THERMAL ENERGY STORAGE IN NANOCOMPOSITES

Ahmed Elgafy [1], Khalid Lafdi [2]

Abstract *— With the urgent need to harvest and store energy, the design of a new generation of energy storage mediums has grown in importance. On the other hand, nanocomposites have been significantly broadened to encompass a large variety of one, two, and three-dimensional systems made of distinctly dissimilar components mixed at the nanometer scale. Besides achieving composites that have desirable properties, there is also the possibility of gaining new properties, which are unknown in the parent constituent materials. In this paper, nanocomposites based carbon nanofibers filled polymer have been designed, fabricated, and introduced as thermal storage mediums. The thermal properties for the new nanocomposites have been measured experimentally and the transient temperature response for each one of them has been recorded during the solidification process to predict the cooling rate. Additionally, the thermal performance of the established nanocomposites has been studied.*

Index Terms — Carbon nanofibers, shear mixing, thermal conductivity, paraffin wax.

INTRODUCTION

Phase change materials (PCMs) have received a great interest in many applications such as energy storage and thermal protection systems as well as in active and passive cooling of electronic devices. The phase change of PCMs falls into the category of moving boundary problems and during their phase change process, both liquid and solid phases are presented and separated by a moving interface. For using phase change materials in active and passive cooling applications, the PCMs should possess high thermal conductivity to meet the required heat exchange rates. Moreover, these PCMs should have a small volume change and little degrees of supercooling. However, it is very challenging to find an ideal PCM that satisfies all the desirable properties [1]. Paraffin waxes are used as PCMs for thermal storage applications because of their desirable characteristics, such as high latent heat of fusion, negligible supercooling, low vapor pressure in the melt, chemically inert and stable, self nucleating, no phase segregation and commercially available at low cost. However, waxes exhibit some inherent limitations, such as low thermal conductivity and large volume change during phase transition. When paraffin waxes are used in energy storing systems, their lower thermal conductivities reduce the heat exchange rate during melting and solidification cycles and therefore the overall power of the phase change regenerator decreases. In case of space based power systems, this represents a great issue because of a large amount of heat should be stored or dissipated in a short period of time [1]. As reported by Bugaje [2] the phase change (melting or solidification) time is the most important design parameter in latent heat storage systems. The thermal conductivities of paraffin waxes could be enhanced using metal fillers, additives and/or fins [2, 3]. In the case of aluminum additives [2], it was found that the phase change time reduced significantly in heating and cooling processes. However, the metal fillers add significant weight and cost to the storage systems. Erk and Dudukovic [4] utilized low-density additives such as porous silica catalyst while Chapotard and Tondeur [5] used activated carbon. They showed how the mean pore size of the additives could be of critical importance on the system performance. If it is too small, the PCM molecular motion will be hindered, thereby it will be very difficult to impregnate the porous media with the PCM, which will affect adversely on the latent heat storage capacity. Conversely, if the pores are too large, there will not be sufficient capillary force to retain the liquid wax. For activated carbons, waxes are well retained in micro-pores but they lose their phase change properties. Pay et al. [6] reported that mesoporous activated carbons would perform better but they added that, those two porous supporters (Silica catalyst and activated carbon) do not present real improvement of the effective thermal conductivity.

On the other hand, carbon fibers have a strong resistance to corrosion and chemical attack, which make them compatible with most PCMs. The thermal conductivities of carbon fibers are considerably high and their densities are less than 2260 kg/m3, which is lower than those of metals that are usually used as additives. Fukai et al. [1] investigated the effect of using carbon fibers as additives by using two sets of carbon fiber architectures. In the first set, carbon fibers were randomly distributed into paraffin wax, while in the second set, carbon fibers were oriented parallel to the heat flow. The transient temperature response and the effective thermal conductivity of the composites were measured. They concluded that in case of random carbon fiber distribution, the fiber length had little effect on the thermal performance and the effective thermal conductivity of the system enhanced significantly by using brush type carbon fibers. Mauran et al. [7] used a solid matrix made of graphite as a support for low thermal conductivity reactive salts.

