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THERMAL PERFORMANCE OF µPCM/MWCNT COMPOSITES AT DIFFERENT AMBIENT TEMPERATURES

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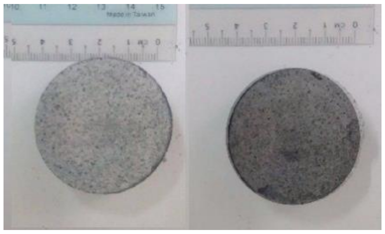
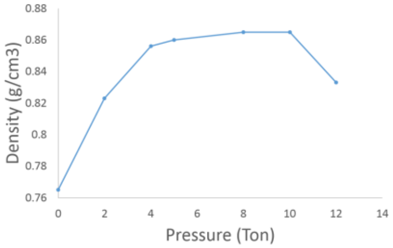
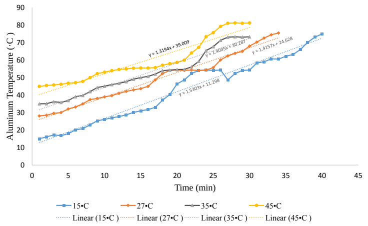
Graphical abstract







Abstract

The aim of this study is to investigate the effect of carbon-based materials on the thermal performance of microencapsulated phase-change material (µPCM) for passive cooling applications. The sample was prepared by mixing 5 wt. % of multi-walled carbon nanotubes (MWCNT) into µPCM using a powder metallurgy technique. The mixed powder was then compacted into a disc, having a diameter of 30 mm and a height of 5 mm, using a hot compaction technique. The samples were tested according to the modified ASTM standard. The experimental results demonstrated that the addition of MWCNT into µPCM enabled it to effectively absorb the heat emitted by the aluminium casing compared to pure µPCM. The model results indicated that the temperature of the aluminium could be maintained well at each ambient temperature by using the µPCM/MWCNT composite, thus showing that µPCM/MWCNT can potentially be used for passive thermal management in the future.

Keywords: µPCM, MWCNT, passive thermal management

Abstrak

Tujuan kajian ini adalah untuk mengkaji pengaruh bahan berasaskan karbon terhadap prestasi termal *microencapsulated phase-change material* (µPCM) untuk aplikasi penyejukan pasif. Sampel disediakan dengan mencampurkan 5 wt% *multi-walled carbon nanotube* (MWCNT) ke dalam µPCM dengan menggunakan teknik campuran serbuk. Campuran kedua-dua bahan dimampatkan kepada bentuk disk dengan menggunakan teknik mampatan panas. Sampel kemudiannya diuji berdasarkan panduan ASTM yang diubah suai. Keputusan eksperimen menunjukkan bahawa penambahan MWCNT ke dalam µPCM meningkatkan keupayaan µPCM untuk menyerap haba yang dihasilkan oleh aluminum berbanding dengan µPCM asli sahaja. Keputusan menunjukkan bahawa suhu aluminum berjaya dikawal dan dikekalkan pada setiap suhu persekitaran dengan menggunakan µPCM/MWCNT, maka membuktikan keberkesanan µPCM/MWCNT terhadap pengurusan termal pasiif pada masa hadapan

Kata kunci: µPCM, MCNT, pengurusan termal pasif

1.0 INTRODUCTION

As a large amount of latent heat energy is involved during the transition of phase-change materials with small temperature changes, PCMs have been proposed for temperature stabilization, and for storing large density energy [1]. Researchers have proposed PCM as a suitable cooling material because of its high latent heat capacity, which makes it capable of removing large quantities of heat generated by the 0 modules [2-3]. PCM also has proper thermal characteristics such as no supercooling, low vapour pressure, chemical stability and self-nucleating behaviour [4-7]. In view of this unique characteristic, PCM has been widely tested to solve problems, especially in thermal energy storage systems, thermal insulators and temperature control. However, PCM has the disadvantage of having a low thermal conductivity, which means heat absorption by PCM is slow and inefficient. Hence, this problem is the main focus of the present research. Micro-encapsulated phase-change material (μPCM) is an enhanced phase change material formed by encapsulating a PCM, commonly paraffin, in a polymeric network structure to obtain a stable structure [8]. The polymeric structure prevents the leakage of PCM during the solid-liquid phase. Therefore, it can be used in a wide range of applications without the need for extra encapsulation. However, the low thermal conductivity of the polymer walls will decrease the heat transfer capability of the PCM. Therefore, high thermal conductivity materials need to be added to the PCM to increase its thermal conductivity. It is difficult to produce an ideally enhanced PCM that possesses all the desirable properties such as thermal conductivity, latent heat capacity and stability. Enhanced phase-change materials have been proposed in many studies by using different methods and materials such as by placing fins in the PCM structure [9], adding a metallic structure [10], impregnating the PCM with porous material [11] and dispersing high thermal conductivity materials within the PCM [12].

