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Vortex generators for active thermal management in lithium-ion battery systems

Bittagopal Mondal [a,*,1], Carlos F. Lopez [a], Ankit Verma [b], Partha P. Mukherjee [b,*,2]

[a] *Department of Mechanical Engineering, Texas A&M University, College Station, TX 77843, USA*

[b] *School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, USA*

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ABSTRACT

The aim of the present study is to determine efficacy of using vortex generators in the cooling channels of a lithium-ion battery thermal management system (BTMS). Numerical simulations of a Li-ion battery module containing 20 prismatic lithium ion cells and associated cooling channels with four different winglet configurations were developed. This study examines the effects of vortex generators on the heat transfer performance of typical battery thermal management solutions. The performance of the BTMS is assessed over a Reynolds number range ($65 \leqslant Re \leqslant 1650$) based on the hydraulic diameter of a rectangular channel. Specialized software designed for studying heat transfer problems in lithium-ion batteries coupled with computational fluid dynamics was used to determine such effects. The performance of the different vortex generator configurations was compared in terms of the Nusselt number, maximum module temperature, and cell-to-cell temperature variation. The addition of vortex generators to the modeled BTMS has shown a significant increase in overall heat transfer of cooling channel, a decrease in the maximum cell temperature, and a lower temperature difference within the cells.

1. Introduction

While electric vehicles (EVs) and renewable energy sources have grown in popularity, energy storage technologies that make such products possible have many hurdles preventing further growth. Drawbacks such as battery safety issues, cycle life, and poor low temperature performance, all of which are thermally dependent, slow the growth of the emerging electric and hybrid electric vehicle (HEV) market. Lithium-ion batteries provide the best solution for portable energy storage in both small and large format applications such as consumer electronics and electric vehicles, due to their relatively high specific energy and power [1–3]. However, large lithium-ion batteries are very sensitive to temperature, and can suffer in both safety and performance if exposed to extreme or imbalanced temperatures [4–6]. This necessitates the use of thermal management systems in large Li-ion modules, particularly when longevity and reliability is paramount [7–13]

Pesaran [14] reported some aspects of designing a thermal management system for lithium-ion battery packs used in EVs and HEVs. Hallaj et al. [15] developed a simplified one-dimensional mathematical model with lumped parameters to simulate temperature profiles inside cylindrical lithium ion cells of 10 and 100 Ah capacities. The model was used for simulating the temperature profiles for different discharge rates, operating conditions, and cooling rates. At lower cooling rates, the cell behaved as a lumped system with uniform temperature. Conversely, at higher cooling rates, a significant temperature gradient was found inside the cell. Hence, an active cooling system was proposed for sufficient thermal management due to the significant rise of cell temperature and risk of thermal runaway at high discharge rates. Sato [16] investigated experimentally and analytically the effects of the various heat generation sources within lithium-ion batteries including reaction heat, polarization heat, and joule heat during charging and discharging. In this study, analysis of the exothermic heat released during cycling not only provided quantitative analysis of heat generation under realistic load conditions, but also provided guidelines for thermally conscious design of Li-ion batteries for EVs and HEVs. Hallaj and Selman [17] reported a novel thermal management system using phase change materials (PCM). This method has high potential for providing effective thermal cooling without the use of moving parts and parasitic power within the thermal management system. PCM cooling provides a relatively

* Corresponding authors.
E-mail addresses: b_mondal@cmeri.res.in (B. Mondal), pmukherjee@purdue.edu (P.P. Mukherjee).

[1] Present address: CSIR-Central Mechanical Engineering Research Institute, Durgapur, India.

[2] Mukherjee group moved from Texas A&M University to Purdue University.

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Nomenclature

a	constant
A	electrode area
b	voltage adjustment
c_p	specific heat
DoD	depth of discharge
E_a	activation energy
h	heat transfer coefficient
J	current density
k	thermal conductivity
I	current
Nu	Nusselt number
q	heat convection
Q	heat generation
t	time
T	temperature
U	fitting parameters
V	voltage
Y	fitting parameters

Greek

ρ	density

Subscripts

avg	average
cell	cell
conv	convection
gen	generation
p	particle
ref	reference
w	wall

simple design and lower cost compared to active cooling systems, but is only capable of absorbing heat equal to the latent heat of the PCM, limiting its use to moderate energy density cells [18].