1 Ahmed Elgafy, Visiting Assistant Professor, Mechanical Engineering Technology Department, College of Engineering and Applied Science, University of Cincinnati, Admin Building, Room 623, 2220 Victory Parkway Ave, Cincinnati, OH 45206, USA, ahmed.elgafy@uc.edu
2 Khalid Lafdi, Professor, University of Dayton Research Institute, 300 College Park, Dayton, OH 45469, Khalid.lafdi@udri.udayton.edu

This support presented several advantages such as achieving high external heat transfer coefficient, very low bulk density, good mechanical properties, and chemical inertness. Graphite matrix is known to be superior to porous metallic foams made of aluminum, copper or nickel. Pay et al. [6] proposed a supported PCM made of paraffin impregnated by capillary forces in a compressed expand natural graphite matrix. They found that the thermal conductivity of the composite equal to that of the sole porous graphite matrix. Moreover, the composite presented the same anisotropy with respect to the compression axis. They concluded that, the compressed expanded natural graphite matrix induced a decrease in the overall solidification time and achieved more stabilization of the thermal storage power.

As another solution for overcoming the undesirable PCMs characteristics, a mixture of different PCMs had been used. Jianfeg et al. [8] studied experimentally the charging process of a cylindrical heat storage capsule filled with stearic acid, sliced paraffin and lauric acid as phase change materials. The geometric structure of the capsule made up of three coaxial red copper tubes. The surface temperature of the outer surface of the outer tubes is kept at constant temperature by putting it in a constant temperature water bath. The results showed that the using of multiple PCMs enhances the charging rate of the PCM storage.

In the present work, carbon nanofibers were used to enhance thermal performance of paraffin wax. Different mass ratios of carbon nanofibers were added into paraffin wax by shear mixing and melting processes. The thermal properties for the new nanocomposites were measured experimentally and the transient temperature response for each one of them was recorded during the solidification process to predict the cooling rate. Also, a comparative study was performed to investigate the effect of carbon nanofibers surface characteristics on the enhancement of the phase change material thermal performance.

EXPERIMENTAL

Nanocomposites Preparation

Several samples were prepared by adding carbon nanofibers at different mass ratios (1, 2, 3, and 4% by weight) into paraffin wax using shear mixing and melting techniques. The carbon nanofibers were provided by Applied Science Inc. and have average outer diameter of 100 nm and average length of 20 μm. For the sake of comparison, a pure paraffin wax sample of 67 ^{o}C melting point was used. The total mass of each sample was 20 grams and each one of them was placed into a separate cylindrical glass enclosure of 2 cm in diameter and 2.5 cm in height. The enclosures were insulated from their tops and bottoms and the heat was allowed to propagate only in the radial direction. All samples were introduced simultaneously and uniformly distributed inside a furnace core, which attained a uniform heat flux.

Thermal Properties Measurements

The thermal diffusivities for all samples were measured at room temperature using laser flash technique in which a very short and uniform laser pulse is directed to the sample, which is in a cylindrical disk shape of 18 mm diameter and 3.3 mm thickness. The radiation energy of the pulse is absorbed at the front surface which results in a temperature rise on the back surface of the sample. A thermal detector measures this temperature rise as a function of time. The thermal diffusivity of the sample in the direction perpendicular to the front and back surfaces at room temperature could be determined by using the formula given by Maglic and Taylor [9]:

$$\alpha = 0.139 \frac{L^2}{t_{1/2}} \qquad (1)$$

On the other hand, the heat capacities of all samples were measured by differential scanning calorimeter technique and their thermal conductivities at room temperature, K, were calculated from the relation

$$k = \alpha \cdot \rho \cdot c_p \qquad (2)$$

Where α, is the thermal diffusivity, ρ is the density, and c_p is the heat capacity.

Experimental Setup and Instrumentation

As shown in Figure 1, the experimental setup consists of a vertical furnace attached to a controlled power supply. Ten molybdenum disilicide heating elements are uniformly spaced in a full circle around the interior furnace wall to achieve a uniform heat distribution inside the furnace core. An airlift mechanism, pneumatic system, with top and bottom plugs is supplied to the furnace to introduce or bring down the samples to or from the furnace core simultaneously. The transient temperature response for each sample was measured by means of multiple K-type thermocouples and a Data Acquisition System was used to convert their outputs to a PC through a standard RS-232 asynchronous serial communication.

