

Evaluation of the Heat Transfer Performance of Stearic Acid PCM/ Porous Aluminium Thermal Composite Structures for Heat Storage Applications

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ABSTRACT

Phase change material (PCM) thermal composites consisting of porous aluminium/stearic acid phase change material have been produced for heat storage applications. Porous aluminium/stearic acid composite structures were produced by infiltrating stearic acid PCM into open-cell porous aluminium materials prepared by using dissolvable spherical salt beads in combination with vacuum casting process. Scanning electron microscopic analysis has been used to characterize the empty porous aluminium materials and the results reveal a cellular structure consisting of spherical pores which are interconnected with smaller windows. The thermal response of empty porous aluminium structures and those infiltrated with stearic acid was measured using an infrared camera. The result showed that the heat transfer performance of the PCM thermal composites was significantly improved and largely dependent on the relative density of the porous structures.

Keywords: Porous aluminium, Phase change material, Heat storage, Relative density, Thermal performance.

1. Introduction

Thermal energy storage plays an important role in the efficient and conservative use of solar energy, as it allows for bridging the gap between energy availability/generation and demand/consumption and thus ensuring performance stability of this renewable energy resource [1],[2]. Due to the impacts of fossil fuel depletion and greenhouse effect caused by carbon dioxide emission occasioned by the excessive usage of fossil fuels, energy issues are becoming more and more challenging in recent years. As a result, energy saving and high efficiency energy utilization attract increasing attention. Meanwhile the development of renewable energy resources as alternative energy resource is becoming an interesting research topic [3]. Solar energy, with the characteristics of abundance, low cost and cleanliness to the environment is a promising renewable energy resource [3]. However, the extensive utilization of solar energy is still hampered by intermittence and instability as a result of its dependence on climatic and weather conditions [3]-[6]. Thermal energy storage is a useful technique to overcome the time-dependent limitation of solar energy resources and waste energy from manufacturing plants [7],[8].

Nowadays, most thermal energy storage systems are based on sensible heat storage using water storage tanks or latent heat storage using the phase change materials [8]. In general, the latent heat storage can provide higher energy density and stable operating temperature compared with the sensible heat storage and in the recent years more attention has been paid to the latent heat energy storage systems and various phase change materials have been developed for practical applications in solar water heating systems, solar air heating systems, solar cookers, energy efficient buildings and in industrial waste heat recovery systems [5]-[9]. Phase change materials (PCMs) absorb substantial amount of energy in the form of latent heat during phase transformation while keeping the temperature nearly constant [10]. This property enables the PCM to absorb large amount of heat energy without significantly increasing the temperature of the system. However, phase change materials used in latent heat energy

storage devices have low thermal conductivity and this reduces the rate of heat storage and extraction during melting and solidification cycles [11].

To overcome this problem, high thermal conductivity materials with porous structures such as graphite and porous metals are embedded into phase change materials to enhance their thermal conductivity [12],[13]. Although extensive studies have been conducted on the use of porous materials to improve the thermal conductivity of phase change materials, majority of the researches have been focused on the graphite matrix and high porosity copper and aluminium foams embedded within phase change materials.

Zhou and Zhao [12], experimentally investigated heat transfer in paraffin and calcium chloride hexahydrate PCMs embedded in copper foam and expanded graphite respectively. The porous copper used in this study had 30 pores per square inch (PPI) and 18.5% relative density while the paraffin and expanded natural graphite composite was made by mixing 3%, 6% and 9% of expanded graphite in molten paraffin. The heat transfer performances of the PCM with and without metal foam and expanded graphite were tested at constant heat flux of 15W/m^2 and all the samples were cooled by natural convection. They concluded that porous copper provided better heat transfer performance than expanded graphite due to their continuous inter- connected structures.

Li et al [13], performed experimental and numerical studies on the melting phase change heat transfer in paraffin-saturated in open- celled porous copper materials. The aim of their study was to investigate the melting process of paraffin in porous copper structures. The experiments were conducted with high porosity porous copper samples with porosity ($\epsilon \geq 90$), and pore size ranging from 10 PPI to 40 PPI. The wall and inner temperature distribution in pure paraffin PCM and porous copper materials saturated with paraffin were measured during the melting process at a constant heat flux of 400 W/m^2 . They observed that the porous copper- PCM composites showed better thermal performance than the pure paraffin material because the effective thermal conductivity of the PCM was improved by the copper metal matrix.

