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Liquid metal gallium laden organic phase change material for energy storage: An experimental study

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ABSTRACT

This paper presents the experimental study on the thermophysical behavior, thermal cyclic characteristics and energy storage performance of liquid metal (LM) laden in organic solid-liquid phase change material (PCM) for energy storage. In this view, Gallium (Ga) is added into D-Mannitol (DM) with a weight fraction of 0.1% and 0.5% by dispersion technique using a ball mill. Repeated melting/freezing cycle was carried out for 350 cycles and the samples were characterized using Differential Scanning Calorimetry (DSC), Thermogravimetry Analysis (TGA) and Fourier Transform Infrared (FTIR). The DM/Ga composite PCM showed enhanced thermal conductivity of ~8.4%, ~27.8% for 0.1 and 0.5 wt % Ga as compared to pure DM. XRD studies reveal that the pure DM exhibited β polymorphic phase while TGA and FTIR analysis confirm the thermal reliability and chemical stability of composites in the temperature range of 50–200 °C. Non isothermal crystal kinetic study proved that the addition of Ga increased the crystallization rate due to heterogeneous nucleation effect and leads to the reduction in subcooling temperature of the PCM. The experimental setup results to test the charging and discharging performance of the composite PCM revealed that the total time for one complete cycle reduced from 97.48 min for pure DM to 84.73 min and 63.92 min for DM-Ga composite with 0.1 wt % and 0.5 wt % respectively. Based on the results obtained, D-Mannitol based composites could be recommended as potential PCM candidates for solar heat and industrial waste heat recovery application due to its high energy density capacity, thermal/chemical stability and good heat transfer performance.

Introduction

Depleting fossil fuel and increasing in CO_2 emission are pushing the research in direction of renewable energy usage as primary fuel, which is becoming a trend currently. Most of the world's leading economies are aiming for zero emission buildings and reusing the waste heat released from the industrial sources [1]. In this view, one of the best method of storing waste heat and solar energy as latent heat are thermal energy storage (TES) systems [2,3]. Energy is stored in these system by the use of phase change materials (PCM). PCM are materials which undergo phase change, usually from solid to liquid absorbing huge quantities of energy at ideally constant temperatures. This stored energy can be retrieved back again by converting the phase from liquid to solid phases. Energy is stored in the form of sensible heat, latent heat and thermochemical heat storage. Phase change materials are generally

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Abbreviation

Al_2O_3	Alumina
CNF	Carbon nanofibres
CNT	Carbon nano tubes
DM	D-Mannitol
DM-Ga	D-Mannitol-Gallium Alloy composites
DSC	Differential Scanning Calorimetry
FT-IR	Fourier Transform Infrared
FWHM	Full Width Half Maximum
Ga	Gallium
GNP	Graphene Nanoplatelet
JCPDS	Joint Committee on Powder Diffraction Standards
LFA	Laser Flash Apparatus
LHES	Latent Heat Energy Storage
LM	Liquid Metal
MWCNT	Multi-Walled Carbon Nanotubes
PCM	Phase Change Material
RSS	Root Sum Square
SiO_2	Silica
SA	Sugar Alcohol
SCF	Short Carbon Filler
SEM	Scanning Electron Microscopy
TES	Thermal Energy Storage
TGA	Thermogravimetric Analysis
TiO_2	Titania
ZnO	Zinc oxide

Greek Symbol

β	Beta Polymeric Phase of D-Mannitol

Nomenclature

C_p	Specific heat (J/kg·K)
T	Temperature(°C)
k	Thermal conductivity(W/m·K)
t	Time(min)
l	Thickness of sample

Subscript

c	Crystallization
e	End
o	Onset
p	Peak

classified into organic, inorganic and eutectic mixtures [4,5]. Organic PCM mainly consist of paraffins, fatty acids and sugar alcohols. Inorganic mixtures are generally salt hydrates, metals and salt solution. Eutectic mixtures are compositions of any two or more organic/inorganic combinations designed for a specific phase change temperatures application. Organic PCM are non-corrosive, have low subcooling temperature and generally have good stable cycling stability as compared to inorganic PCM [6]. Paraffin and fatty acids are solid-liquid organic phase change materials that have been researched extensively for low temperature heat storage application due to their good heat storage density, low cost and stability over the working range of temperatures. Sugar alcohols (also called as polyalcohols or polyols) are organic PCMs mainly considered for medium temperature latent heat storage systems in the temperature range of 50–200 °C [7]. One of the disadvantages of the organic PCM for energy storage is its very low thermal conductivity leading to inefficient heat transfer performance during charging and discharging cycle. Various researches have been done to improve the thermal performance of the LHES system by using enhancement techniques such as PCM encapsulation, design of container shape and orientation, integration of fins, multi PCM design, and high conductivity additives in PCM. Of the many enhancement techniques, the addition of high thermal conductive additives in base PCM to form composites has gathered much attention from the research community [8]. Among the additives include metal/metal oxides, metal nano wires [9–12], carbon nanofibres (CNF), carbon nano tubes (CNT) [13,14] and graphene/graphene nanoplatelets (GNP) [15–17]. Although the addition of high thermal conductive material in micro or nano scale in the base PCM has resulted in an increase in effective thermal conductivity of the composites, research shows that other properties like latent heat, melting and solidification points and decomposition temperatures get affected by the presence of nanoparticles. Teng et al. [18] studied the effect of adding nanosized metal oxide in paraffin using direct synthesis method. Alumina (Al_2O_3), Titania (TiO_2), Silica (SiO_2) and Zinc oxide (ZnO) were dispersed in the concentration of 1, 2 and 3 wt % to form nanocomposites PCM. Their study showed that addition of TiO_2 reduces the melting onset temperature and increases the solidification temperature of paraffin. They demonstrated that as compared to all other metal oxide nano additive, TiO_2 is the most effective in thermal storage performance and the proposed nanocomposites has significant potential for enhancing thermal storage characteristic of paraffin. Moloud et al. [19] studied the thermal behavior of paraffin enhanced with Al_2O_3 nanoparticles with a mass fraction of 2.5, 5, 7.5 and 10% respectively for the application of low temperature range of 50–60 °C. They conducted thermal cycling study for 120 cycles and the results showed that addition of nano-Al_2O_3 enhanced the thermal conductivity of samples by 31% for 10 wt % mass fraction while the melting rate increased by 27%. Tao et al. [20] investigated the increase in thermal conductivity of liquid paraffin based suspension using various carbon nano-additives of various size and shapes. Carbon nano-additives included short and long multi-walled carbon nanotubes (MWCNTs), carbon nanofibers and graphene nanoplatelets. From the results obtained it was concluded that of the various carbon nanofillers tested, GNPs exhibited highest thermal conductivity enhancement. For 4 wt % GNPs, the thermal conductivity was measured to be as high as 0.29 W/m·K, which was nearly 100% increase as compared to pure paraffin. Yanbin et al. [21] explored experimentally the effect of addition of carbon nanofiber (CNF) and carbon nanotube (CNT) on thermal behavior of paraffin wax. CNF and CNT were mixed in paraffin wax with the level of 1, 2, 5, and 10 wt %. The results showed that compared to CNT, CNF showed effective thermal conductivity enhancement of the paraffin composite due to better dispersion in the matrix. Sahan et al. [22] reported an improvement in thermal conductivity of paraffin by adding nanomagnetite (Fe_3O_4) by mixing technique. Nanoparticles were added in the ratio of 10% and 20% mass fraction in the