Experimental Results

As shown in the Figure 2, nanocomposite thermal diffusivity increases with increasing carbon nanofibers ratio into paraffin wax. The thermal diffusivity of pure paraffin wax is about (0.00151 cm^2/sec) while the thermal diffusivity of the paraffin wax filled with 4% is about (0.00268 cm^2/sec). Conversely, the specific heat decreases by increasing carbon nanofibers ratio, which means that nanocomposites display less ability to store heat but high aptitude to conduct heat, Figure 3. However, the thermal conductivity at room temperature increases by increasing the carbon nanofibers mass percent as shown in Figure 4.

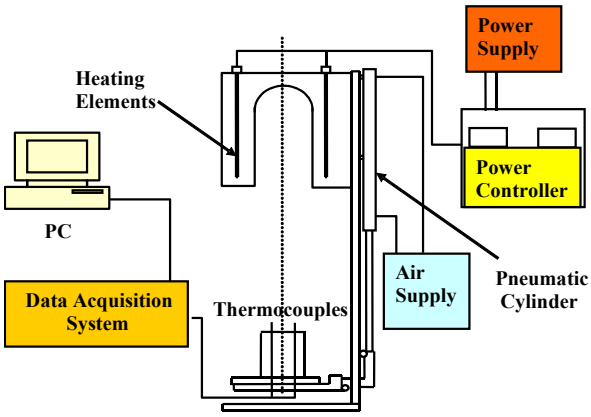

FIGURE. 1
EXPERIMENTAL SETUP FOR THE HEATING PROCESS AND TEMPERATURE MEASUREMENT OF THE SAMPLES

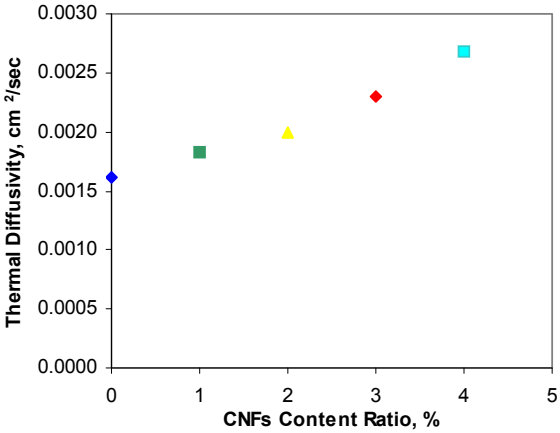

FIGURE. 2
MEASURED VALUES OF THE THERMAL DIFFUSIVITY AT ROOM TEMPERATURE FOR ALL SAMPLES

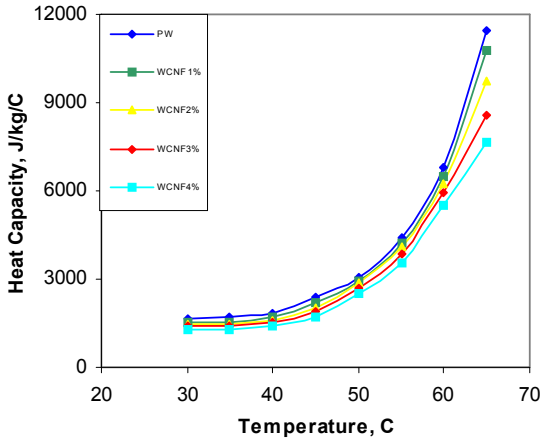

FIGURE. 3
MEASURED VALUES OF THE HEAT CAPACITIES FOR ALL SAMPLES

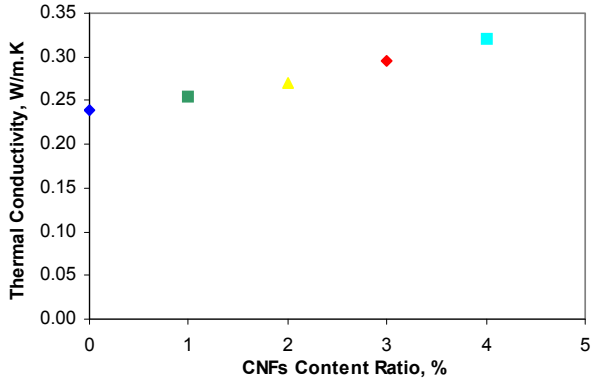

FIGURE. 4
THE THERMAL CONDUCTIVITY AT ROOM TEMPERATURE FOR ALL SAMPLES

Solidification Process Results

All samples were introduced simultaneously and uniformly distributed into the furnace core, which attained a uniform heat flux. After sufficient duration time for melting, which is about four hours for a heat flux level of 1 kW/m^2, the pneumatic air system was activated to bring down the samples from the furnace core. The transient temperature response for each sample was recorded against elapsed time during the solidification process simultaneously by means of multiple K-type thermocouples, which are connected to a Data Acquisition System. To perform a comparative study for the thermal behavior of pure paraffin wax and the new nanocomposites during their solidification process; a solidification characteristic curve for the temperature-time history for each sample was established. Figure 5 represents the solidification characteristic curve for pure paraffin wax sample, while Figure 6 represents the solidification characteristic curve for the nanocomposite sample of 1% CNFs content ratio. Figure 5 shows that the duration time elapsed during the latent heat phase of pure paraffin wax, which is corresponding to 67 ^{o}C, is about 450 sec, while it has a value of 350 sec for the nanocomposite sample of 1% CNFs content ratio, Figure 6. The decrease in the duration time indicates that the heat dissipation from the nanocomposite sample is higher than that of pure paraffin wax sample. The transient temperature response for each sample during the solidification process is shown in Figure 7, which shows that the duration time for the solidification process decreases with the increase of CNFs content ratio. The output power from each sample during its solidification process was estimated by dividing the liberated energy from it over its solidification duration time. Figure 8 shows that the output power from the samples increases with the increase of the CNFs content ratio due to the enhancement of their thermal performance.

