International Journal of Heat and Mass Transfer 121 (2018) 967–977

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Thermal management optimization of a prismatic battery with shape-stabilized phase change material

Weixiong Wu, Wei Wu, Shuangfeng Wang *

Key Laboratory of Enhanced Heat Transfer and Energy Conservation of the Ministry of Education, School of Chemistry and Chemical Engineering, South China University of Technology, Guangzhou 510640, Guangdong, China

ARTICLE INFO

Article history:
Received 12 July 2017
Received in revised form 4 December 2017
Accepted 14 January 2018

Keywords:
Prismatic battery
Thermal optimization
Phase change material
Heat transfer
Thermal performance

ABSTRACT

In this paper, a three-dimensional thermal model of a prismatic battery with multi-layer structure was established and validated by the measured surface temperature of the battery. The proposed model was used to analyze and optimize thermal performance of the battery in three cases that its surface was integrated with one of three shape-stabilized phase change material (PCM) configurations. The results showed that the internal anisotropic characteristics of the prismatic battery have significant effect on the heat transfer and thermal performance of the configurations. The configuration that PCM wrapped around the battery had the best performing temperature rising and distribution due to the large thermal storage capacity of PCM and highest contact area between the PCM and the battery. Furthermore, there were critical values of PCM thickness and convective heat transfer coefficient (e.g., 2.08 mm and 10 W $m^{-2} K^{-1}$ for PCM around the cell) at which the process of phase change was almost completed, and the temperature distribution was significantly different across these values. The temperature gradient across the cell decreased as the thickness increased. However, the effect of increasing convective heat transfer coefficient on the decrease of temperature gradient was limited due to the relatively low internal heat conduction ability of the battery.

1. Introduction

With the continuous increasing pressure of environmental protection and energy shortage, the electric vehicles (EVs) using green energy power sources have attracted worldwide attention. However, the power source, i.e., rechargeable battery pack is sensitive to temperature which significantly impacts the vehicle performance, reliability and lifespan [1–3]. Hence, an effective battery thermal management (BTM) strategy is crucial for batteries needing to operate in an appropriate temperature range. In general, the BTM techniques can be summarized as several types based on the employment of heat transfer medium, such as air [4], liquid [5] and phase change material (PCM) [6] and the combination of the mediums [7]. In this way, passive thermal management strategy, such as using solid-liquid PCM as the heat transfer medium, has been demonstrated as a viable solution for BTM [8].

As an innovative solution, PCM can absorb/release abundant latent heat during the melting/solidifying process and maintain a relatively constant temperature for the PCM based system [9–11]. The PCM based system has many advantages, such as passively buffering against high operating temperature, extending life cycle and eliminating thermal runway [12–15]. In recent years, improvements for PCM based system have been widely studied. The focus of such studies has concentrated on the optimization of the thermal conductivity enhancement of PCM, the figuration and stability of composite PCM, and the temperature decrease and uniformity of batteries at module/pack level [7,16–20].

In general, a battery pack consists of hundreds or thousands of cells for EVs to fulfill the requirement of voltage and power. For the usage on cell level, PCM based strategy has been investigated experimentally and numerically for single cells in two shapes (i.e., cylindrical and prismatic shape) [21]. Duan and Naterer [22] experimentally studied the effects of PCM on a cylindrical cell. Two PCM configurations were investigated, one with a PCM cylinder surrounding the cell and the other with a PCM jacket wrapping the cell. It was shown that both configurations were effective in maintaining the cell temperature in a desired range. Rao et al. [23] proposed a three-dimensional model for individual cylindrical battery cell to investigate the effects of internal conduction and external natural convection on the temperature response and distribution. Following this study, a lattice Boltzmann model for the PCM was performed by Huo and Rao [24] to investigate the effects of thermal conductivity, latent heat and environment temperature

* Corresponding author.
E-mail address: sfwang@scut.edu.cn (S. Wang).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.01.062
0017-9310/

Nomenclature

Bi	Biot number
C	capacity (J kg^{-1} K^{-1})
H	enthalpy (J K^{-1})
h	sensible heat (J K^{-1})
I	current (A)
k	thermal conductivity (W m^{-1} K^{-1})
L	thickness (m)
m	mass (kg)
Q	heat (kW)
q	volumetric heat generation rate (kW m^{-3})
R	resistance(Ω)
T	temperature (K)
t	time (s)
U	open circuit potential (V)
V	cell potential (V)

