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Research paper

Assessment of the forced air-cooling performance for cylindrical lithium-ion battery packs: A comparative analysis between aligned and staggered cell arrangements

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HIGHLIGHTS

- Forced air-cooling performance for cylindrical lithium-ion battery is evaluated.
- Thermal performances for aligned and staggered cell arrangements are compared.
- Geometric optimization is investigated for the battery air-cooling system.

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ABSTRACT

An appropriate cell arrangement plays significant role to design a highly efficient cooling system for the lithium-ion battery pack. This paper performs a comparative analysis of thermal performances on different arrangements of cylindrical cells for a $LiFePO_4$ battery pack. A thermal model for the battery pack is developed and is solved in couple with the governing equations of fluid flow in the numerical simulations. The experiments for model validation are conducted on a single cell of the battery pack with forced-air cooling system. The effects of longitudinal and transverse spacing on the cooling performances are analyzed for the battery pack with the aligned and the staggered arrays. Under a specified flow rate of cooling air, the maximum temperature rise is proportional to the longitudinal interval for the staggered arrays, while it is in inverse for the aligned arrangement. Increasing the transverse interval leads to the increase of the battery temperature rise for both aligned and staggered arrangements. By trade-off the design requirements (maximum temperature rise, temperature uniformity, power requirement and cooling index), an appropriate solution in term of the optimal combination of the longitudinal interval, transverse interval, and air inlet width is obtained for the aligned arrangement.

1. Introduction

Lithium-ion batteries are considered to be the best option for electric vehicles (EVs) and hybrid electric vehicles (HEVs) due to several advantages. Compared to lead-acid batteries or nickle-metal hydride batteries, it has more energy density, longer cycle life, lower self-discharge rate, and greater efficiency [1]. It is also known that the performances (e.g., the cycle life [2,3], discharge capacity, voltage platform, etc.) of lithium-ion batteries are greatly affected by the operating temperature. A battery pack is formed by multiple single cells connected in series and/or parallel to deliver the desired voltage and capacity. A poor heat dissipation design for the battery pack induces the heat accumulation during charge or discharge. The accumulated heat in the battery pack can cause the battery to overheat, and even becomes a safety hazard. Additionally, the overheat operating accelerates the battery degradation process [3]. A favorable battery cooling system is required to control the temperature rise and temperature differences with the battery pack for EV applications.

Several thermal models of battery packs have been developed with the battery heat generation rate determined by direct measurement [4,5] and experimentally fitting formula [6,7]. The heat generation rate dynamically changes with the fluctuation of the state of charge (SOC), current, and ambient temperature during discharge/charge [8–10]. A fitted formula from experimental data usually cannot cover all operating conditions of EVs for calculating

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the battery heat generation rate. The theoretical physics models of heat generation were developed by many researchers [8,11–15]. Most of these models focus on the heat generation of lithium-ion single batteries (cells) during discharge. Zhu et al. [16] investigated the thermal performances for a prismatic lithium-ion battery pack. However, little work has been done to develop a theoretically based thermal model for a lithium-ion battery pack.

Many studies were performed on the thermal management system [5,6,17–20] of the battery pack. Karimi and Li [17] investigated the effect of cooling conditions on the battery temperature distribution. Their research showed that the distributed forced convection was an efficient and cost-effective method for the cooling of batteries. Li et al. [6] used a reduced-order model to predict the maximum cell temperature in a battery module. Xun et al. [7] studied the effect of the cooling channel design on the thermal behaviors of both the flat-plate and cylindrical battery stacks during discharge. Fan et al. [19] analyzed the influence of different cooling channel designs on the cooling performances for a prismatic lithium-ion battery module. Park [18] discussed a forced-air cooling strategy for the lithium-ion battery system of HEVs. Although, much research was devoted to the battery cooling system, little involved the configuration design and optimization of air flows for the cooling of cylindrical battery modules. In this paper, a physical thermal model coupled with the governing equations of air flow is developed for the lithium-ion battery pack. Parametric analysis is performed on a cylindrical battery pack with forced air cooling in across-flow configuration. The cooling performances between the staggered and aligned cell arrangements are compared. The temperature distribution, maximum temperature rise, fan power, and cooling index are investigated for different cooling designs. An optimized design of forced air-cooling system is presented for the cylindrical battery pack.

2. Model development

A basic cell configuration of a lithium-ion battery is shown in Fig. 1 and includes the negative electrode, the separator, the positive electrode, and the current collectors. Generally, the negative electrode material is carbon, and the positive electrode material is a metal oxide such as $LiCoO_2$, $LiMn_2O_4$ or $LiFePO_4$. The lithium ions de-intercalate from the active particles in the negative electrode and intercalate into the positive electrode particles during discharge. The above process reverses during charging.

