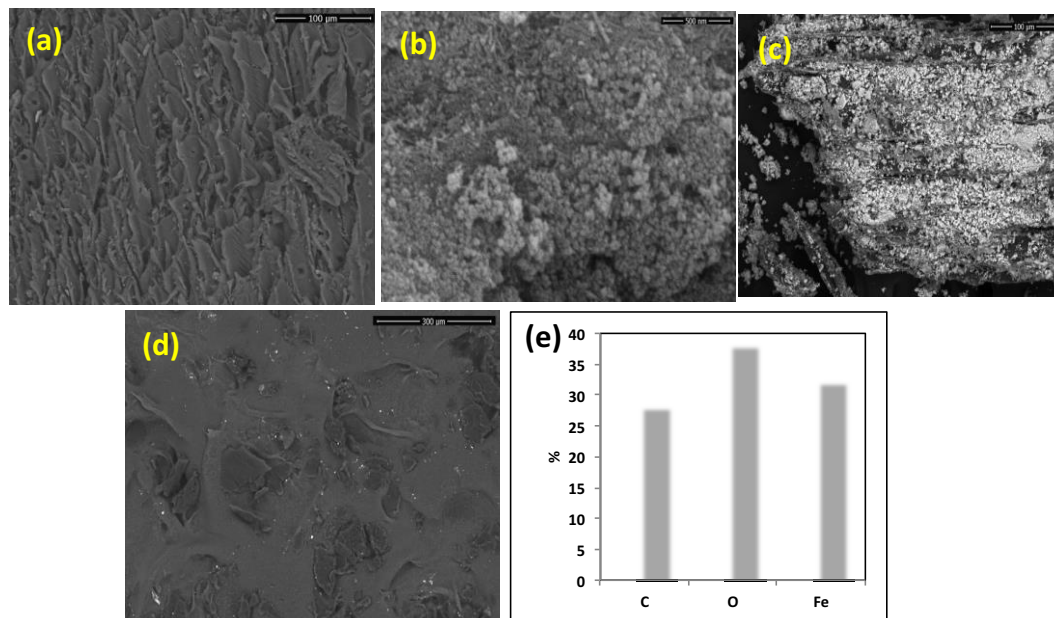


Figure 2. SEM images of (a) cellulose fiber, (b) magnetite nanoparticles; (c) WM-(4:1) composite (d) AP25/WM-(4:1) composite and (e) EDX analysis.

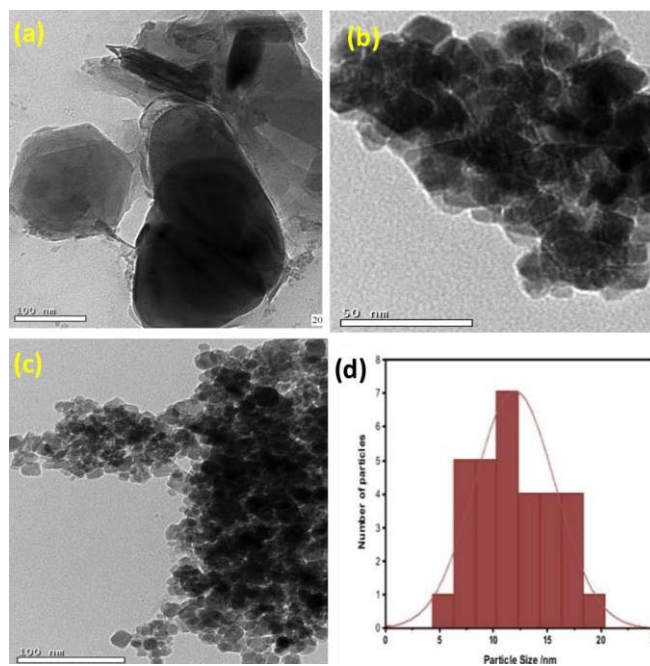


Figure 3. TEM images of (a) cellulose fibre, (b) magnetite nanoparticles and (c) WM-(4:1) composite and (d) average particle size distribution of the composite material