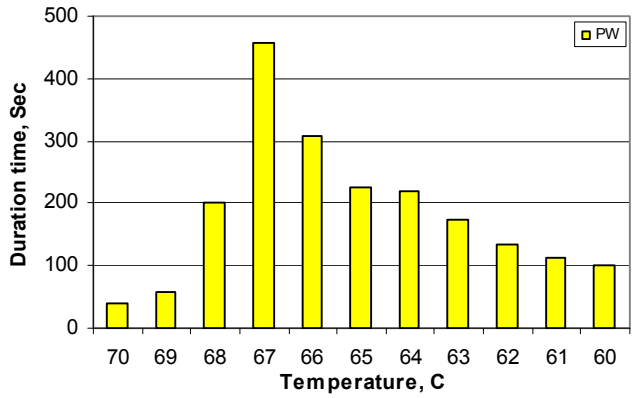

FIGURE. 5
COOLING OF PURE PARAFFIN WAX

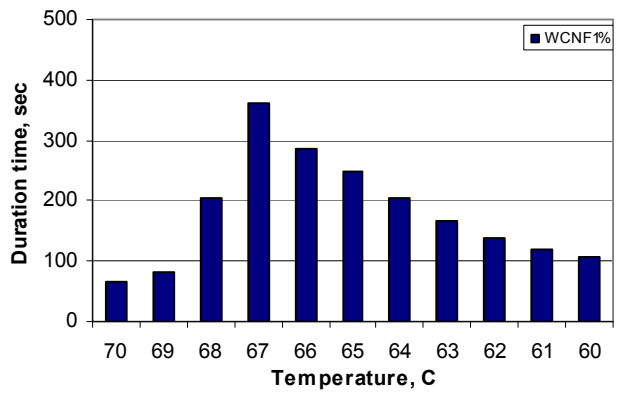

FIGURE. 6
COOLING OF NANOCOMPOSITE WITH 1% CNF ADDITIVES

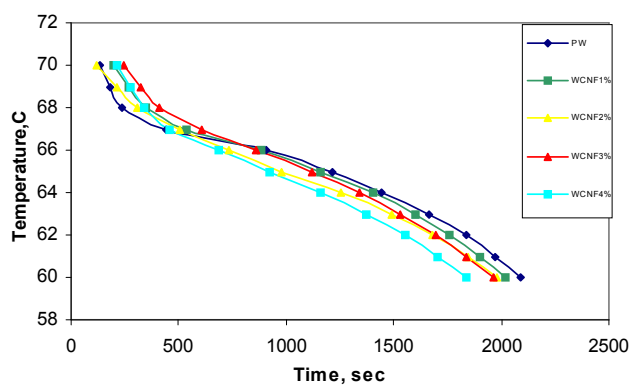

FIGURE. 7
TRANSIENT TEMPERATURE RESPONSE DURING SOLIDIFICATION PROCESS

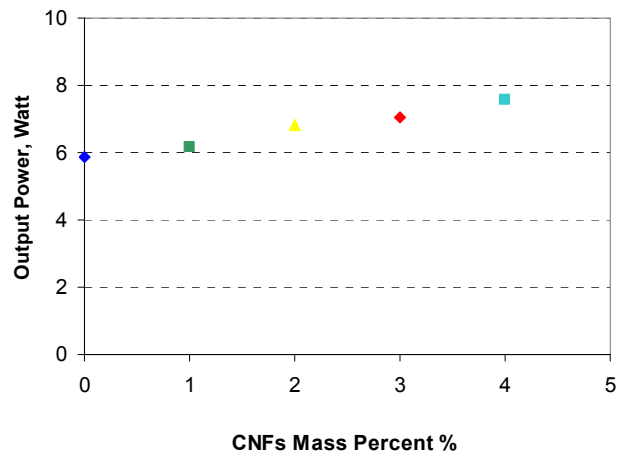

FIGURE. 8
OUTPUT POWER DURING SOLIDIFICATION PROCESS

EFFECT OF CNFS SURFACE CHARACTERISTICS

From macroscopic point of view, it is common knowledge in heat transfer that when lateral surface area increases, the heat transfer rate increases. In this study, we investigated if this fact was valid at nanoscale. The Carbon Nano Fibers, CNFs, were surface treated using standard electro-chemical treatment [10, 11] to change their specific areas and their surface energies. Then, a comparative study was carried out between two nanocomposite samples that contained the same CNFs content ratio, but the CNFs have different surface characteristics. One was made of 4% pristine CNFs (untreated surface) and the second was made of 4% surface treated CNFs into paraffin wax. Figure 9 represents the cooling rate curve for the two samples. From the figure one can see that the nanocomposite which contains treated surface CNFs has higher cooling