Zhao et al [14] reported that high porosity ($\geq 85\%$) open- celled porous metals are considered as one type of most promising thermal conductivity enhancer of phase change materials due to their high thermal conductivity and high surface area density, They investigated the thermal conductivity enhancement of paraffin wax RT 58 with porous copper samples having porosities between 85% to 95% and pore sizes ranging from 10- 30 PPI. Their results showed that the thermal performance of the paraffin wax increased as the pore density of porous copper was increased and relative density increased.

Lafdi et al [15] investigated the effects of using porous aluminium as a thermal conductivity enhancer for thermal cooling of electronic system with pulsed power profile. Results of their numerical simulation showed that the performance of porous aluminium/PCM composite is dependent on porosity/relative density, pore size, foam thermal conductivity and viscosity of the liquid phase of the PCM. Senobar et al [16] experimentally compared the effectiveness of using copper oxide nanoparticles and porous copper foams together and separately for improving the performance of an organic PCM (RT44HC) and reported that the PCM- nanoparticle- metal foam composites showed the highest heat transfer performance and that this was followed by the PCM- copper foam composites and then by the PCM- nanoparticle composites.

The total charging time is a critical design parameter for latent heat thermal energy storage systems. The literatures- thus reviewed show that incorporation of porous metals into phase change materials can improve the thermal performance of the PCMs and hence reduce their charging time. Till date majority of researches on PCM enhancement technique by means of incorporation of porous metals have centred mainly on the high porosity copper foam/paraffin system and have shown that the embedding of PCM in porous metals improves thermal conductivity and thermal performance. The heat transfer process and performance of PCMs infiltrated into medium porosity (60- 70%) - porous metals is much less understood. The thermal efficiency of these relatively cheap porous materials which have structures that are uniquely different from the high porosity porous metals has not been well researched even though that the medium porosity porous metals produced from high thermal conductivity material such as aluminium can be manufactured at low cost and can in theory produce higher rates of heat transfer, thus resulting in shorter melting time than their high porosity equivalents due to the increased effective thermal diffusivity. Moreover, no investigation has so far been seen for the performance of porous aluminium structures with dual pore sizes on the thermal performance enhancement of phase change materials used in thermal storage systems. This research work will focus on evaluating the heat transfer performance of stearic acid PCM infiltrated in medium porosity porous aluminium structures.

2. Experimental Procedure

2.1. Porous aluminium manufacturing and characterization

Seven porous aluminium samples with different pore sizes and porosities were fabricated and infiltrated with stearic acid to form PCM/porous aluminium thermal composites. The porous aluminium samples were manufactured by infiltrating molten 99.5% aluminium (at 800⁰C) through sodium chloride beads of different size ranges in a stainless steel mould (pre-heated to 600⁰C) part- inserted into a vacuum chamber and allowing the melt to solidify under a suction pressure of 0.9 bar. Four different salt bead size ranges (1.0-1.4 mm; 1.4-2.0 mm; 2.0-2.5 mm and 2.5- 3.1 mm) were used. The different bead sizes were used to vary the pore size of the porous aluminium samples while the porosity of the samples was varied by varying the packing density of the NaCl beads by means of combining large (2.0-2.5mm) and small (0.5-1.0mm) beads and by compacting a bed of beads using a hydraulic press. The salt beads were produced using the procedure described in [17]. Manufactured samples (with solid base) were machined into Ø 30 X 45 mm cylinders and immersed in a hot water bath maintained at 70⁰C for 48 hours in order to dissolve the salt beads. The pore structure of the resulting porous aluminium samples was characterized using the scanning electron microscope (SEM). The samples were weighed and infiltrated with stearic acid by immersing them in a beaker containing molten stearic acid wax, maintained at 90⁰C for 30 minutes. The arrangement was put inside a desiccator in which a pressure of 1.02 bar was applied for infiltration of PCM to occur. The PCM/porous aluminium thermal composite samples were cooled, re- weighed and preserved for subsequent analyses.