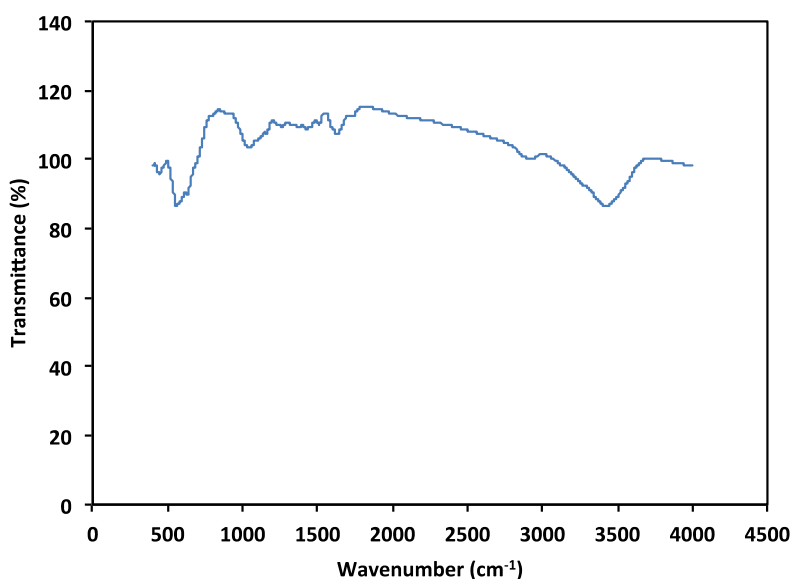


Figure 4. FTIR spectrum of WM-(4:1) composite

3.1.4. XRD: To assess the crystalline behavior of the modified sawdust/magnetite sample, the XRD analysis is conducted. Fig. 5 displays the distinct peaks of magnetite that is signified by the most intensive peaks (311) and (440), which are linked to 2θ of 35.52 and 60, respectively [6]. Also, noted 2θ of 34.7°, corresponding to the (400) phase of crystalline cellulose I. such results confirm the presence of magnetite peaks in sawdust sample composite.

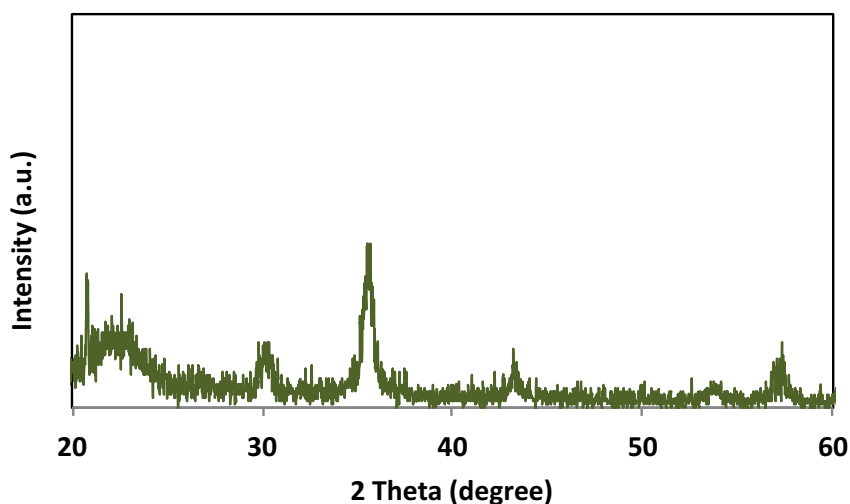


Figure 5. X-ray diffraction of WM-(4:1) composite

3.2 Thermal energy storage studies

3.2.1. PCM Charging/ Discharging systems: This section is targeted to evaluate the various cellulose thermal energy storage (TES) systems. The systems of AP-25 embedded with 0, 0.5, 1, 2, and 4 % and labeled as PCM-0% WM-(4:1) PCM-0.5% WM-(4:1) PCM-1% WM-(4:1) PCM-2% WM-(4:1) and PCM-4% WM-(4:1), respectively are assessed through charging and discharging cycles. Melting and solidification cycles are corresponded to the charging and discharging cycles. Fig. 6 displayed the melting cycles of the various PCM systems. Remarkably, as demonstrated in Fig. 6 composite fraction embedded into the AP25 phase change

material exposes numerous ranges of melting temperatures. The temperature profile upsurge is noticed by the addition of hybrid composite into the AP25 up to 2% of the filler. But further filler embedded into the paraffin results in a decline in the system performance. Such results are in agreement with the previous conducted work in literature since the addition of particles onto the base PCM is amendment the value of the charging temperature [6]. Also, it is notably that from the EDX results (Fig. 2 (e)) the presence of carbon and iron in the hybrid composite also enhances the overall PCM latent heat.

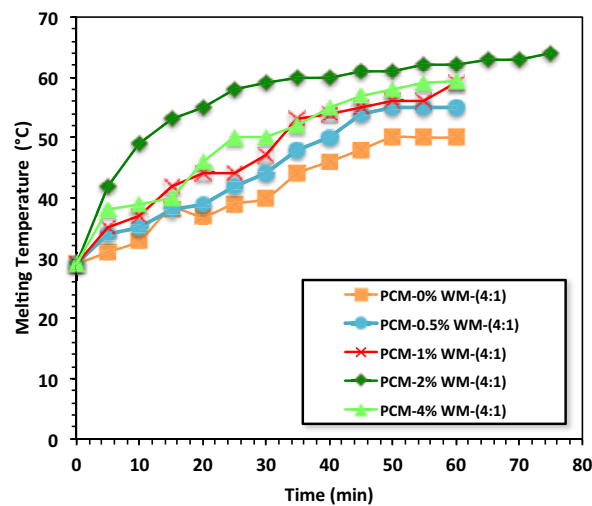


Figure 6. Temperature profile of charging PCM cycle

The data displayed in Fig. 7 is illustrating the solidification cycle of the various systems. The results revealed that the corresponding solidification is linked to the melting cycle. The temperature rising of the melting temperature profile also increases the solidification degree till to the addition of 2% of filler. This is linked to the dispersed hybrid filler into the host paraffin-PCM. Consequently, this might deliver extra inorganic spots and hence upsursges the chance of absorbing heat that delivering extra latent heat of fusion of the AP25 embedded with the sawdust/magnetite composite. This might be associated with the agglomeration/sedimentation phenomenal in the case of excess filler. Subsequently, longer time is required and thus, more heat is recovered. But further fraction increase is negatively affecting the performance due to the decline in the solidification temperature-profile. Previous work reported similar trends [6, 17).