One alternative way of enhancing the thermal conductivity of PCM is to add in a material with a high thermal conductivity, but this will gradually result in a lower thermal performance in the long-term period because of the size and surface properties of the additive [13]. In addition, it also adds significant weight to the system. Nano technology addresses the problem by developing nano-scale additives, which have smaller sized particles and less weight. The carbon nanotube (CNT) is a viable option as it has a high thermal conductivity. Carbon particles in nanotubes can be impregnated into the PCM structure and react by holding together the PCM when it reaches its melting point.

In this work, improvements in the thermal properties of μPCM were investigated through the addition of a carbon-based matrix, which is a multi-walled carbon nanotube (MWCNT). The combination of these materials was tested experimentally to investigate the effect of the μPCM/MWCNT composite on cooling applications at different ambient temperatures.

2.0 EXPERIMENTAL METHOD

2.1 Materials

μPCM, with a melting temperature of 52 ˚C, was obtained from Rubitherm Technologies. The multi-walled carbon nanotube was supplied by Nano Technologies. The thermo-physical properties of these materials are presented in Table 1. All the properties are based on the data sheets provided by the companies.

Table 1 Properties of μPCM and MWCNT

Materials	Surface Area	Melting Temperature	Latent Heat Capacity	Thermal Conductivity
PX35 μPCM	-	52	100	0.10
NC700 MWCNTs	271	3625	-	3500

2.2 Preparation of μPCM/MWCNT

μPCM has a high latent heat capacity but less thermal conductivity. Therefore, MWCNT, which has a high thermal conductivity, was added to the PCM composite in order to investigate the influence of MWCNT on the thermal properties and thermal behaviour of μPCM/MWCNT. Several samples were prepared by mixing 5% MWCNT with μPCM using the direct synthesis method. A pure μPCM sample was also considered as a comparison [14]. The size of the specimen was fixed at a diameter of 30 mm and a height of 5 mm Fig. 1).

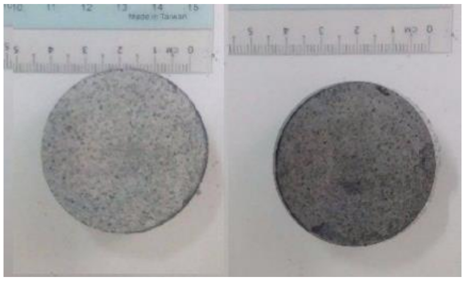

(a) (b)

Figure 1 Photo of a sample of (a) μPCM, and (b) μPCM/MWCNT composite

The composite was compressed using a hydraulic laboratory press, which has an adjustable. The effects of the pressure on the density were studied to determine the optimum pressure for the fabrication of the specimen. Based on the results obtained in Fig. 2, the compression pressure was fixed at 10 tons as the highest density of the material was obtained at that pressure.

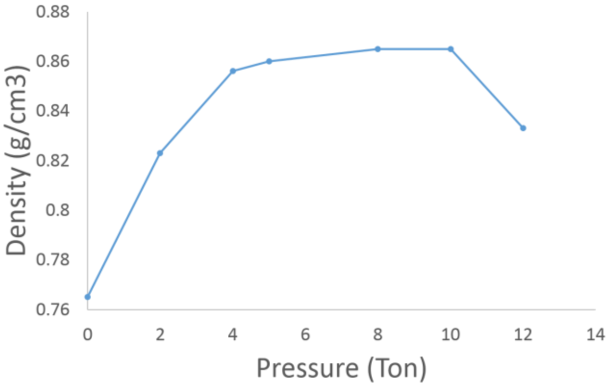


Figure 2 Density saturation curve using different compaction pressures

2.3 Experimental Setup

All the prepared samples were tested for their effect on cooling applications according to the modified ASTM C518–10, which is the standard test method for steady-state thermal transmission properties by means of the heat flow meter apparatus. The results were obtained in the form of a temperature profile for aluminium over time. This test method covered the measurement of the steady state thermal transmission through flat slab specimens using a heat flow meter apparatus. The test method was applicable for the measurement of thermal transmissions through a wide range of specimen properties and environmental conditions [15].

