Energy Conversion and Management 103 (2015) 157–165

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Thermal performance of mini-channel liquid cooled cylinder based battery thermal management for cylindrical lithium-ion power battery

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ARTICLE INFO

Article history:
Received 2 April 2015
Accepted 7 June 2015
Available online 30 June 2015

Keywords:
Battery thermal management
Liquid cooled cylinder
Maximum temperature
Local temperature difference

ABSTRACT

Battery thermal management is a very active research focus in recent years because of its great essentiality for electric vehicles. In order to maintain the maximum temperature and local temperature difference in appropriate range, a new kind of cooling method for cylindrical batteries which is based on mini-channel liquid cooled cylinder is proposed in this paper. The effects of channel quantity, mass flow rate, flow direction and entrance size on the heat dissipation performance were investigated numerically. The results showed that the maximum temperature can be controlled under 40 °C for 42,110 cylindrical batteries when the number of mini-channel is no less than four and the inlet mass flow rate is 1×10^{-3} kg/s. Considering both the maximum temperature and local temperature difference, the cooling style by liquid cooled cylinder can demonstrate advantages compared to natural convection cooling only when the channel number is larger than eight. The capability of reducing the maximum temperature is limited through increasing the mass flow rate. The capacity of heat dissipation is enhanced first and then weakened along with the rising of entrance size, when the inlet mass flow rate is constant.

1. Introduction

There are numerous rechargeable power batteries such as lead-acid, nickel-based, zinc/halogen, metal/air [1], among which Li-ion batteries are becoming widely used as the power source in EVs, ships, aircrafts and some other power equipments due to its high efficiency, high capacity, high discharge voltage, low self-discharge rate and harmony to the environment [2,3]. However, some problems, like thermal safety, discharge efficiency reduction and cycle life degeneration of the Li-ion battery, are seriously restricting the development of EVs [4,5]. Maximum temperature and temperature homogeneity of a battery module/pack are two important factors which affect the performance of the whole battery system. On the one hand, high temperature during charge and discharge will result in temperature exceeding permissible range, decreasing the battery performance, even causing rupture, fire and explosion [6,7]. On the other hand, the uneven temperature distribution in the battery pack will lead to a localized deterioration and SOC mismatches. Therefore, BTM has become an very active research focus in recent years because of its great essentiality [1,3,8].

Predecessors around the world have done lots of work in the BTM field, including the establishment of thermal models, the exploration of cooling strategies, the investigation of cooing materials and so on. Among the research directions of BMS, cooling strategies in present can be divided into three parts according to different cooling medium, that is air cooling, liquid cooling and PCM cooling [9–12].

In the air cooling aspect, Choi and Kang [13] proposed and validated a mathematic analytical model based on battery's electrical and mechanical properties in order to predict the thermal behaviors of an air-cooled prismatic Li-ion battery system. And Liu et al. [9] presented a shortcut computational and analytical method to rapidly estimate the flow and temperature profiles in a parallel airflow-cooled large cylindrical battery pack with wedge-shaped plenums. Both two analytical models are quite important to the development of BTM theory. Fan et al. [14] and Mahamud and Park [15] studied the effects of several parameters on rectangular and cylindrical battery modules through 3D and 2D numerical simulation, respectively. Among which, Mahamud proposed a novel reciprocating air cooling style, contributing to reduction of temperature difference. Mohammadian and Zhang [16] also utilized numerical simulation method to investigate the thermal management optimization design of battery module based on air-cooled pin–fin heat sinks.

In the PCM cooling aspect, Rao et al. [17–20] took advantage of experiment or simulation method to study BTM with PCM from different research ideas, which includes different PCM, cooling or heating, battery monomer and battery module, different battery

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http://dx.doi.org/10.1016/j.enconman.2015.06.056
0196-8904/

Nomenclature

A	area (mm^2)
C_0	capacity of battery (Ah)
F	Faraday constant (C/mol)
Re	Reynolds number
SOC	state of charge
ΔS	entropy change (J/(mol °C))
T_{max}	maximum temperature (°C)
ΔT	local temperature difference (°C)
c_p	specific heat capacity (J/(kg °C))
h	convective heat transfer coefficient (W/(m^2 °C))
i	discharging electrical current (A)
k	thermal conductivity (W/(m °C))
n	number of electrons
q	heat generation (W/m^3)
r_i	internal equivalent resistance (Ω/m^3)
$\vec{v}$	velocity vector
τ	time (s)
ρ	density (kg/m^3)

