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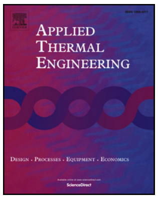


Research Paper

Thermal performance of a novel confined flow Li-ion battery module

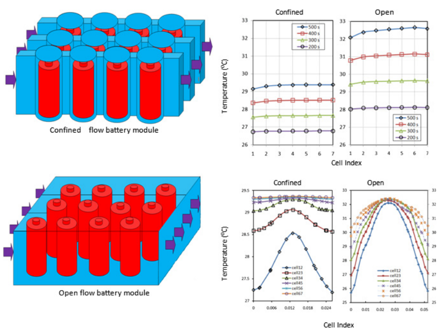
Ravindra D. Jilte[a,*], Ravinder Kumar[a], Lin Ma[b]

[a] *Department of Mechanical Engineering, Lovely Professional University, Punjab 14411, India*
[b] *Department of Mechanical and Aerospace Engineering, University of Virginia, Charlottesville, VA, USA*

HIGHLIGHTS

- The conventional open flow battery modules modified with a guided flow.
- Maximum cell temperature difference found lower than 0.24 °C.
- Cell temperature reduced up to 6.19 °C compared with open flow case.
- The arrangement allows easier sub-module deployment for vehicular application.

GRAPHICAL ABSTRACT



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ABSTRACT

Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) are clean energy vehicles in comparison with a traditional internal combustion engine. Li-ion batteries are a viable option for EVs and HEVs due to their advantages of high specific energy and energy density. At high discharge rate, there is a significant increase in battery temperature and non-uniform cell temperature. This work presents a numerical study of the transient behavior of a novel confined flow battery module dissipating the heat at very high discharge rate around 6.94 C and 11.11 C. The conventional open flow battery modules are modified considering the controlled/ guided flow stream around the cell for reducing the local heat spots and unevenness in the cell temperatures. The results provide insights and comparisons into a cell-to-cell heat interaction based on three-dimensional transient thermal response and thermal regimes developed in a conventional open flow module and confined flow module. During battery discharging condition, the proposed battery module exhibit lower surface temperature as well as near uniform cell temperature as compared to open flow module.

1. Introduction

Li-ion batteries are a viable option for Electric vehicles (EVs) and Hybrid Electric Vehicles (HEVs) due to their advantages of high specific energy and energy density as compared to other electrochemical batteries [1,2]. Rechargeable Li-ion batteries are a promising enabling technology for electric vehicles (EVs) and hybrid electric vehicles (HEVs) to reduce pollution caused by transportation and to reduce our dependence on fossil fuels.

Several factors affect the lifespan of the battery; among cell temperature plays a significant role [3,4]. At higher discharge rate, battery temperature increases due to increased heat generation in battery [5]. Sato et al.[6] 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 [7]; performance falls drastically at low temperature [8]. Li-ion batteries

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[*] Corresponding author.
E-mail address: rdjilte@gmail.com (R.D. Jilte).

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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 [9]. Zang et al [10] observed that capacity of Li-ion battery decreases up to 95% at low temperature (−10 °C) compared to at 20 °C. Wu et al. [11] found that capacity of a fresh Li-ion battery at 3 C discharge was decreased from 800 mAh to merely 20 mAh after storing at 60 °C. Giuliano et al.[12] observed at high-rate discharge, there is a significant increase in battery temperature and non-uniform surface temperature. At high-current levels, batteries generate much heat during operation such as quick acceleration, long-discharge cycles or rapid charge [13].

Based on studies above, 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:

1. In application, there are large numbers of cells required for EV or HEV power capacity.
2. A considerable 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 solve with battery thermal management system which can group into 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 [12].

Among the different methods reported, air-cooled BTMS perhaps is the simplest, both conceptually and mechanically [12]. Air cooled BTMS uses typically uses fan to create force convective currents as natural convective air is generally not adequate for a battery cooling. With an advantage of lightweight, forced air cooling is widely used to control battery pack temperature in some automotive companies [14].