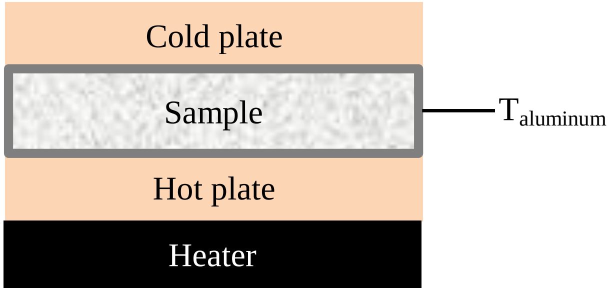


Figure 3 Apparatus configuration

Fig. 3 shows the configuration of the experimental apparatus. The sample was placed between the hot and cold copper plates. The hot plate above the electric heater ensured that the flow of heat from the heater up through the sample was unidirectional. The cold plate above the sample provided a uniform temperature distribution on its surface. A unidirectional heat flow was achieved by adjusting the electric power supply to such a level that the temperature of the heater was equal to that of the hot plate. The sample was covered with aluminium, which was the source of heat emission. The aluminium was heated at a nominal voltage of 12 Volts and a power of 5 Watts. The temperature of the aluminium was recorded at each minute by using an infrared thermometer. The results were obtained in the form of a temperature profile of aluminium over time. The experimental rigs were set up at different ambient temperatures of 15, 27, 35 and 45 ˚C by modifying the freezer and incubator to obtain the required temperatures. A thermocouple was attached to the freezer and the incubator to monitor the temperatures. Errors, ranging from 3 to 11 ˚C, were detected in the test results. This was because the heat from the system affected the environmental temperature.

3.0 RESULTS AND DISCUSSION

The temperature profile of aluminium over a period of time was obtained and investigated. The results presented in Fig. 4 show that the temperature of aluminium increased sharply when there was no thermal management system at all (without any attachments). In the case of thermal management, it was observed that the temperature increase differed slightly for both conditions (µPCM and µPCM/MWCNT). The µPCM/MWCNT attachment provided better cooling compared to the µPCM attachment. This was due to the fact that MWCNT has a higher thermal conductivity compared to µPCM. The MWCNT that had been impregnated into the µPCM successfully improved the thermal properties of the µPCM. M. Lajvaerdi et al. [16] reported that the thermal conductivity of paraffin (PCM) increased by 31 % with the addition of 2 wt. % of MWCNT. Fig. 4 gives the comparison of three different conditions; without a thermal management system, with a µPCM attachment, and with a µPCM/MWCNT attachment for different ambient temperatures of 15, 27, 35 and 45 ˚C [17].