2.2. Thermal Analysis

The test rig for the evaluation of the thermal performance of the PCM/porous aluminium thermal composite samples is schematically shown in fig.1. It consists of three main parts: main test section; infrared camera (FLIR

SC7000); and a data acquisition system. Heat transfer performance was determined by measuring the time for both the empty porous aluminium and PCM/porous aluminium thermal composite samples to attain 60 and 80°C at ¾ height using an infrared camera. The temperature reading of the infrared camera was measured at emissivity values ranging from 0.96- 1.0 and compared with a K-type thermocouples embedded in the samples and the camera measurements at emissivity of 0.96 compared very closely with those of the thermocouple. The outer surface of the samples was covered with high temperature adhesive tape to avoid PCM leakage, spray- painted with matt black paint to improve emissivity and the base was coated with a thermal paste (RS 217-3835) to reduce contact resistance between the samples and the hot plate. Stainless steel and copper plates were used to act as thermal buffer. The infrared camera was operated at a frequency of 10 Hz for 600 seconds at a constant hot plate temperature of 100 °C. Thermal analysis of the PCM was performed using K- type thermocouples positioned at ¼, ½, ¾ of the height of a PCM cylinder cast into a hollow concrete (thermal conductivity, K = 0.2- 0.3 W/m.K [18]) with core size measuring Ø33x45 mm (weighing 46 g) and which was mounted on an aluminium base plate with 5 mm thickness. Concrete was chosen because it has a comparable thermal conductivity with stearic acid and this will ensure one- dimensional heat flow. The PCM, encased in a hollow concrete was heated at 100 °C and temperature changes with time was recorded for 4 hours.

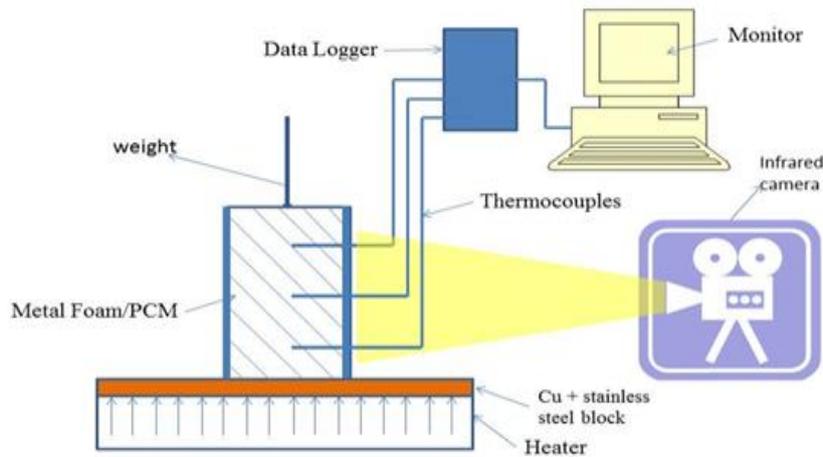


Fig.1. Experimental set-up for thermal analysis

3. Results and Discussion

Some physical properties of the porous aluminium samples and the amount (Δm_i) and degree of PCM infiltration into the porous structures are presented in Table 1. The Relative density (ρ_r), porosity (ϵ) and the degree of PCM infiltration (α) into the porous samples were determined using the following equations [19],[20]:

$$\rho_r = \frac{\rho^*}{\rho_s} \quad (1)$$

$$\epsilon = 1 - \frac{\rho^*}{\rho_s} \quad (2)$$

and

$$\alpha = \frac{M_{actual}}{M_{ideal}} = \frac{\Delta m_i}{\epsilon V_t \rho_{pcm}} \quad (3)$$

Where, ρ_s is the density of the solid material the porous material is made of ($\rho_{Al} = 2.7\text{g/cc}$ [18]) and ρ^* is the density of porous metal, M is the mass of PCM, Δm_i is the mass of infiltrated PCM and V_i is the total volume of sample. ρ_{PCM} is the density of PCM. ($\rho_{PCM} = 0.94\text{ g/cc}$ [21]). It can be noticed from Table 1 that the degree of infiltration of PCM into the porous materials ranges from 79 to 86%.

