Engineering Science and Technology, an International Journal xxx (2018) xxx–xxx

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Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

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

Full Length Article

Numerical investigation on cooling performance of Li-ion battery thermal management system at high galvanostatic discharge

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ARTICLE INFO

Article history:
Received 21 March 2018
Revised 18 June 2018
Accepted 19 July 2018
Available online xxxx

Keywords:
Battery thermal management system (BTMS)
Li-ion Battery module
Battery temperature
Heat generation
Transient three-dimensional CFD study

ABSTRACT

Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) are clean energy transportation options emerged over traditional internal combustion engine. Li-ion batteries are a viable option for EVs and HEVs due to their advantages of high energy density. At high battery discharging condition, there is a significant increase in battery temperature and non-uniform cell temperature. The cooling performance of battery module at constant current discharge rate about 6.94 C (25 A) have presented. The two side wall of the battery module kept fully open for inflow and outflow of cooling media and better heat dissipation. Larger inter-cell spacing was considered to provide sufficient circulation of cooling air and removal of gases generated by the batteries. The heat generation in the battery cell during discharge process has simulated with the help of user-defined function (UDF). The paper gives insight into a three-dimensional transient thermal response, flow field and thermal regimes developed in the battery module. Different air temperature profiles are confirmed in the flow direction and across the width and depth of the battery pack. At specific zones, the air temperature rises to 7 °C thus indicating the localized heat spots. In the considered BTMS, maximum cell-to-cell temperature non-uniformity is restricted to 0.11 °C and battery temperature is lesser than 28 °C despite the high discharge rate and lower cooling air flow condition.

1. Introduction

The energy is required to drive industrial developments and other mankind needs. Due to limited reserves of fossil fuels and their environmental effect, efforts have been given to harnesses alternative sources of energy. The energy generated using solar and wind route is required to be stored and supply for off-grid applications due to its intermittent nature. Li-ion battery packages can be employed for storing the off-grid electricity [1]. Li-ion batteries are a viable option for Electric vehicles (EVs) and Hybrid Electric Vehicles (HEVs) due to their advantages of high energy density as compared to other electrochemical batteries [2]. Currently, lithium-ion batteries have been widely used in the latest EV, such as the Tesla Model S, Nissan Leaf, and Chevy Volt.

The use of EVs reduces our dependence on fossil fuels and emission of pollutants and greenhouse gases. Andersen et al. [3] depicted that up to 40% reduction of greenhouse gas emission is possible if the EVs get charged with electric power resources using renewable route. In case of EVs and HEVs battery efficiency is the key parameter. During the discharge mode of the battery, cell temperature increases thus reducing the thermal efficiency.

Several factors affect the lifespan of the battery; among cell temperature plays a significant role [4,5]. At higher discharge rate, battery temperature increases due to a higher rate of heat generation in battery [6]. Sato et al. [7] observed that the charging efficiency and lifecycle will be reduced if operating temperatures are above 50 °C. Usually, Li-ion batteries operate in the optimal temperature range of 20–40 °C [8]; performance falls drastically at low temperature [9]. Li-ion batteries operating beyond safe temperature range results in major capacity loss; for example for every degree rise in operating temperature, the calendar life of the battery reduces almost by two months [10]. Zang et al. observed that capacity of Li-ion battery decreases up to 95% at low temperature (−10 °C) compared to at 20 °C [11]. Wu et al. [12] found that capacity of a fresh Li-ion battery at 3C discharge was decreased from 800 mAh to merely 20 mAh after storing at 60 °C. Giuliano et al. [13] observed at high-rate discharge, there is a significant increase in battery temperature and non-uniform surface temperature.

Based on aforementioned studies, along with providing safe operating cell temperature and cell to cell temperature uniformity, other issues associated with battery usage in EVs and HEVs can be listed as:

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Peer review under responsibility of Karabuk University.

https://doi.org/10.1016/j.jestch.2018.07.015
2215-0986/

Please cite this article in press as: R.D. Jilte, R. Kumar, Numerical investigation on cooling performance of Li-ion battery thermal management system at high galvanostatic discharge, Eng. Sci. Tech., Int. J. (2018), https://doi.org/10.1016/j.jestch.2018.07.015