To provide better insight into behaviors of high-power LIBs under realistic discharge conditions, a simplified unsteady, three-dimensional thermal model was developed by Zhang et al. [19]. This study modeled an air-cooled battery module consisting of closely packed cylindrical cells. The results showed a significant effect of flow rate on temperature rise within the cells for all discharge rates, and an increase in required flow rate to maintain safe temperatures with an increase in discharge rate. Rad et al. [20] carried out a numerical study based on a simple radial-axial model to evaluate the thermal behavior of Li-ion batteries. Their results showed that the core temperature of a cell is much higher than that at the surface of the cell, as shown in previous experiments [5,18]. To analyze the thermal behavior of a Li-ion battery module, a three-dimensional numerical study was carried out by Karimi and Li [21]. Different cooling strategies including natural convection, forced convection with different cooling mediums, and passive cooling using a PCM were considered during the examination of BTMS performance. Numerical analysis suggested that distributed cooling methods reduce the temperature non-uniformity between cells and improve the overall performance of the battery pack. Fan et al. [22] numerically studied an air-cooled module using a three dimensional transient model available in commercial computational fluid dynamics software. The module contained eight prismatic lithium-ion cells subjected to an aggressive drive cycle. The effects of gap spacing between cells and airflow rate on cooling effectiveness of the existing air-cooled battery module were studied. Temperature rise was decreased by reducing gap spacing between the neighboring cells and increasing flow rate of the fan. They also reported the results for a variety of configurations such as one-sided vs two-sided cooling, uneven vs even gap spacing, and their combinations. Recently, a fully coupled electrochemical-thermal model was developed for a single spirally wound lithium-ion cell within a larger battery pack [23,24]. Anisotropic thermal conductivity of the cell and induced resistive heating in the current collectors were incorporated in their model. Using a liquid coolant significantly reduced the peak module temperature compared to an air coolant [25], but increased the module thermal gradient slightly. A new thermal management strategy based on edge and internal cooling was discussed to reduce the volume occupied by the entire battery and thermal management system [24].

In many applications, heat transfer can be enhanced by generating vortices in the flow field through introducing wings or winglets in the form of rectangular or delta shapes on the heat transfer surfaces. It has been reported that the increase in convective heat transfer due to swirling motion can surpass the increase from increasing heat transfer area [26]. A considerable amount of research on heat transfer enhancement using longitudinal vortex generators has been reported in last few decades [27–36]. The theoretical basis for the vortex induced heat transfer enhancement was discussed by Jacobi and Shah [27]. Fiebig [28] numerically studied the influence of vortices on heat transfer for laminar channel flow with two types of periodic vortex generators including transverse ribs and rectangular winglets. The local and global parameters for the velocity and temperature fields were computed from the full unsteady, three-dimensional conservation equations. The experimental investigations on heat transfer enhancement of heat exchanger surfaces due to longitudinal vortices generated by delta and rectangular wings or winglet pairs were carried out by Tiggelbeck et al. [29,30]. They studied the increase in heat transfer and drag in a channel with single and double rows of vortex generators in aligned and staggered arrangements. They reported that the ratio of heat transfer enhancement and drag increase is higher for larger Reynolds numbers. It was also pointed out that the pressure loss and heat transfer enhancement is highly sensitive to the angle of attack of the vortex generators. Gentry and Jacobi [31] experimentally studied the heat transfer enhancement using delta wing vortex generator placed at the leading edge of a plate-fin heat exchanger. They also observed the similar trends of improvement in heat transfer performance. Biswas et al. [32] numerically investigated the flow structure and heat transfer enhancement in a channel with built-in delta winglet pairs (DWP). In presence of winglet type, longitudinal vortex generator in the wake region behind the cylinder, a local heat transfer enhancement of more than 240% was reported. Three dimensional unsteady flow and heat transfer in a channel with rectangular vortex generators was considered to study the effect of vortex generators on heat transfer enhancement for different Reynolds numbers and angles of attack [33]. The influence of several design parameters of longitudinal vortex generators on heat transfer enhancement and flow resistance were numerically computed and compared with experimental results by Wu and Tao [34]. They carried out a detailed parametric study to quantify the effect of shape and type of vortex generator (delta or rectangular), angle of attack and height of the winglet on heat transfer and pressure