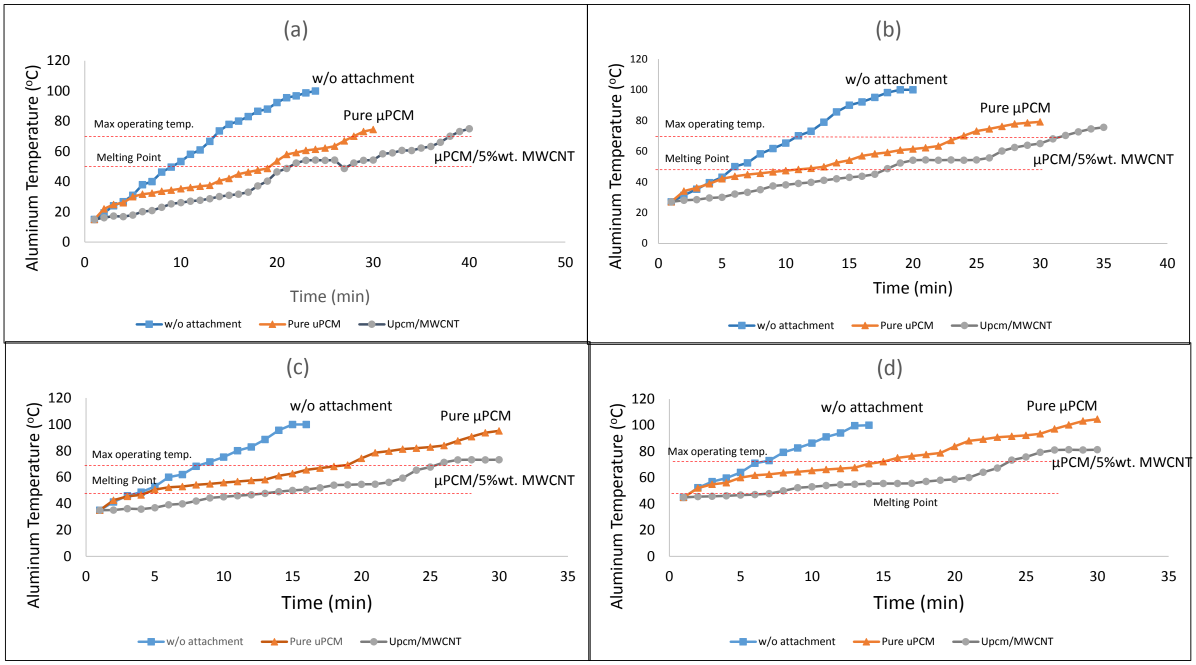


Figure 4 Temperature profiles of aluminium casing
(a) 15 ˚C, (b) 27 ˚C, (c) 35 ˚C, (d) 45 ˚C

The effect of thermal management was significant with both thermal management systems, but was substantial in the absence of such a system. The results showed that when thermal management was issued, the temperature profile of aluminium decreased by up to 83.90% for the µPCM/MWCNT attachment and 58.31% for the µPCM attachment. The results also indicated that when thermal management was issued to cool the system, the life cycle of the system could be optimized. Assuming that the aluminium is a battery module that will run away when the temperature profile exceeds the maximum operating temperature of 75 ˚C [18], the time for the aluminium to reach the maximum operating temperature will be extended when the thermal management is issued, which means that the thermal management maintains the aluminium within the safety limit and significantly improves the life cycle. At ambient temperatures, the aluminium took 11 minutes to exceed the maximum temperature, while this time was extended to 24 and 31 minutes with the µPCM and µPCM/MWCNT attachments, respectively. This proved the µPCM was capable of removing heat due to its high latent heat of fusion, while the high thermal conductivity of the MWCNT impregnated into the µPCM ensured a high rate of heat removal. The temperature control led to significant utilization of the life cycle, which was consistent with previous research results [19].

The µPCM started to melt when the temperature exceeded its melting point (52 ˚C) and the temperature was regulated around that point. The results also showed that the phase change period increased when there was an increase in the ambient temperature. For the µPCM/MWCNT attachment, the phase change periods for different ambient temperatures (15, 27, 35 and 45 ˚C) were 4, 6, 8 and 12 minutes, respectively. This means that the µPCM/MWCNT was more effective at higher ambient temperatures as the rate of thermal conductivity of the µPCM/MWCNT increased with an increase in the ambient temperature. Song [20] stated that the coefficient of thermal conductivity increases with an increase in ambient temperature.

Three conclusions can be drawn from the results: (1) thermal management has a significant effect on the temperature profile; (2) the life cycle can be extended when the thermal management is issued, and (3) the coefficient of thermal conductivity increases with an increase in the ambient temperature. The detailed results for each condition and ambient temperature are shown in Table 2.

Table 2 Thermal conductivity and latent heat of composite and pure µPCM

Performance Testing	Ambient Temperature	w/o attachment	µPCM	Improvement, %	µPCM/5 wt. % MWCNT	Improvement, %
Aluminium Temperature (·C)	15	73.60	40.50	58.01	30.10	83.90
	27	85.50	52.50	47.83	42.10	68.03
	35	95.60	61.10	44.03	49.10	64.27
	45	100.00	70.60	34.47	55.40	57.40
Phase Change Period (min)	15	-	2	-	4	-
	27	-	4	-	6	-
	35	-	7	-	8	-
	45	-	8	-	12	-
Life cycle (min)	15	15	31	69.57	40	90.91
	27	13	27	70.00	35	91.67
	35	10	21	70.97	32	104.76
	45	7	16	78.26	25	112.50

