



# Design, fabrication and numerical analysis of compact thermal management system integrated with composite phase change material and thermal bridge

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## ABSTRACT

Thermal management system requires robust design as well as suitable paraffin/expanded graphite composites for confining the temperature of heat source within safe limits. However, paraffin/expanded graphite composites provide thermal management only for a certain period of time i.e. until the attainment of saturation energy storage limit. Herein, design, fabrication and simulation of a compact paraffin based thermal management system equipped with thermal bridge are presented. By keeping the highest safe temperature limit of batteries i.e. 65 °C and phase transition of paraffin as the test standards, performance of heat source was evaluated in terms of its total temperature retardation time along with quantitative effect of paraffin/expanded graphite composite. In the light of fundamental theories on mass and energy balance, substantial design steps and certain empirical equations have been introduced with further validation through experimental analysis. With heat dissipation rate of 6 W, it has been found that 75 g paraffin/expanded graphite composite with melting temperature of 54 °C kept the heat source temperature under the highest safe limit for around 13,000 s, providing the longest temperature retardation time in comparison to other types of paraffin/expanded graphite composites. Further, differential scanning calorimeter depicted that latent heat of 5 wt% paraffin/expanded graphite composite was slightly reduced from 182 J/g to 174 J/g even after 400 accelerated thermal cycles, demonstrating the promising thermal reliability and long life, which fits well with the set criterion of overall life expectancy of batteries. Besides, finite element analysis conducted via computational fluid dynamics software Fluent established qualitatively reliable fitness with experimental results.

## 1. Introduction

Energy utilization with long-term reliability and better safety control has become the main concern across the globe. Battery technology is getting widespread attention especially for deploying the heavy transportation means on Li-ion batteries [1]. And also based on the highest specific energy, Li-air batteries are acquiring fame in the automobile industry [2]. Meanwhile, the safety threats like thermal runaway, capacity fade and poor thermal management of batteries require more consideration [3]. In specific, the batteries commonly suffer from the undesired heat dissipation issues. For example, each 10 °C elevation above the certain level renders the chemical reaction rate in batteries almost double [4]. Thus, such vulnerabilities need to be controlled through vigorous thermal management systems (TMS) for performance

enhancement and failure prevention at quite higher temperatures [5]. To address such issues, latent heat based passive thermal management system integrated with forced draft water cooling has been proposed, providing temperature control capacity better than active systems alone [6]. Consequently, attention has been paid on the thermal storage units incorporated with phase change materials (PCMs), which are safe, compact and economically feasible [5]. Regarding solar energy based devices, drastic temperature rise rates of solar panels found a reliable temperature control, for instance, less than 50 °C for 200 min with paraffin/expanded graphite composites [7]. Likewise, undesired heat dissipation from batteries can be managed via carbon-fiber loaded phase change composites so as to avoid the thermal runaway conditions [8]. However, low thermal conductivity and liquid exudation especially of paraffin waxes are the key challenges, hampering their robustness in

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**Nomenclature**

$A$	area (m <sup>2</sup> )
$c_{ps}$	specific heat before solid–solid phase change
$c_{pl}$	specific heat after solid–liquid phase change
$c_p$	specific heat capacity of PCM (J/gK)
$c_{pw}$	specific heat of water (J/kg K)
$H$	enthalpy (J)
$h_w$	water convection coefficient (W/m <sup>2</sup> K)
$h_a$	air convection coefficient (W/m <sup>2</sup> K)
$I$	current (A)
$K$	thermal conductivity (W/m K)
$LH_{sl}$	latent heat of solid–liquid phase change (J/g)
$LH_{ss}$	latent heat of solid–solid phase change (J/g)
$m_{PEC}$	mass of PEC (g)
$Q_d$	heat dissipation rate (W)
$Q_{gen}$	total heat generation (J)
$Q_r$	total heat retained (J)
$Q_l$	total heat losses (J)
$Q_{lh}$	total latent heat of PCM (J)
$Q_{sh}$	total sensible heat of PCM (J)
$Q_t$	thermal energy storage capacity of PCM (J)

$R$	resistance ( $\Omega$ )
$T_s$	solid–solid phase change temperature (K)
$T_l$	solid–liquid phase change temperature (K)
$T_i$	initial temperature (K)
$T_f$	final temperature (K)
$T_{fw}$	final temperature of water (K)
$T_{iw}$	initial temperature of water (K)
$T_w$	temperature of TMS' walls (K)
$T_{rt}$	total temperature retardation time (s)
$v_w$	volume of water (m <sup>3</sup> )
$\rho_w$	density of water (kg/m <sup>3</sup> )

**Abbreviations**

CCU	composite containment unit
DSC	differential scanning calorimetry
$L_f$	liquid fraction
PCM	phase change material
PEC	paraffin/EG composite
RCCU	rectangular based cuboid CCU
SCCU	square based cuboid CCU
TMS	thermal management system

different applications. To date, these challenges have been overcome by using various thermal conductivity enhancers [9]. Among them, expanded graphite (EG) has a significant impact in enhancing thermal conductivity as well as controlling the liquid leakage of paraffin waxes [10] due to its pronounced thermal conductivity and large surface area consisting of crevice-like and net-like pores [11].