There are many studies available on cooling performance of battery thermal management system. He, et al. [15] carried out an 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. Mao-Sung Wu et al. [16] presented a comparison of heat dissipation performance under natural air cooling, forced air cooling and heat pipe cooled battery system. Pesaran et al. [17] numerically compared 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 [18] in his experimental and numerical study found that an increase in air velocity could not control cell temperature below 55 °C when the ambient temperature was 45 °C at 6.67 C discharge rate. Nelson [19] 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. Rajib Mahamud and Chanwoo Park [9] have studied a reciprocating air flow for cylindrical Li-ion batteries, Liwu Fan et al. [20] have performed three-dimensional transient thermal analyses of an air-cooled prismatic Li-on batteries.

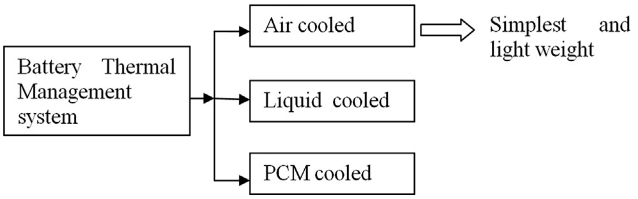

Fig. 1. Types of battery thermal management systems.

Extensive studies have been reported on forced-air cooling of cylindrical cells employed in battery packs. The cylindrical cells were arranged in an inline or staggered configuration [21] in the battery modules. These studies have been performed at different cell arrangement structures, such as 1P × 24S, 3P × 8S, and 5P × 5S arrays rectangular arrangement [22] where P stands for parallel connection and S stands for series connection, 2P × 7S configuration [23], 2P x 4S configuration [15], 2P × 8Sconfiguration [24], 2P × 12S configuration [25],1P × 8S (eight-cell sub module) [9,26].

Based on studies available on BTMS, the present work attempt to address the following issues pertaining to forced air cooled system:

1. Maintain cell temperature uniformity in an air-cooled battery module is an challenging task and it becomes more significant for battery module operating at high discharge rate.
2. Maintain battery pack temperature below safe limit with simplified air cooled system is desirable for constrained simple and low weight application.
3. Provide sufficient space for circulation of cooling air and removal of gases generated by the batteries.
4. Provide an easier modular arrangement to meet any pack capacity.

Under such case, BTMS considering controlled and confined flow passages would be of interest to maintain cell temperatures under the preset threshold and to minimize non-uniform cell temperatures. Therefore, it is the goal of this work to investigate novel BTMS methods based on confined flow Li-ion battery sub modules and to compare their performances with conventional open flow rectangular modules.

2. Description of battery module

The battery pack considered in the present work consists of a total of 21 cells arranged in a 3P × 7S cell configuration. The dimensions of the Li-ion cell and their thermo-physical and chemical properties are listed in Table 1. The battery material considered as isotropic [22–25]. Therefore, the battery cell components (cathode, anode, separator, current collector tabs) were treated as a homogenous body with constant values of thermal conductivity and specific heat.

2.1. Conventional open flow battery module

In a battery module, inter-cell spacing are characterized by two parameters: the transverse pitch (S_T) and the longitudinal pitch (S_L). The longitudinal pitch is defined as the center-to-center distance between two adjacent cells in the flow direction whereas the transverse spacing was defined as the center-to-center cell distance in the transverse (normal to the flow) direction as shown in Fig. 2b. the values of S_L and S_T were 50 mm and 50.4 mm, respectively, in this work. The width and breadth of the battery module were kept as 151.2 mm and 392.40 mm respectively. The height of the pack was kept as 110 mm. The spacing above the cells was designed to allow proper air ventilation and space for circuit connection. The open flow battery module is

Table 1
Dimensions and thermophysical properties of battery cell [9,26].

Parameters	Details
Battery details	Li-ion battery, cathode: $LiMn_2O_4$, anode:Carbon
Capacity, Ah	3.6
Number of cells	9
Diameter (D), mm	42.4
Length (L), mm	97.7
Mass of cell, kg	0.3
Density, kg/m^3	2007.7
Thermal conductivity, W/mK	1.0 (in radial direction)
Specific heat, J/kg K	837.4