



Research Paper

Probing the cooling effectiveness of phase change materials on lithium-ion battery thermal response under overcharge condition

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HIGHLIGHTS

- A lumped model of battery under overcharge scenario with composite PCM was built.
- The current rates and thickness of PCM influence the cooling effectiveness of PCM.
- The thermal contact resistance makes inconformity of temperature rise between cell and PCM.
- The utilization of PCM with lower melting temperature has better cooling effect.

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ABSTRACT

Usage of phase change materials (PCM) can help reduce the safety risk during LIB operation. This work investigates the cooling effectiveness of PCM on lithium ion battery operation under overcharge scenario. Combined with adiabatic overcharge tests at 0.1, 0.2, 0.5, 1, 2 current rates (C-rate), the relationship of cell thermal performance and cooling efficacy with C-rates, thermal contact resistance, amount and melting temperature of PCM are analyzed by lumped model. Results indicate steep decline of cooling effectiveness with C-rate increase. Temperature difference between cell and PCM is stable below 1C, however, abrupt hikes are observed at higher C-rates. Effectiveness increase with PCM thickness is also seen up to a critical thickness of 3 mm beyond which minimal change is observed while thermal contact resistance is found to enlarge the temperature difference between cell and PCM during the melting process causing wide variability in cooling effectiveness magnitude. For similar latent heat and density material, low melting temperature PCM exhibits superior cooling characteristics as compared to its high temperature counterpart. The results contribute to enhanced understanding of the thermal performance of PCM and LIB during overcharge process under varying conditions.

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1. Introduction

Lithium ion batteries (LIBs) are the most popular portable energy storage units, with a tremendous range of applications. Depletion of non-renewable energy sources and environmental concerns [1,2], in conjunction with the ever increasing energy and power densities afforded by LIB, have helmed the commercial viability of electric vehicles [3–5]. Nonetheless, although the manufacturing technique and production quality have progressed substantially, safety poses a big challenge [6,7]. The explosion event of Samsung cellphone is a typical battery safety accident because of the manufacturing error induced internal short of battery [8].

Abnormal operations such as short circuit, penetration, overheat and overcharge induce large heat generation which also accelerate deleterious side-reactions to produce more heat inside the battery [9–13]. A protection mechanism is necessary for LIB to impede the rapid heat generation leading to runaway behavior.

For optimal operation of LIB, a few cooling methodologies have been adopted in large applications such as the electric vehicle and grid energy storage. In these applications, battery cells are usually connected in parallel and series to provide higher power and electrical voltage. A proper battery thermal management system (BMS) is utilized to keep the battery in optimum operating temperature between 20 and 40 °C. Air and liquid based BMSs are conventionally adopted in vehicles [14]. However, such BMSs are plagued by certain deficiencies, such as the low heat transfer coefficient of air based system and potential danger of short circuit in liquid based system. To circumvent these drawbacks, phase change