Table 1. Some physical properties of the porous aluminium samples

Sample	Density (g/cc)	Relative density	Porosity	Δm_i (g)	α
2.5L	1.07	0.40	0.60	13.01	0.81
2.0L	1.03	0.38	0.62	12.98	0.79
1.5L	1.10	0.41	0.59	12.90	0.81
1.0L	1.20	0.44	0.56	12.96	0.86
1.5P	0.90	0.33	0.67	14.10	0.79
2.0+0.5L	1.00	0.37	0.63	13.94	0.83
2.0+0.5P	0.92	0.34	0.66	14.22	0.81

In the nomenclature of the samples presented in Table 1, 2.5L represents a porous sample manufactured by using the 2.5-3.1 mm loosely packed sodium chloride beads while 2.0+1.5P represents a sample which was manufactured by combining the 2.0-2.5mm and 1.5-2.0 mm NaCl beads and pressed prior to infiltration with molten aluminium.

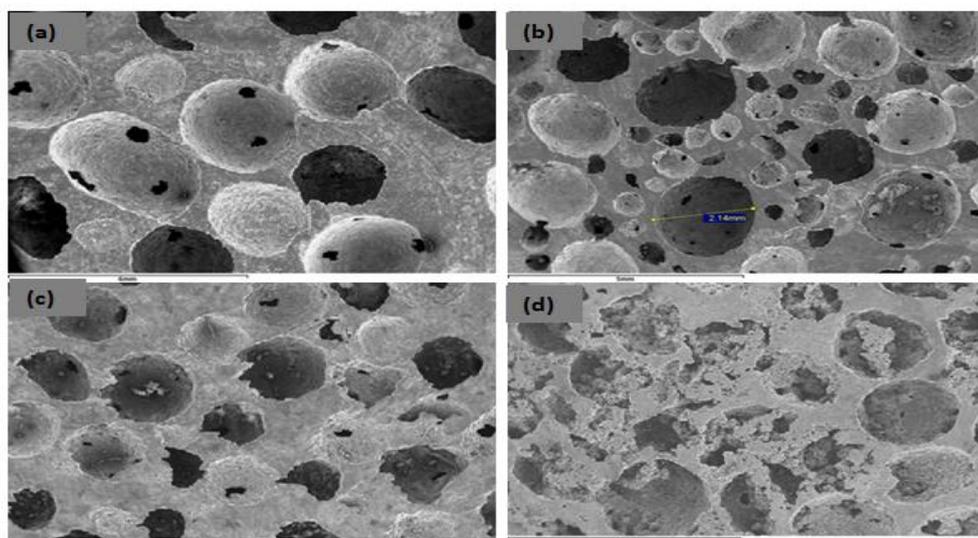


Fig.2. SEM images of porous aluminium samples: (a) Single pore porous aluminium with cell size of 2.25mm; (b) Dual pore sized porous aluminium; (c) Single pore porous Al with pore size of 1.75 mm and (d) Porous Al formed from compressed NaCl beads

Fig.2 shows the SEM images of the porous aluminium samples and as shown, the structure consists of spherical pores which replicate the shape and size NaCl beads from which they were manufactured and which are interconnected by windows. The windows allow the passage of fluid within the porous materials. Figs. 2a and 2c present SEM images of single pore porous aluminium samples. Fig.2b shows SEM image of a dual core sample while Fig.2d shows the SEM image of a porous Al sample manufactured from compressed beads. The effective thermal conductivity and the ability of the porous material to transfer heat by convection are largely dependent on the physical (porosity and relative density) and morphological (pore size and ligament thickness) characteristics of porous metal [22].

