Journal of Power Sources 257 (2014) 344–355

Contents lists available at ScienceDirect

Journal of Power Sources

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

A theoretical and computational study of lithium-ion battery thermal management for electric vehicles using heat pipes

Angelo Greco [a], Dongpu Cao [b], Xi Jiang [a,*], Hong Yang [c]

[a] Department of Engineering, Lancaster University, Lancaster LA1 4YR, UK
[b] Department of Automotive Engineering, Cranfield University, Bedford MK43 0AL, UK
[c] McMaster University, Hamilton, ON L8S 4L8, Canada

HIGHLIGHTS

- Battery thermal management using heat pipes is considered.
- The heat pipe set is arranged in a sandwiched configuration to enhance the cooling.
- A one-dimensional (1D) model using the thermal circuit method is proposed.
- The simplified 1D model is in good agreement with the analytical solution.
- The 1D model is also in agreement with the corresponding 3D CFD results.

ARTICLE INFO

Article history:
Received 9 December 2013
Received in revised form
30 January 2014
Accepted 1 February 2014
Available online 11 February 2014

Keywords:
Battery thermal management
Heat pipe
Li-ion battery
Passive cooling management
Thermal network model

ABSTRACT

A simplified one-dimensional transient computational model of a prismatic lithium-ion battery cell is developed using thermal circuit approach in conjunction with the thermal model of the heat pipe. The proposed model is compared to an analytical solution based on variable separation as well as three-dimensional (3D) computational fluid dynamics (CFD) simulations. The three approaches, i.e. the 1D computational model, analytical solution, and 3D CFD simulations, yielded nearly identical results for the thermal behaviours. Therefore the 1D model is considered to be sufficient to predict the temperature distribution of lithium-ion battery thermal management using heat pipes. Moreover, a maximum temperature of 27.6 °C was predicted for the design of the heat pipe setup in a distributed configuration, while a maximum temperature of 51.5 °C was predicted when forced convection was applied to the same configuration. The higher surface contact of the heat pipes allows a better cooling management compared to forced convection cooling. Accordingly, heat pipes can be used to achieve effective thermal management of a battery pack with confined surface areas.

1. Introduction

Electrical vehicles can be used to reduce the emissions from the traditional internal combustion engine powered vehicles. A wider spread usage of electrical vehicles depends on the development of rechargeable batteries. Lithium-ion (Li-ion) battery has been dominantly utilised for electric vehicles, due to its excellent performance characteristics, such as high energy density, long life-time and low self-discharge. However, its narrow desirable operating temperature range imposes a significant challenge on the thermal management of Li-ion batteries. Thermal management of Li-ion batteries is crucial to safety issues like thermal runaway or overheating during operation. These issues can strongly affect the battery performances and lifespan. In addition, more research needs to be done for transport applications of Li-ion batteries where high electric power is used in a relatively short time period.

It has been shown that temperature affects the longevity, efficiency, and safety of the battery. Thermal runaway, electrolyte fire, and in certain cases explosions [1] can occur when the temperature in the battery is too high. Therefore, an efficient battery thermal management system (BTMS) is required in order to maintain the battery temperature between 20 °C and 40 °C [2]. Moreover, to avoid any short circuit leading potentially to destroy the battery, an even temperature distribution must be achieved in the battery module and pack. For achieving a uniform temperature

* Corresponding author. Tel.: +44 1524 592439.
E-mail addresses: x.jiang@lancaster.ac.uk, qmwxjiang@hotmail.com (X. Jiang).

http://dx.doi.org/10.1016/j.jpowsour.2014.02.004
0378-7753/

Nomenclature

a	height of the groove channel [m]
b	width of the groove channel [m]
$[C]$	matrix of the thermal capacitance [J K^{-1}]
e_b	thickness of the battery cell [m]
F	Faraday constant [C mol^{-1}]
$[G]$	matrix of the conductance [W K^{-1}]
h_{conv}	heat transfer coefficient for natural convection [W m^{-2} K^{-1}]
h_{fg}	specific enthalpy [J kg^{-1}]
i	discharge current per unit volume [A m^{-3}]
k	thermal conductivity [W m^{-1} K^{-1}]
K	permeability of the capillary structure [m^2]
k_{wall}	thermal conductivity of the heat pipe material envelop [W m^{-1} K^{-1}]
L_{adia}	length of the adiabatic section [m]
l_b	width of the battery cell [m]
L_b	length of the battery cell [m]
L_c	length of the condenser section [m]
L_{ev}	length of the evaporator section [m]
L_{total}	length of the heat pipe [m]
M	working fluid merit number [m^2]
n	number of electron exchange during the discharge
N_C	capillary number [W m^{-2}]
N_{GS}	number of groove section in one heat pipe
N_{HP}	number of heat pipe in the set
$[P]$	matrix of internal power [W]
q	internal heat generation in the battery [W m^{-3}]
Q_{max}	capillary limit [W]
R	radius [m]
R_i	internal equivalent resistance per unit volume [Ω m^3]
S	entropy [J mol^{-1} K^{-1}]
S_b	surface of the battery cell at $x = e_b$ [m^2]
S_l	liquid section of the heat pipe [m^2]
$[T]$	matrix of the temperature [°C]