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Nomenclature

A	surface area (m^2)	σ_{asp}	RMS surface roughness (m)
A_x	pre-exponential factor	P	contact pressure (Pa)
c_1	Vickers micro-hardness coefficient (GPa)	P_g	gas pressure (Pa)
c_2	Vickers correlation size index	Pr	Prandtl number
c_x	concentration of reactant x (mol m^{-3})	Q_{gen}	heat generation of cell (J)
C_Λ	mean free path constant ($\text{N m}^{-1} \text{K}^{-1}$)	Q_p	heat generation of over-potential heat (J)
$C_{p,\text{al}}$	specific heat capacity of aluminum ($\text{J kg}^{-1} \text{K}^{-1}$)	Q_{rev}	heat generation of reversible heat (J)
$C_{p,\text{PCM}}$	specific heat capacity of composite PCM ($\text{J kg}^{-1} \text{K}^{-1}$)	Q_h	heat generation of side reactions heat (J)
$C_{p,s}$	specific heat capacity of PCM in solid phase ($\text{J kg}^{-1} \text{K}^{-1}$)	R	gas constant ($\text{J K}^{-1} \text{mol}^{-1}$)
$C_{p,l}$	specific heat capacity of PCM in liquid phase ($\text{J kg}^{-1} \text{K}^{-1}$)	R_{B-P}	thermal contact resistance between battery and PCM (K W^{-1})
E_a	activation energy (J mol^{-1})	R_{amb}	ambient thermal resistance (K W^{-1})
h_{amb}	ambient heat convection coefficient ($\text{W m}^{-2} \text{K}^{-1}$)	R_x	reaction rate ($\text{mol m}^{-3} \text{s}^{-1}$)
h_c	equivalent contact heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)	T_{amb}	ambient temperature (K)
h_g	equivalent exchange heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)	T_{PCM}	composite PCM temperature (K)
h_r	equivalent radiation heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)	T_{cell}	cell temperature (K)
H_c	contact hardness (Pa)	T_s	starting temperature of phase change from solid to mushy phase (K)
k	thermal transfer coefficient ($\text{W m}^{-1} \text{K}^{-1}$)	T_l	end temperature of phase change from mushy phase to liquid phase (K)
k_g	thermal conductivity of gas ($\text{W m}^{-1} \text{K}^{-1}$)	T_i	initial temperature (K)
k_l, k_s	thermal conductivity of PCM in liquid and solid phase ($\text{W m}^{-1} \text{K}^{-1}$)	T_g	gap temperature (K)
L	latent heat (J kg^{-1})	T_d	Temperature drop of battery (K)
M_{cell}	cell mass (kg)	T_{melt}	melting temperature (K)
M_{PCM}	composite PCM mass (kg)	ΔT	temperature difference between battery and PCM (K)
M_g	molecular weights of the gas (g/mol)	U	internal energy (J)
m	mean absolute slope	\dot{U}	rate of internal energy (W)
n	reaction order	$U_{\text{meltmin}}, U_{\text{meltmax}}$	minimum and maximum energy required to phase change (J)
Greekletters		Y	thickness of gap (m)
α	thermal accommodation coefficients	P	density (kg m^{-3})
γ	specific heats ratio	ρ_{al}	density of aluminum (kg m^{-3})
Λ	molecular mean free path (m)	ρ_s, ρ_l	density of PCM in solid and liquid phase (kg m^{-3})
σ_0	reference roughness, equals to $1 \mu\text{m}$	ε	porosity

materials (PCM) based passive thermal management system has attracted increasing interest in recent years owing to its durability, compactness, high efficiency and stationary deployment [15–18]. In the range of 0–100 °C phase change temperature, available PCMs can be divided into two categories: organic (paraffin wax, fatty acid, eutectic alloys) and inorganic (salt hydrate) materials [19]. Among them, paraffin wax exhibits high solid to liquid phase change latent heat. However, low thermal conductivity is an inherent drawback of most PCMs. High thermal conductivity additives such as metal foam, carbon foam and graphite are embedded in the PCM matrix to boost its thermal conductivity [20,21]. Mancin et al. [22] demonstrated that composite PCM presented substantially better heat transfer characteristics than pure PCM. Li et al. [23] experimentally studied the cooling effect of BMSs based on air, pure PCM and composite PCM. Results indicate that the composite PCMs exhibit the best performance in surface temperature reduction and improving uniformity of the temperature distribution, while air based natural convection cannot meet the safety demands in the battery pack. Further, Khateeb et al. [24] investigated four different modes of heat dissipation in thermal management system. The use of aluminum foam with PCM resulted in around 50% temperature decline compared to no thermal management. Many modeling works have also been conducted on PCM based battery management system. Qu et al. [25] computationally studied the cooling effect of PCM in contrast with air convection for adiabatic conditions at 1C and 3C discharge rate. Results show that PCM can dramatically reduce the surface temperature to the allowable range. Alipanah et al. [26] numerically simulated the

discharge time of battery with the BMS based on pure octadecane, pure gallium and octadecane–Al foam composite materials. Results exhibit that for temperature rise to a critical limit of 60 °C, the discharge time for composite PCM is remarkably longer than pure materials. Schweitzer et al. [27] also developed a lumped (0-D) model for simulating the thermal response of a lithium-ion battery pack with phase change materials.

Above studies mainly focused on balancing temperature variation and distribution during normal operation, with very few insights geared towards safety protection mechanisms to prevent rapid heat generation or thermal runaway behavior when cells encounter accidental abuse operations. Overcharge is one of the likely abnormal operations in practical applications. As mentioned previously, in the battery pack, cells are connected in parallel and series for high energy and power density. Inaccurate BMS control circuits coupled with internal resistance and voltage difference between individual cells can trigger overcharge or over-discharge of some of these cells during operation [28]. Pouch cells usually lack a positive temperature coefficient (PTC) and current interruption devices (CID) to protect the cell from overcharge induced high temperature and pressure. Thus, even standard battery pack operation can trip individual cells beyond the critical temperature expediting exothermic abuse reactions leading to thermal runaway [29]. Consequently, constraining individual cell temperature below the critical limit is necessary for impeding thermal runaway behavior. Here, PCM based BMS is an attractive alternative owing to its stationary deployment and passive control with good thermal characteristics. Wilke et al. [30] experimentally studied the effectiveness

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