Subscripts

b	battery
g	generation
i	internal
max	maximum
w	water

Acronyms

BMS	battery management system
BTM	battery thermal management
EV	electric vehicle
LCP	liquid cooled plate
LCC	liquid cooled cylinder
OHP	oscillating heat pipe
PCM	phase change materials
SOC	state of charge
UDF	user defined function

shape and so on. Duan and Naterer [21] experimentally investigated two different PCM designs, with/without PCM jackets, applied to BTM, and found that both designs exhibit good effectiveness in maintaining temperature in a desired range. Javani et al. [22] studied the influence of PCM thickness around cells on heat dissipation performance of BTM where PCM is integrated with a Li-ion battery. It was found that the maximum temperature and temperature difference within the battery were reduced evidently due to the function of PCM. Lin et al. [23] constructed a battery module including six $LiFePO_4$ batteries cooled by composite PCM which is made of expanded graphite plate, paraffin and graphite sheet. The graphite sheet is between two neighbor batteries and stuck to the surface of batteries. The thermal dissipation of the battery module was validated to be nice through both experiment and simulation.

The definition of liquid cooling in this paper is according to the cooling medium, which was liquid in the whole or part of working process, consisting of cooling styles based on heat pipes, boiling, mini-channel LCP and so on. Rao et al. [24] designed and experimentally studied an OHP-cooled BTM system, and the result showed that the start-up temperature of OHP is determined by the desired maximum temperature and the acceptable maximum temperature difference of the battery and the OHP should not be placed horizontally in order to reduce the reflow resistance of the working fluid within OHP. Boiling was innovatively applied to control the temperature of a battery monomer by van Gils et al. [25]. The cooling performance was preliminarily investigated and the cooling style desired further research. Jarrett and Kim [26,27], Huo et al. [28] and Jin et al. [29] designed serpentine-channel LCP, multiply straight mini-channel LCP and ultra-thin mini-channel LCP, respectively. Parametric researches with the help of numerical simulation method were performed in those papers and the results have great significance to the design of BTM system.

It is difficult to acquire the inner temperature of batteries using the conventional measurement methods. As an excellent mean, numerical simulation can be utilized to investigate the heat transfer process within the battery, obtain the working status and guide the optimal design and control of BTS [26–30]. In this paper, a novel cooling method for cylindrical batteries based on mini-channel LCC is proposed. Next, the effects of several important operating parameters, such as channel quantity, mass flow rate, flow direction and inlet size, on the thermal management performance based on this method are preliminarily investigated. The purpose is to reveal the thermal performance of cooling method and develop guideline for system design and parametric research based on numerical model is an effective mean for the purpose.

2. Model and methodology

2.1. Physical problem

In EV applications, the flat-plate batteries and cylindrical batteries are often preferred with relatively higher power density [6]. The surface of flat-plate batteries is flat and large and it is easy to joint with LCP. Referring to the idea of LCP, a new idea for cooling cylindrical batteries based on LCC is proposed. Fig. 1(a) showed the schematic of Li-ion battery with LCCs which contains 40 battery monomers. Each battery is covered by a LCC. The cold liquid flows into the flow-distribution plate from the inlet at the bottom of the battery pack. The entrances of each LCC are connected to the flow-distribution plate, which can ensure the pressure homogenization in each entrance due to its large surface and volume. The liquid is heated when passing through the LCC and then flows into the flow-collection plate, which can guarantee the pressure stabilization of liquid within it for the same reason. The whole battery pack can be seen as parallel structure, so only a battery cooled by LCC needs to be investigated. Fig. 1(b) exhibits the enlargement of the 1/4 part of a battery unit and its relative dimensions. It can be seen that cooling channels distribute equidistantly in the LCC.

The battery used in this paper is 42,110 cylindrical $LiFePO_4$ battery [17,31]. The quantity of mini-channels within the LCC considered in this paper is 2, 4, 6, 8, 12 and 16. Aluminum was used for each LCC and liquid water was employed as cooling medium. The thermo-physical parameters of the LCC, water and battery used in the following simulation are summarized in Table.1. During the discharging and charging processes, the electrochemical reactions in anode and cathode are as Eq. (1) and (2) [16,32]:

$$\text{anode}: \ LiC_6 \underset{\text{charge}}{\overset{\text{discharge}}{\leftrightarrow}} Li_{1-X}C_6 + xLi^+ + e^- \tag{1}$$

$$\text{cathode}: xLi + xe^- + Li_{1-X}FePO_4 \underset{\text{charge}}{\overset{\text{discharge}}{\leftrightarrow}} LiFePO_4 \tag{2}$$

Heat generation in the Li-ion battery can be calculated by Eq. (3) [33,34].