rate than that of the nanocomposite with untreated surface CNFs. This leads to a conclusion that the heat transfer rate was enhanced by modifying the surface characteristics of the added Carbon Nano Fibers. The comparative study showed also that the heat transfer phenomenon at nanoscale seems to be surface dependent.

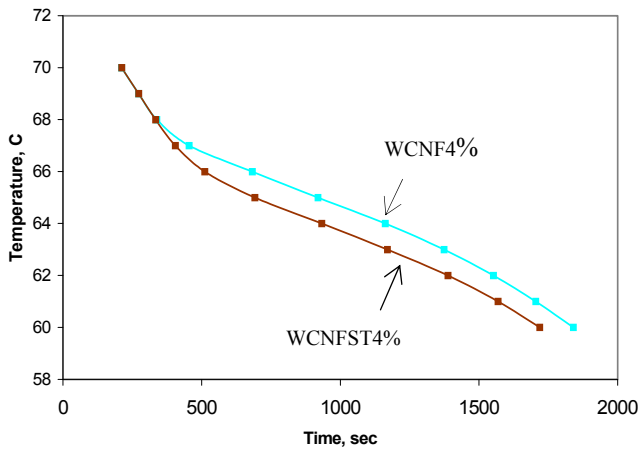

FIGURE. 9

COOLING RATE FOR NANOCOMPOSITES WITH SURFACE TREATED AND UNTREATED CNFS

CONCLUSIONS

Carbon nanofibers were employed to enhance the thermal performance of a PCM during its phase change. The thermal properties of the modified PCM were enhanced significantly by dispersing CNFs into it. As a result of this enhancement, the cooling rate during the solidification process of the new nanocomposites increased significantly by increasing the mass ratio of the CNFs. A comparative study was made to investigate the effect of CNFs surface characteristics on the enhancement of the thermal performance of the nanocomposites. The comparative study showed that the heat transfer phenomenon at nanoscale seems to be surface dependent. Further studies will be conducted to include surface energy and specific surface area of nano-additives.

ACKNOWLEDGMENT

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