Journal of Power Sources 293 (2015) 458–466

Contents lists available at ScienceDirect

Journal of Power Sources

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

Internal cooling of a lithium-ion battery using electrolyte as coolant through microchannels embedded inside the electrodes

Shahabeddin K. Mohammadian [a], Ya-Ling He [b], Yuwen Zhang [a, b, *]

[a] Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia, MO 65211, USA
[b] Key Laboratory of Thermo-Fluid Science and Engineering of MOE, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, PR China

HIGHLIGHTS

- Transient thermal analysis of a prismatic Li-ion cell has been carried out.
- Internal and external cooling methods for Li-ion battery packs have been compared.
- Internal cooling effectively decreases the bulk temperature and improves uniformity.
- Internal cooling improves the temperature uniformity of the cell up to 5 times.

ARTICLE INFO

Article history:
Received 18 March 2015
Received in revised form 20 April 2015
Accepted 15 May 2015
Available online xxx

Keywords:
Internal cooling
Lithium-ion battery pack
Thermal management
Hybrid electric vehicles

ABSTRACT

Two and three dimensional transient thermal analysis of a prismatic Li-ion cell has been carried out to compare internal and external cooling methods for thermal management of Lithium Ion (Li-ion) battery packs. Water and liquid electrolyte have been utilized as coolants for external and internal cooling, respectively. The effects of the methods on decreasing the temperature inside the battery and also temperature uniformity were investigated. The results showed that at the same pumping power, using internal cooling not only decreases the bulk temperature inside the battery more than external cooling, but also decreases the standard deviation of the temperature field inside the battery significantly. Finally, using internal cooling decreases the intersection angle between the velocity vector and the temperature gradient which according to field synergy principle (FSP) causes to increase the convection heat transfer.

1. Introduction

Destructive effects of fossil fuels on environmental pollution and global warming stimulated researchers to develop various types of clean energy transportation systems. Because of their high energy density, high efficiency, charge retention capabilities and long cycling life, lithium-ion (Li-ion) batteries have been considered as one of the most promising battery technologies compared with the other secondary rechargeable batteries. Due to the effects of internal resistance during operation, heat is generated inside the Li-ion cells. Heavy power demand of electric and hybrid electric vehicles requires that Li-ion packs couple in series and parallel combinations which leads to excessive rise in pack temperatures and causes to deteriorate the performance of the packs significantly [1].

Therefore, designing an appropriate thermal management system is crucial to transfer the generated heat out of the battery back and to ensure that the cells are operating in the desired temperature range. Also this system should mitigate the temperature non-uniformity inside the pack. Different types of thermal management systems can be classified as: (a) active cooling such as air or liquid cooling, and (b) passive cooling such as phase change materials and heat pipes.

The use of air cooling for thermal management of Li-ion batteries can be considered to be one of the simplest methods of heat dissipation. Giuliano et al. [2] investigated an air-cooled thermal management system for high-capacity Lithium Titanate batteries by fabricating metal-foam based heat exchanger plates and showed that the air-cooled systems can be an effective method for the thermal management of automotive battery packs. Fan et al. [3]

* Corresponding author. Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia, MO 65211, USA.
E-mail address: zhangyu@missouri.edu (Y. Zhang).

http://dx.doi.org/10.1016/j.jpowsour.2015.05.055
0378-7753/

computationally investigated an air-cooled module in transient thermal state and found that increasing the air flow rate and lowering the gap spacing, decrease the maximum temperature rise. They also showed that one-side cooling is less effective than the two-side cooling for the same gap spacing and air flow rate.

He et al. [4] studied thermal management of Li-ion battery module in a wind tunnel facility and compared the results with that from the CFD simulations. Reasonable agreements between the experimental and CFD results were found. Choi and Kang [5] proposed a simple modeling methodology to describe thermal behavior of an air-cooled Li-ion battery system and showed that their model can simulate convective heat transfer cooling during battery operation accurately. Fathabadi [6] utilized several distributed thin ducts for cooling the Li-ion battery pack based on distributed natural convection and illustrated that their proposed battery pack can satisfy all thermal and physical issues relating to the battery packs used in vehicles, and increases the battery life cycle and charge and discharge performances.

As temperature uniformity inside the battery is an important parameter that effects on battery life, some researchers investigated it more precisely. Mohammadian and Zhang [7] introduced a special kind of pin fin heat sink whose heights of pin fins increase linearly through the width of the channel; they showed that this kind of pin fin heat sink decreased the standard deviation of the temperature field inside the battery and improved the temperature uniformity.