Referring to the batteries, they habitually generate heat due to electrochemical reactions and other resistive actions during charge and discharge cycles [12]. Particularly, experimental observations elucidate that the heat dissipation occurs faster under discharge rates compared with charge rates [13]. Therefore, it is highly recommended to keep the temperature of the batteries within safe operational limits. Several authors have stated that the safe operating temperature limits of batteries should be less than or maximum up to 40 °C [14], 50 °C [15] and/or 65 °C [16]. Also, it has been demonstrated that temperature rise rates almost vary directly with discharge rates [17]. Additionally, Satyam et al. determined actual heat generation rates of prismatic Li-ion battery at discharge rates of 1C, 2C, 3C and 4C as 13 W, 52 W, 69 W and 91 W, respectively [18]. Briefly, a robust thermal management system for the better life and proper performance of the batteries is indispensable. For instance, sandwich type structure has been proposed for thermal management of 10 Ah Li-ion batteries using paraffin/foam composite. Results showed that phase change based thermal management system kept the temperature under 65 °C for total time of 1080 s at 3C discharge rate [16]. In another case, thermal management of 4 V Li-ion cells being enclosed in aluminum cylinders was done by simply inserting paraffin/graphene composite in the spaces among the batteries [19]. In addition, a passive thermal management system integrated with paraffin/graphite-sheet composite has also been experimented and simulated. Results depicted that the highest temperature rise at discharge rate of 2C was lowered down from 43.4 °C to 27.7 °C [20]. Therefore, paraffin-based phase change systems provide quite a reliable thermal management to the batteries. However, selection of the right paraffinic thermal storage material is vital as it would directly affect the thermal performance of thermal storage units.

Substantial design steps of thermal management systems and fabrication of models are still far away from the industrial breakthrough, and heat regeneration of phase change material itself needs to be addressed especially when heat source works at high heat dissipation rates for a longer period of time. Therefore, we focus on design and fabrication, and a prototype model proposal of PCM-based TMS in

collaboration with mathematical modeling and numerical analysis through ANSYS Fluent. Paraffin/expanded graphite composites (PEC) with various melting temperatures of 42–44 °C, 52–54 °C, 58–60 °C and 60–62 °C have been utilized to optimize the thermal performance of battery thermal management system. Further, performance of thermal management enclosure has been determined in terms of total temperature retardation time of heat source with and without enlisted paraffin/EG composites. Besides, thermal reliability of paraffin/EG composites has been precisely taken into account via thermal cycling analysis followed by measurement of total latent heat.

**2. Experimental****2.1. Materials and prototype fabrication**

Paraffin waxes were bought from Shanghai Huayong Ltd., China. EG has been used with 50 mesh size micro-particles. Paraffin/EG composites were prepared at 5 wt% loading of EG. Thermophysical properties of paraffin and paraffin/EG composites have been enlisted in Table 1. In the current work, cylindrical shaped resistor ( $\varnothing 10$  mm  $\times$  65 mm, 20 W & 12 V) has been used as a heat source. Resistance of the resistor measured using multimeter (Fluke 179) was 10  $\Omega$ . In an insulated enclosure, resistor was subjected to constant current 0.55 A, 0.77 A and 1.1 A through regulated DC power supply (TPR3005T-3C) with further conversion of these values into corresponding heat dissipation rates 3 W, 6 W and 12 W, respectively. Resistor's surface temperature was recorded by thermocouples of paperless temperature recorder (YOKOGAWA GP10). Subsequently, performance of heat source was evaluated by inserting it in the middle of fabricated enclosure, which was filled with slightly heated paraffin/

**Table 1**

Thermo-physical properties of paraffin (P) and 5% paraffin/EG composite (PEC) at 25 °C.

Properties/materials	P	PEC <sub>44</sub>	P	PEC <sub>54</sub>	P	PEC <sub>60</sub>	P	PEC <sub>62</sub>
Melting temperature (°C)	42–44		52–54		58–60		60–62	
Specific heat (J/gK)	1.90	2.01	2.03	2.22	1.93	2.02	1.92	2.03
Density (kg/m <sup>3</sup> )	930	1056	967	1002	982	1013	901	1012
Thermal conductivity (W/m K)	0.27	4.77	0.22	3.16	0.24	2.88	0.26	2.59
Total latent heat (J/g)	205	179	184	173	183	170	193	182

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