In this work, the active electrode materials are considered to be composed of spherical particles with uniform size. According to the Fick's 2nd law, the mass conservation of Li in the electrode particles is described by

$$\frac{\partial c_{s,i}}{\partial t} = \frac{D_{s,i}}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial c_{s,i}}{\partial r}\right) \tag{1}$$

where i = n and p. The boundary conditions are expressed by

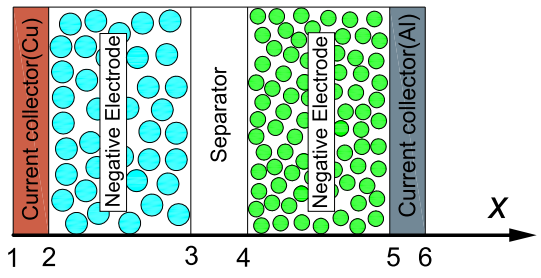

Fig. 1. Cell configuration of lithium-ion battery.

$$-D_{s,i}\frac{\partial c_{s,i}}{\partial r}\bigg|_{r=0} = 0 \tag{2}$$

$$-D_{s,i}\frac{\partial c_{s,i}}{\partial r}\bigg|_{r=r_{s,i}} = j_i \tag{3}$$

Based on the concentrated solution theory, the mass conservation of Li in the electrolyte solution is given by

$$\varepsilon_{l,i}\frac{\partial c_i}{\partial t} = D_{eff,i}\frac{\partial^2 c_i}{\partial x^2} + a_i(1-t_+)j_i \tag{4}$$

where i = n, s and p. D_{eff} is the effective diffusion coefficient of Li in the electrolyte and is given by $D_{eff,i} = D\varepsilon_{l,i}^{brug}$. The specific area of the electrode particles is defined as $a_i = 3\varepsilon_{s,i}/r_{s,i}$. The boundary conditions are given by

$$D_{eff,i}\frac{\partial c_i}{\partial x}\bigg|_{x=2} = D_{eff,i}\frac{\partial c_i}{\partial x}\bigg|_{x=5} = 0 \tag{5}$$

where 2 and 5 are the boundary points in the direction of cell thickness (see Fig. 1).

The charge conservation in the electrode materials is determined by Ohm's law

$$i_{s,i} = -\sigma_{eff,i}\frac{\partial \phi_{s,i}}{\partial x} \tag{6}$$

where i = n and p. The effective electric conduction is defined by $\sigma_{eff,i} = \sigma_i\varepsilon_s$. The boundary conditions are given by

$$\phi_s|_{x=1} = 0 \tag{7}$$

$$-\sigma_{eff,i}\frac{\partial \phi_{s,i}}{\partial x}\bigg|_{x=3} = -\sigma_{eff,i}\frac{\partial \phi_{s,i}}{\partial x}\bigg|_{x=4} = 0 \tag{8}$$

$$-\sigma_{eff,i}\frac{\partial \phi_{s,i}}{\partial x}\bigg|_{x=6} = i_{\text{app}} \tag{9}$$

where 1, 3, 4 and 6 are the boundary points in the direction of cell thickness (see Fig. 1), i_{app} is the current density applied to the battery electrode.

The charge conservation in the electrolyte solution is expressed as:

$$i_{e,i} = -\kappa_{eff,i}\frac{\partial \phi_{e,i}}{\partial x} + \frac{2\kappa_{eff,i}RT(1-t_+)}{F}\left(1+\frac{d\ln f_\pm}{d\ln c_i}\right)\frac{\partial \ln c_i}{\partial x} \tag{10}$$

where i = n, p. The effective electric conductivity of the electrolyte is defined by $\kappa_{eff,i} = \kappa_i\varepsilon_{l,i}^{brug}$. The boundary conditions are given by

$$\frac{\partial \phi_{e,i}}{\partial x}\bigg|_{x=2} = \frac{\partial \phi_{e,i}}{\partial x}\bigg|_{x=5} = 0 \tag{11}$$

where 2 and 5 are the boundary points in the cell thickness direction (see Fig. 1).

The governing Eqs. (1), (4), (6) and (10) are coupled by the Bulter–Volmer electrochemical kinetic equation.

$$j_i = k_i\left(c_{s\_\max,i} - c_{s\_\text{surf},i}\right)^{\alpha_a} c_{s\_\text{surf},i}^{\alpha_c} c_i^{\alpha_a}\left\{\exp\left(\frac{\alpha_a F\eta_i}{RT}\right) - \left[\exp\left(-\frac{\alpha_c F\eta_i}{RT}\right)\right]\right\} \tag{12}$$