Nomenclature

A_s	Surface area of a single battery cell, (m^2)
Bi	Biot number (–)
C	Discharge rate (1C is equal to 3.6 Amp)
$C_{p,}$	Specific heat, (J/kg K)
D	Diameter of battery cell, (m)
E	Cell potential, (Volt)
E_{oc}	Open circuit potential, (Volt)
g	Gravitational acceleration (m/s^2)
h	Convective heat transfer coefficient of cooling air (W/m^2K)
I	Current, (Amp)
K	Thermal conductivity, W/mK
L	Length of the battery cell, (m)
L_c	Characteristics length, (m)
m_f	Mass flow rate of the supplied air, (kg/s)
Nu	Nusselt number (–)
Pr	Prandtl number (–)
Q_g	Rate of heat generation in a battery cell, (J/s)
$Q_{entropic}$	Entropic heating, (J/s)
Q_{Ohmic}	ohmic heating, (J/s)
R	The internal resistance of battery cell (Ohm)
Re	Reynold number (–)
S_T	Transverse pitch, (m)
S_L	Longitudinal pitch, (m)
T	Instantaneous cell temperature, (°C)
Tf_{in}	Area-weighted average air temperature at the inlet of the battery domain, (°C)
Tf_{out}	Area-weighted average air temperature at the inlet of the battery domain, (°C)
T_s	Area weighted average surface temperature of the battery cell (°C)
T_∞	Ambient air temperature, (°C)
V	Air flow velocity, (m/s)
Vb	Volume of a single battery cell, (m3)
V_{max}	Maximum air flow velocity in module, (m/s)

Greek symbols

ρ	Density, (kg/m^3)
μ	Dynamic viscosity of air (Pa-s)

Abbreviation List

BTMS	Battery thermal management system
EV	Electric vehicle
HEV	Hybrid electric vehicle
Li-ion	Lithium ion
UDF	User defined function

Subscripts

b	Battery material
f	Air

1. In application, there are large numbers of cells required for EV or HEV power capacity.
2. The large amount of heat generated from these cells has to remove from vehicle body.
3. There should be space and scope for removing hazardous gases formed during battery operation.
4. The arrangement should be compact and lightweight and scalable as per capacity.
5. The arrangement should provide safe battery operation throughout discharge/charge cycle.

The issues listed above can be resolved with battery thermal management system which can be grouped under three major categories based on cooling media (Fig. 1). In general, most of the commercial EVs use air or liquid cooling strategies for effective control of battery module temperature [2]; air-cooled BTMS is the simplest and lighter [14].

There are many studies available on cooling performance of battery thermal management system. He et al. [15] carried out experimental and numerical study on thermal management of multiple cells Li-ion modules. The experimental setup consists of an open wind tunnel to provide controlled air cooling. The battery was tested experimentally for 0, 1, 2.5 and 5 m/s air flow velocities. Pesaran et al. [16] compared numerically cooling of battery module by arranging air direction in series or parallel flow. The observed maximum temperature difference was 8 °C and 18 °C respectively in parallel and series flow. Sabbah et al. [17] in his experimental and numerical study found that an increase in air velocity could not controlled cell temperature below 55 °C when ambient temperature is 45 °C at 6.67 C discharge rate. A C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 h. Nelson [18] also pointed that if the cell temperature rises above 66 °C, then it is difficult to cool it to below 52 °C by air-cooling.

Based on studies available on BTMS, the present work attempt to address the following issues:

1. Air-cooled battery module working at high discharge rate necessitates throughout understanding of parameters like a transient thermal response, development of flow field and temperature regimes, cell-to-cell temperature non-uniformity and location of heat spots for proper design of BTMS.

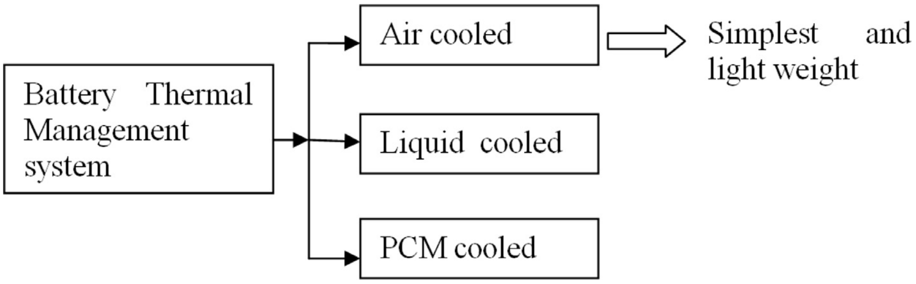

Fig. 1. Types of battery thermal management systems.

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