Greek Symbols

ρ	density (kg m^{-3})
β	liquid fraction
γ	specific phase change enthalpy
Δ	change in variable

Subscripts

b	battery
dis	dissipation
d	discharge
gen	generation
max	maximum
n	negative
P	positive
0, amb	ambient

Acronyms

BTM	battery thermal management
EG	expanded graphite
EVs	electric vehicles
HPPC	hybrid pulse power characterization
PCM	phase change material
PCMP	phase change material plate
SOC	state of charge

on the thermal performance of the cylindrical battery. More information about the cylindrical cells with composite PCM and their properties and thermal performance can be found elsewhere [25–27]. Nevertheless, cylindrical cells designs are normally limited to below 4 A h while prismatic designs can be used for higher capacity [28]. In addition, from thermal management point of view, the prismatic type seems to be more suitable for EVs due to its relatively large surface area for dissipating heat [29]. A prismatic lithium-ion cell integrated with different thicknesses of PCM was proposed and numerically studied by Javani et al. [30]. This configuration was selected to develop a sub-module using the prismatic cells. Their results showed that the position of maximum temperature can be influenced by increasing the PCM thickness around the cell. Also, as indicated by Ramandi et al. [31], different PCM configurations have significant effect on the thermal performance and the exergy efficiency. By now, however, little attention has been devoted to the prismatic cell with different PCM configurations and their corresponding thermal performances.

As the thermal conductivities inside the prismatic cell is orthotropic, the temperature gradient in the cell is inevitable [32]. To achieve a comprehensive analysis, it is essential to establish a three-dimensional thermal model that considers the thermal properties and geometrical parameters of different components at cell level. In this study, a three-dimensional prismatic battery thermal model without the consideration of electrochemical side is developed and compared with the experimental data for validation. In the following sections, evolution of the temperature field and heat transfer characteristics in the battery is discussed for different shape-stabilized PCM configurations. Further, the effects of thickness and surface heat transfer coefficient on temperature rise and distribution of the battery during discharge process are also investigated in detail. These results aim to provide guidelines for thermal design and thermal management design of PCM based BTM systems.

2. Problem formulation

In general, a battery is usually formed by stacking the electrode plates together. As the geometry and the thermo-physical properties of different components within the cell are significantly different, those components can be modeled as a bulk material with an anisotropic thermal conductivity for studying the thermal performance [33]. A prismatic cell with multi-layer structure is studied in this work. Each layer of the cell consists of two current collectors (copper for anode and aluminum for cathode), a separator and two electrodes (anode and cathode), as shown in Fig. 1. Since the heat transfer and thermal performance are the main concerns here, some simplified strategies are adopted in cell modeling, such as treating the layered structure as the homogenous materials and dividing the cell into three parts, the core, the positive and negative terminals [34].

PCM/expanded graphite (EG) composite can be compressed into a mold to form a plate-shape structure by hot-compaction [35]. Such structure has obvious advantages of improved thermal conductivity and shape-stability without leakage during the solid-liquid phase change, which are favorable for practical applications in BTM system. For the external flat surface and internal multi-layer structure of prismatic cell, three different shape-stabilized PCM plate (PCMP) configurations, as shown in Fig. 2, are considered to investigate the corresponding thermal performances. In case 1, PCMP is located at the broad side surface (XY plane) of the battery cell; in case 2, PCMP is located at the narrow side surface (ZY plane) of the battery cell; in case 3, PCMP is wrapped around the cell. The volume of PCMPs in the three configurations are the same but the thickness of PCMPs are different (a, b and c). As it is symmetric in the Z direction, a half plate as shown in Fig. 2 is considered to reduce computation load.

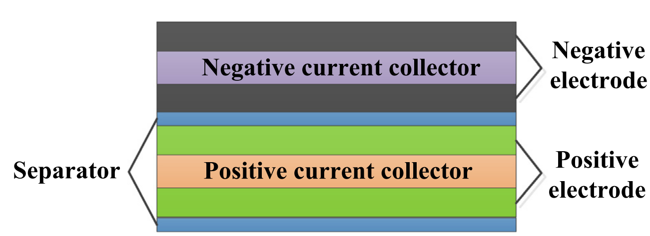

Fig. 1. Multi-layer structure within battery cell.