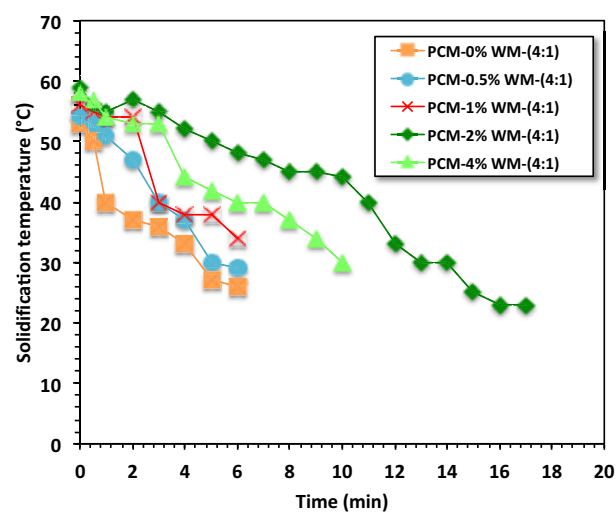


Figure 7. Temperature profile of discharging PCM cycle

3.2.2 Overall performance: It is essential to calculate the overall thermal storing efficiency. The amount of the heat achieved from the heat transfer transporter investigated from the relation of $Q_{gained} = \dot{w} C_w \theta_w$ (where: \dot{w} : water mass flow rate (g/s); θ is inlet and outlet water temperature and C_w is its specific heat capacity). Correspondingly, the heat gained from the systems could be explored from the relation of $(Q_{PA25-PCM\ system} = m_{PCM} C_{PCM} \theta_{PCM} + m L_f)$ since, the m_{PCM} is the mass of PCM (Kg), C_{PCM} is its specific heat capacity (kJ/kg.K), θ_{PCM} is corresponding inlet and outlet temperature difference temperatures. Thus, the system efficiency is the relation between Q_{gained} and $Q_{QPA25-PCM\ system}$. Fig. 8 demonstrates the attained effectiveness enhanced with the embedded filler of 2% of the hybrid composite which is corresponding to 82%. It is expected that as the mass fraction of composite embedded in PCM increases, the thermal conductivity upsurge, whereas the latent heat drops, which might designate that the upsurge in the PCM's thermal conductivity using the filler the decreased latent heat of the PCM substance. Subsequently, additional thermal measurements are needed, with a fitting mass fraction of embedded composite in PCM needing to be measured, based on the application.

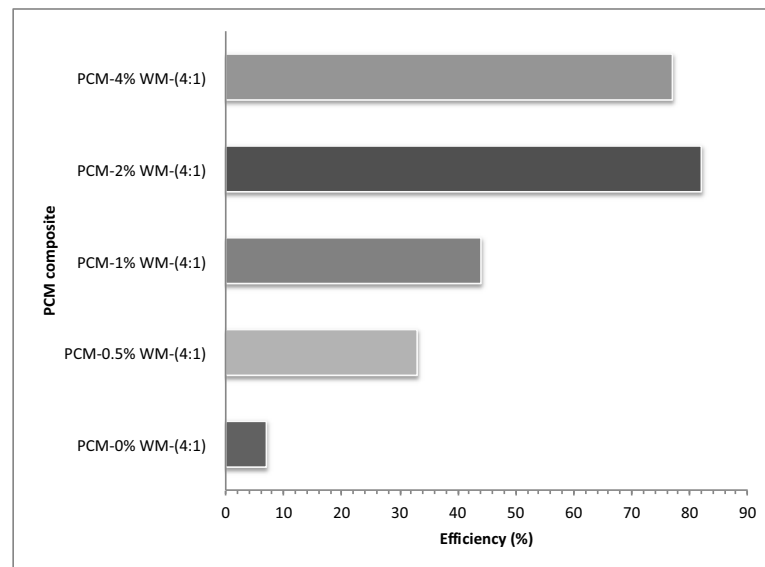


Figure 8. overall thermal systems efficiency

4. Conclusion

The data revealed from such work confirmed the improvement in the thermophysical characteristics of the PCM system when the cellulose/magnetite filler is embedded in the PCM than the pristine paraffin wax. A superior thermal behavior exhibited the optimal addition of 2% is exhibited in relations of melting/solidification cycles the superior efficiency of the system. The overall heat is resulting 82% enchantment. The development system competent form the current investigation is showing a high overall efficiency compared to 7% of the solo system. Thus, the use of such inorganic encapsulations as the supporting PCM is manageable thermal behavior superior to the single paraffin system. Hence, extra future work is essential to yield renewable solar energy using solar collector operating such projected system for building heating.

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