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Research paper

Thermal management of cylindrical power battery module for extending the life of new energy electric vehicles

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HIGHLIGHTS

- Air cooling models were established for cylindrical lithium-ion power battery pack.
- Local temperature difference increased firstly and then decreased with wind speed.
- The gap spacing size of battery pack should not be too small and too large.
- It is prone to thermal runaway when the ambient temperature is too high.
- The ratio of S/D is gradually reduced with the increase of cell diameter.

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ABSTRACT

Thermal management especially cooling plays an important role in power battery modules for electric vehicles. In order to comprehensively understand the heat transfer characteristics of air cooling system, the air cooling numerical simulation battery models for cylindrical lithium-ion power battery pack were established in this paper, and a detailed parametric investigation was undertaken to study effects of different ventilation types and velocities, gap spacing between neighbor batteries, temperatures of environment and entrance air, amount of single row cells and battery diameter on the thermal management performance of battery pack. The results showed that the local temperature difference increased firstly and then decreased with the increase of wind speed. Reversing the air flow direction between adjacent rows is not necessarily appropriate and the gap spacing should not be too small and too large. It is prone to thermal runaway when the ambient temperature is too high, and the most suitable value of *S/D* (the ratio of spacing distance between neighbor cells and cell diameter) is gradually reduced along with the increase of cell diameter.

1. Introduction

In the past decades, four complementary megatrends including the emergence of global climate change policies, the rising concerns of economic and security issues related to oil, the increase in congestion which is creating significant air quality problems, and the rapid technology advancement have lead vehicle propulsion toward electrification. In hybrid electric vehicles (HEVs), renewable energy is a new option for improving vehicle efficiency and is economical with lower toxic gas emission [1]. Power battery technology can restrict the development of electric vehicles (EVs). Many scientific researchers and production units have been focused on prolonging the cycle life, increasing the power density and energy density and ensuring the safety and stability [2,3]. A lithium-ion battery is one of the promising energy storage devices due to its light weight, high specific energy, high specific power and high energy density. Additionally it has no memory effect and poisonous metals [4–6]. $LiFePO_4$ is one of the most attractive materials for the cathode, which is the most promising candidate for lithium-ion battery in large-size and high-rate applications [7]. There are two main problems caused by temperature of battery pack. Firstly, the high temperature during charging and discharging will lead to the possibility that temperatures will exceed permissible levels and decrease the battery performance. Secondly, the uneven temperature distribution in the battery pack will lead to a localized deterioration. Therefore, maximum temperature and temperature uniformity are two important factors which affect the cycle life and performance of a battery pack [4]. In order to improve the battery

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Nomenclature

T	Temperature [K]
$\overline{T}$	Volume-averaged temperature [K]
ΔT	Local temperature difference [K]
Q	Battery heat generation [W]
I	Discharging electrical current [A]
E_{oc}	Open circuit voltage [V]
E	Operating voltage [V]
R	Electrical resistance [mΩ]
Nu	Nussel number
Re	Reynolds number
Pr	Prandtl number
h	Convective heat transfer coefficient [W/(m^2 K)]
$\dot{M}_f$	Mass flow rate [kg/s]
ε	Correction factor
U	Velocity [m/s]
W	Width of each inlet [mm]
D	Diameter of battery [mm]
L	Length of the battery [mm]
S	Gap spacing size [mm]
A	Area [mm^2]
V and v	Volume [m^3]
n	Total number of batteries
ρ	Density [kg/m^3]
μ	Viscosity [Pa s]
λ	Thermal conductivity [W/(m K)]
c_p	Specific heat capacity [J/(kg K)]
t	Temperature [K]
$\vec{v}$	Velocity vector

Subscripts

a	air
al	Al clapboard
s	surface or simulation
f	fluid phase
g	generation
r	reaction
b	battery
p	polarization
j	Joule
t	total
e	electrical or environmental
max	maximum
in	inlet
out	outlet
w	wall
oc	open circuit

life and avoid safety accident, thermal management of battery packs are essential especially in adverse operating conditions [8].

The battery cooling methods mainly consist of air cooling (dividing into natural air cooling and forced air cooling), liquid cooling and phase change material (PCM) cooling [9]. Considering the cost and space limitations, forced air cooling is widely used to control the maximum temperature and local temperature difference of battery pack in some automotive companies [10,11]. There are many investigations about the air-cooled approach by scientists and researchers all over the world. Mao-Sung Wu et al. [6] have comparatively studied the heat dissipation performance of a lithium-ion battery pack through natural air cooling, forced air cooling and heat pipe cooling using a two-dimensional transient heat-transfer model. Heesung Park [12] has designed a specific air-cooled prismatic battery system to satisfy the required thermal specifications through theoretically investigation and numerically simulation. Rajib Mahamud and Chanwoo Park [13] have studied a new battery thermal management method using a reciprocating air flow for cylindrical Li-ion ($LiMn_2O_4$/C) batteries, which was numerically analyzed using a 2D computational fluid dynamics model and a lumped-capacitance thermal model for batteries. Liwu Fan et al. [14] have performed 3D transient thermal analyses of an air-cooled module which contains prismatic Li-on batteries operating under an aggressive driving profile using a commercial CFD code. Michael R. Giuliano et al. [15,16] have outlined a method to conduct thermal analysis of lithium-titanate cells under laboratory conditions. Then they designed and fabricated an air-cooled thermal management system for lithium-titanate battery pack employing metal-foam based heat exchanger plates. Jingzhi Xun et al. [17] have developed a numerical model and an analytical model for the thermal management of lithium-ion battery stacks to investigate the thermal behaviors of flat-plate and cylindrical stacks with different channel sizes and Reynolds numbers during discharging processes. G. Karimi et al. [18] have studied the effects of cooling conditions and pack configuration on the temperature of prismatic battery pack and obtained the information about how to maintain operating temperature by designing proper battery configuration and choosing proper cooling systems.

In this paper, a comprehensively parametric investigation on the thermal management system of several cylindrical battery (18650, 26650, 42110) packs based on air cooling was performed numerically. The variation laws of maximum temperature rising (T_{max}) and local temperature difference (ΔT) at the condition of different ventilation types, gap spacing, temperatures of environment and entrance air, amounts of single row cells and cell diameters are presented in detail in the following sections.

2. Model and methodology

2.1. Model description

Three kind of cylindrical Li-ion batteries (18650, 2.5 Ah; 26650, 3.2 Ah; 42110, 10 Ah) were considered in this paper. The dimensions and thermo-physical properties of those batteries are listed in Table 1. The arrangements of batteries are shown in Fig. 1 (a) According to the ventilation mode, the battery pack can be divided into three types named as type I (Fig. 1b), type II (Fig. 1c), type III (Fig. 1d) respectively. There are four same air inlets on the left side and a larger outlet on the right side in type I. There exists a thin aluminum clapboard with the thickness of 1 mm in the middle of type II and in every two adjacent rows in type III. The thin aluminum clapboards in type II and III are only used to

Table 1
Dimensions and properties of the three cylinder cells.

Dimensions and properties	18650	26650	42110
Dimensions [$D \times L$] [mm]	18 × 65	26 × 65	42 × 110
Density [kg/m^3]	1760	1760	1760
Specific heat capacity [J/(kg K)]	1108	1108	1108
Thermal conductivity [W/(m K)]	3.91	3.91	3.91
Capacity [Ah]	2.5	3.2	10