3.1. Heat Transfer Performance

Heat transfer performance of the porous aluminium samples and PCM thermal composite samples was determined by thermography and by measuring the change in time (Δt) for the empty porous aluminium samples and those infiltrated with stearic acid phase change material to be heated through 60 and 80°C. The temperatures, 60 and 80°C were chosen because the stearic acid PCM melts within this temperature range [23]. Δt for the empty and PCM- filled samples are shown in Tables 2 and 3 respectively for the temperature field of the samples acquired at a small area of the $\frac{3}{4}$ of the height of the samples while Table 4 shows a comparison of heat transfer performance shown by the thermal composites.

Table 2. Time for empty porous aluminium samples to attain 60°C and 80°C, at $\frac{3}{4}$ Height and operating temperature of 100°C

	2.5L	2.0L	1.5L	1.0L	1.5P	2.0+0.5L	2.0+0.5P
$t_{60}(\text{sec})$	21.7±.8	23.4±.4	18.8±.5	21.1±.8	30.9±.4	22.3±.3	23.4±.5
$t_{80}(\text{sec})$	40.2±.7	47.6±.5	36.7±.4	40.2±.6	65.2±.3	47.5±.4	50.7±.6
$\Delta t(\text{sec})$	19.1	24.2	18.5	17.9	34.3	25.2	27.3
ρ_r	0.40	0.38	0.41	0.44	0.33	0.37	0.34

Table 3. Time for composite porous aluminium/PCM structures to attain 60°C and 80 °C at $\frac{3}{4}$ Height and operating temperature of 100°C

	2.5L	2.0L	1.5L	1.0L	1.5P	2.0+0.5L	2.0+0.5P
$t_{60}(\text{sec})$	50.2±0.2	65.0±.6	53.1±.5	44.6±.8	100.6±.7	70.7±.5	93.1±.9
$t_{80}(\text{sec})$	174.2±.9	226.9±.7	175.5±.5	129.1±.4	305.6±.4	244.4±.4	301.8±.5
$\Delta t(\text{sec})$	124.0	161.9	122.4	84.5	205.0	173.7	208.7
$\Delta t/\text{g pcm}$	9.53	12.53	9.49	6.52	14.54	12.46	14.68

Table 4. Comparison of heat transfer performance enhancement shown by the thermal composite samples

Sample	Mass of PCM (g)	Time @ 60 °C (t_{60}) Sec	t_{60}/g PCM (Sec/g)	Performance Enhancement
2.5L	13.01	50.2±0.2	3.9	18X
2.0L	12.98	65.0±0.6	5.0	14X
1.5L	12.90	53.1±0.5	4.1	17X
1.0L	12.96	44.6±0.8	3.4	20X
1.5P	14.10	100.6±0.6	7.1	10X
2.0+0.5L	13.96	70.7±0.5	5.1	14X
2.0+0.5P	14.22	93.1±0.9	6.6	11X
PCM (only)	46.00	3200 ±2.1	69.6	-

It can be noticed from tables 2 and 3, that the heat transfer performance of the empty porous aluminium samples and the PCM thermal composites as estimated by Δt , increases with relative density and is highest for the 1.0L samples and least for the 2.0+0.5P test coupons. The temperature versus time curve for the stearic acid PCM is shown in fig.3. The time for the stearic acid (46g) to attain 60°C can be estimated from the thermograph of the PCMs transient thermal behaviour at $\frac{3}{4}$ height as 3200 seconds. As shown in Table 4, the thermal composites can show up to 20 times improvement of performance as their relative densities are increased.