Another form of thermal management solution is liquid cooling. Nelson et al. [8] compared air cooling and cooling with a silicone transformer fluid and showed that silicon transformer fluid is more effective than air cooling in removing heat from the cell surface. Giuliano et al. [9] studied a liquid-cooled thermal management system for Lithium Titanate batteries and found that heat generation inside the battery cells closer to the terminals is higher. Jarrett and Kim [10] designed 18 different geometric channels to study the thermal optimization of cooling plates. They suggested that in order to lower average temperature, the channels' width should be as wide as possible. Also, they found that narrow inlet channel that widens toward the outlet is the optimum geometric for temperature uniformity. Jin et al. [11] introduced oblique minichannel heat sink as a cooling device of the Li-ion batteries and showed that heat transfer coefficient of the oblique minichannels is higher than that of the conventional straight minichannels.

Compared with active cooling technique, passive cooling can transfer heat without any requirement to spend energy for pumping and it has attracted attentions of many researchers. Thermo-mechanical properties of *PCM/EG* (Phase Change Material-Expanded Graphite) composites was investigated by Alrashdan et al. [12] using blocks which made of paraffin wax. They showed that as mass fraction of paraffin wax increased, the thermal conductivity, tensile strength, compression strength, and burst strength were improved while tested at low temperatures. However, reversed behaviors were found when tested at relatively high temperatures. Rao et al. [13] discussed the thermal energy management performance of aging commercial $LiFePO_4$ power batteries using *PCM* and thermal behavior related to thermal conductivity between the PCM and the cell. Goli et al. [14] showed that using hybrid phase change material with graphene fillers improves thermal management and reliability of Li-ion batteries. Rao et al. [15] experimentally showed that the use of heat pipes can control the maximum temperature to be below *50* °C when the heat generation rate was lower than *50W*.

As mentioned above, the performance of the batteries are sensitive to the temperature. Active and passive methods of cooling that mentioned above have this ability to maintain the surface temperature of the battery at an appropriate level, but they are unable to control heat generation and consequently to maintain the temperature inside the battery at a desirable level. For example for a liquid external cooling system as an active cooling, with increasing the pumping power the slope of decreasing the maximum temperature inside the battery and also standard deviation of the temperature field is too low and cannot change sufficiently. Also, using PCM as passive cooling would be ineffective in the long run because of completely melting of PCM.

To overcome these problems, there are new ideas that use cooling devices inside the batteries. Bandhauer and Garimella [16] introduced a novel internal cooling system that utilized passive, liquid–vapor phase change processes and showed that there was a slight influence of saturation temperature on the performance of the system. Internal cooling methods can be the appropriate ways for thermal management of Li-ion batteries. In this study, a special kind of internal cooling (using electrolyte as coolant inside rectangular microchannels in the positive and negative electrodes) was introduced to optimize the thermal management of Li-ion battery pack. Three dimensional transient thermal analysis of an internal cooling of a prismatic Li-ion cell was performed and compared with the results of two dimensional transient thermal analysis of liquid external cooling (Fig. 1).

2. Problem statement

In this investigation, *5Ah* prismatic battery unit was considered to study the thermal management of the Li-ion batteries. For both internal and external cooling methods, only one symmetrical part was considered to simplify the simulations and to focus on the temperature and its deviation inside the battery (Fig. 1). The gap spacing of *3 mm* was considered for water flow channel height at external cooling. Fig. 2 shows the geometric dimensions and boundary conditions of both cooling methods. Battery material and thermo–physical parameters were tabulated in Table 1 [17,18].

For comparing the cooling methods efficiencies, the energy cost was taken into consideration and pumping power was defined as:

$$P = \dot{V}\,(p_{in} - p_{out}) \tag{1}$$

where p_{in} and p_{out} are the pressure at the inlet and outlet of the channels respectively; and $\dot{V}$ is the volumetric flow rate (m^3/s):

$$\dot{V} = u_{in}A_{in} \tag{2}$$

where A_{in} and u_{in} are the area of the inlet channel cross section and the inlet velocity, respectively.

3. Heat generation in a Li-ion unit cell

A typical Lithium ion battery consists of a graphite anode as the negative terminal of the battery and lithium metal oxide as the positive terminal. The electrolyte of the battery consists of a solution of a lithium salt in a mixed organic solvent. During the discharge process, the Lithium ions intercalate into solid particles of the positive electrode and de-intercalate from solid particles of the negative electrode. The electrons released during the process will flow through the external circuit to the positive electrode.

Li-ion batteries have no memory effects, and they have low self-discharge rate that prevents them from losing their charge for a long period of time. In addition, these batteries have high voltage and can work on a wide temperature range of operation [19]. While the above features make Li-ion batteries appropriate candidates for energy sources of electric and hybrid electric vehicles, some practical problems such as heat generation and thermal runaway can be encountered during their utilization [20–23].