Greek letters

Δ	variation
Θ	thermo-physical property group [m^2]
μ	viscosity [kg m^{-1} s^{-1}]
ρ	density [kg m^{-3}]
Φ	geometric dimensions group [m^2]
σ	surface tension [N m^{-1}]
Ψ	dimensionless number defined in Eq. (16) [19]

Subscripts

adia	adiabatic
amb	ambient
c	condenser
ev	evaporator
GS	groove section
HP	heat pipe
v	vapour
x, y, z	coordinates

distribution, the temperature difference from cell to cell and module to module should be normally within 5 °C.

The thermal behaviour of the battery is strongly coupled to the electrochemical process. To simplify the analysis, the heat generated by exothermic chemical reaction during discharge can be represented by a global term linked to the major electrochemical characteristics. Gao et al. [3] modelled the transient behaviour of a commercial Li-Ion battery using an equivalent electric circuit. Based on their work, Chen et al. [4] simplified the mathematical solution. However, these simplified models were not sufficiently developed to describe the temperature distribution in a battery cell to aid the design of the thermal management system.

Different two- and three-dimensional (2D and 3D) numerical models of temperature prediction were developed in the past. Inui et al. [5] developed 2D and 3D codes for cylindrical and prismatic shaped batteries respectively, to predict the transient distribution of temperature during discharge. Karimi and Li [6] extended the study by Inui et al. to a 2D numerical simulation of an entire pack of prismatic battery cooled by natural and forced convection. They also demonstrated that a distributed configuration of the cooling system was the best solution to maintain an equal temperature distribution in the battery pack (stack of prismatic battery cell).

Three-dimensional numerical simulations using global thermo-physical properties to represent the physical properties of the battery multi-layer structure were carried out [7,8]. The battery was cooled by active air cooling and the results showed a good agreement between simulations and measurements. Taheri et al. [9] developed a 3D analytical model to predict the transient thermal behaviour of a Li-ion battery cell cooled by convection. The modelling was based on integral-transform technique and used an internal heat generation term. The derived analytical solution was efficient to compute the different values of convective heat coefficient applied at different positions of the battery cell. A surface averaged Biot number was proposed to simplify the solutions in 1D or 2D depending on the value of thermo-physical properties of the battery and the heat transfer coefficient applied on the battery's surfaces.

Researches have also been performed on effective thermal control of the battery pack. Pesaran [10] showed that for heat exchanger design, a parallel cooling flow was effective in order to achieve an even temperature distribution in the battery pack. Chacko [11] used a liquid cooling plate composed of a serpentine channel, but this configuration was not developed to achieve an even temperature distribution. Mahamud and Park [12] performed a numerical analysis of cylindrical cells cooled by reciprocating air flow. Their results showed a 4 °C decrease in the temperature difference in the battery pack.

Active air or liquid flow convection as a cooling solution implies a bulky flow management system and additional costs due to the maintenance and the weight. Therefore, as an alternative method, passive cooling management (PCM) is investigated as a BTMS solution, especially for confined spaces where intensive heat transfer is required. For example, phase change materials [13,14] are very simple to use, but their low conductivity limits their applications. A possible solution for further improvements is to add a high conductive matrix in the structure of the phase change materials to enhance the thermal conductivity.

Wu et al. [15] showed experimentally the importance of a good surface contact between the heat pipe and the battery in achieving effective cooling. Rao et al. [16] performed experimental studies of a prismatic shape battery cooled by heat pipes. Their results showed a maximum battery cell temperature under 50 °C for a heat generation rate lower than 50 W and a temperature variation within 5 °C for a heat generation rate not exceeding 30 W. This work can be completed by analysing the impact of heat pipe on the temperature distribution of the battery cell or pack. Besides, further