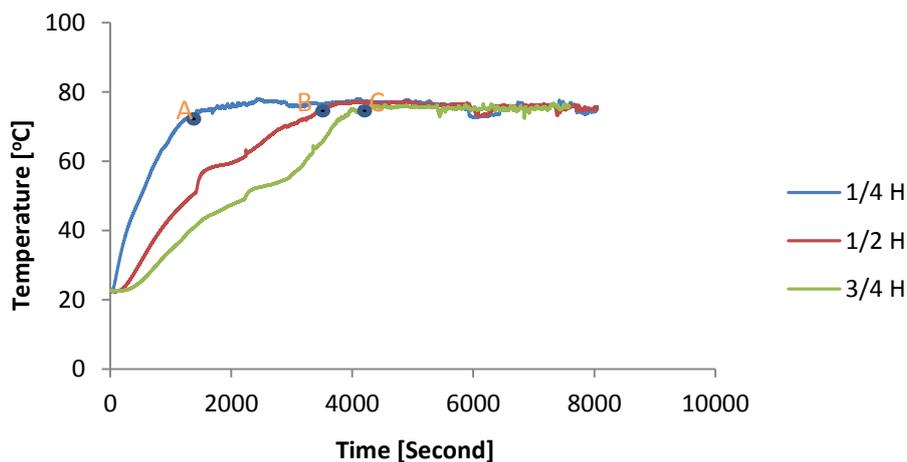


Fig.3. Temperature Vs time curves for pure stearic acid PCM heated at 100°C

3.2. Effect of Relative Density

The effect of relative density on the temperature changes with time for the PCM/porous aluminium thermal composite samples at $\frac{3}{4}$ H and operating temperature of 100°C is shown in figs. 4 and 5 for the mono-pore and dual pore PCM thermal composite samples respectively. As seen in fig.4, the thermograph of the 1.5L thermal composite sample shows an initial steeper temperature versus time curve and shorter melting duration as well as

attained higher temperature than the 1.5P sample before approaching a near- steady state condition. This can be attributed to higher effective thermal conductivity of the 1.5L sample. Fig.4 also shows a typical heating profile of stearic acid- phase change material infiltrated in porous aluminium material. As shown, three distinct regions can be identified: solid; melting; and molten. The temperature of the stearic acid rises quickly at the beginning of the heating process and then reaches to a plateau, at about 60°C, indicating the commencement of a phase change process (melting). Heat transfer prior to the plateau region is dominated by conduction. A combination of conduction and convection determines the rate of heat transfer at the plateau or melting region and in the molten region [24]. The slope of the Temperature-Time curve reduces on completion of melting since the PCM at this stage is approaching the temperature of the hot plate and ΔT for heat transfer is significantly low.

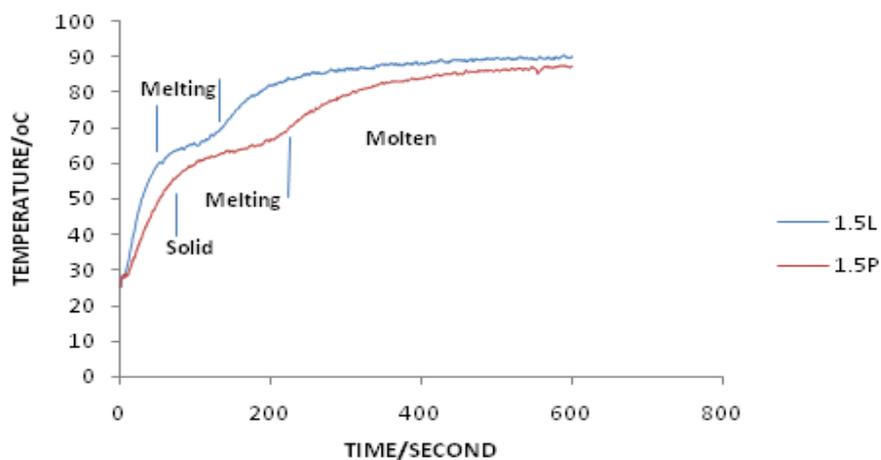


Fig.4. Effects of relative density on the transient temperature changes at $\frac{3}{4}$ H for mono pore- sized Al foam/PCM samples heated at 100°C