Figure 5 shows the temperature profiles of an aluminium casing with an attachment of µPCM with 5 wt. % of MWCNT at different ambient temperatures. The rates of increase in the temperature profiles for ambient temperatures of 15, 27, 35 and 45 ˚C were 1.5303, 1.4157, 1.4045 and 1.3194, respectively. This means that the increment in the aluminium temperature was higher at lower ambient temperatures. This occurred because the µPCM was able to store larger latent heat energy at its melting point of 52 ˚C. Therefore, the nearer the ambient temperature was to the melting point of µPCM, the lower the temperature rate (gradient). Since the µPCM reacted quickly during the phase transition, the temperature increase could be maintained earlier. Sasmito et al. [21] found that at an ambient temperature of -5 ˚C, the stack temperature decreases to 5 ˚C after around 60 hours; while at -30 ˚C, it takes nearly half the time (35 hours) to reach the same temperature. This means the rate of heat loss increases at lower ambient temperatures. This is due to the higher heat loss to the environment at lower ambient temperatures [21]. However, the low temperature gradient proved that the µPCM/MWCNT regulated the temperature rise efficiently. Yang et al. [22] stated that the maximum temperature gradient should not be larger than 6 ˚C to guarantee the permissible cell life inconsistency.

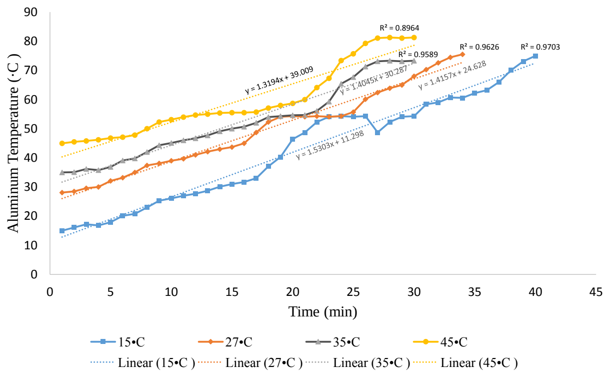


Figure 5 Temperature profiles of aluminium casing with attachment of µPCM/ 5 wt. % MWCNT

4.0 CONCLUSION

The results obtained in this work clearly demonstrate the advantage of using µPCM/MWCNT thermal management for cooling systems. For the µPCM/MWCNT attachment, the temperature of the aluminium casing (with ambient temperatures of 15, 27, 35 and 45 ˚C) was reduced by up to 83.90, 68.03, 64.27 and 57.40%, respectively; while for the µPCM attachment, the temperature was reduced by up to 58.01, 47.83, 44.03 and 34.47%, respectively. The differences in the temperature reduction between the attachment of pure µPCM and µPCM/MWCNT composite were 25.89, 20.20, 20.24 and 22.63%, respectively. This proves that the addition of MWCNT improved the thermal properties of µPCM.

The phase change period was increased by the increase in ambient temperature. For the µPCM/MWCNT attachment, the phase change periods for the different ambient temperatures (15, 27, 35 and 45 ˚C) were 4, 6, 8 and 12 minutes, respectively. The phase change period for µPCM/MWCNT was longer at higher temperatures as the µPCM was in a melting state, and thus was functioning at an optimum level.

The µPCM/MWCNT composite can extend the life cycle of aluminium at different ambient temperatures (15, 27, 35 and 45 ˚C) within the range of 90.91, 91.67, 104.76 and 112.50%, respectively as it can extend the time for the system to reach the maximum temperature limit. At the maximum temperature of 75 ˚C for the system, the aluminium took 11 minutes to exceed it at the ambient temperature, while it took the µPCM and µPCM/MWCNT attachments 24 and 31 minutes, respectively. This proves that the µPCM/MWCNT composite is able to successfully control the temperature of aluminium.

The rate at which the temperature rose increased at lower ambient temperatures. The temperature profiles for ambient temperatures of 15, 27, 35 and 45 ˚C were 1.5303, 1.4157, 1.4045 and 1.3194, respectively. Therefore, attention should be given to the lower ambient temperatures. However, the maximum temperature gradient for aluminium with thermal management was less than the maximum temperature gradient of 6 ˚C, thus verifying its effectiveness and superiority.

The use of μPCM/MWCNT in the proper management and design of cooling systems promises to be an effective solution for cooling and energy storage purposes.

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