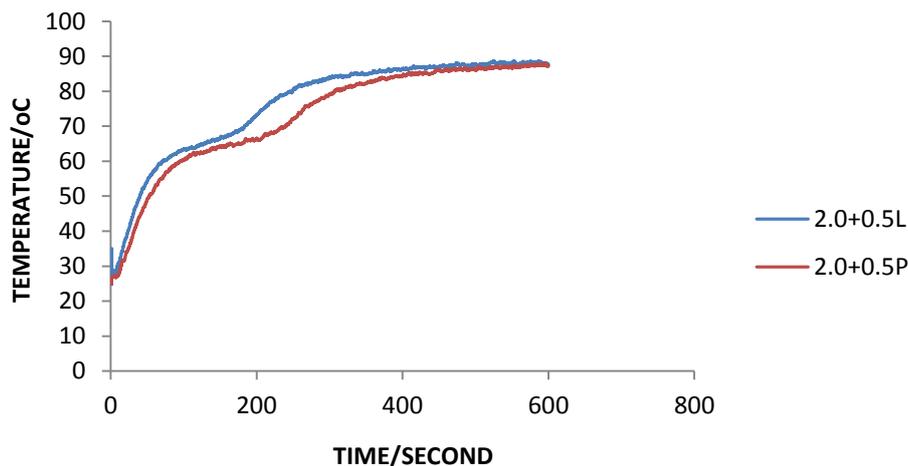


Fig.5. Effects of relative density on the transient temperature changes at $\frac{3}{4}$ H for dual pore- sized Al foam/PCM samples heated at 100°C

3.3. Comparison between Mono and Dual Pore Thermal Composites

The effect of infiltrating PCM in porous aluminium structures with mono and dual pore sizes on its thermal response is shown in fig.6. It can be seen from this figure that the time for the PCM to attain the melting

temperature range is approximately the same in these porous samples. The samples have relative density of 0.38 and 0.37 (table 2) for the mono and dual- sized foam respectively. The marginal improvement in heat transfer performance by the 2.0L thermal composite is probably due to its slightly higher relative density.

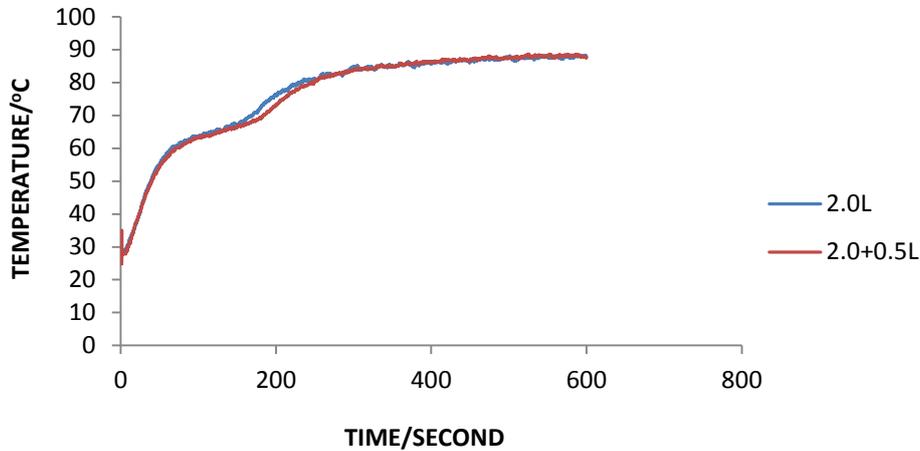


Fig.6. Effect of dual pore sized porous structure on thermal response of PCM

4. Conclusions

Utilization of porous aluminium in the manufacturing of PCM thermal composites can be more beneficial in reducing the time for attaining phase change temperature in energy storage systems based on stearic acid than using ‘pure’ stearic acid as phase change material. The porous aluminium materials were manufactured by infiltrating liquid aluminium through the pore space between dissolvable sodium chloride beads under a specific infiltration pressure while the relative density of the porous aluminium was varied by using NaCl beads of different sizes and packing densities and by compacting the beads. The study finds that infiltrating stearic acid into porous aluminium structures can reduce the time for the PCM to attain phase change temperature and increase heat transfer performance by up to twenty times. The study further indicates that the heat transfer performance of the PCM thermal composites increases with the relative density of the porous aluminium structures and that heat transfer performance are dependent more on relative density than on the duality of the pore structure. Future research will seek to further enhance the stearic acid/porous aluminium thermal composite performance through the addition of nanoparticles.

Declarations

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Competing Interests Statement

The author declares no competing financial, professional and personal interests.

Consent for publication

Author declares that he/she consented for the publication of this research work.

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