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Development and analysis of a technique to improve air-cooling and temperature uniformity in a battery pack for cylindrical batteries

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ABSTRACT

In this paper, a passive approach to improve temperature uniformity in a simple battery pack, in which an inlet plenum is added as a secondary inlet to a battery pack with an axial air flow, is examined. This inlet plenum changes the direction of the flow and eliminates the problem of recirculation and non-availability of air between the adjacent cells. Three different configurations are considered to examine the effects of the orientation of inlet plenum and the cells. CFD (computational fluid dynamics) is used to perform detailed simulations of the battery packs and the results are validated with data obtained experimentally from one of the battery pack configuration. The thermal performance of the battery packs is compared to the baseline case, and the results indicate an average maximum temperature reduction of the cells by ~4% and an improvement in temperature uniformity of the cells by ~39%. This is a simple battery pack that uses forced air passive cooling (no moving parts required in the battery pack) and introduces mixing and turbulence in the air flow to increase the temperature uniformity in the battery pack.

1. Introduction

Climate change is the most important environmental issue today and as a result many countries are adopting various methods to promote sustainability. One of the major contributors to greenhouse gasses and global warming is the transportation industry.

The current transportation systems contribute significantly to the increasing amounts of greenhouse gasses in the atmosphere. For instance, the transportation sector in the US contributed 27% in 2015 to the greenhouse gas emissions [1]. Governments around the world are therefore putting pressure on the automotive industry to produce much more efficient cars and reduce the amount of greenhouse gasses they emit. Transportation electrification is currently one of the most innovative changes coming to the automotive sector. Hybrid electric vehicles (HEV) and electric vehicles (EV) are considered sustainable and environment-friendly options. In the past few years, the market share of these vehicles has been increasing and is bound to continue to increase further over the coming years. It was reported that electric vehicles reduce emissions of greenhouse gasses by approximately 20% and if the electricity used is produced by renewable sources then, this percentage increases to 40% [2].

One of the main challenges to the advancement of EVs is the development of high power density and high energy density cells. This is needed to overcome the issue of range which is critical for the mass adoption of EVs. There are a number of potential candidate batteries in the market including lithium-ion polymer (LiPo), lithium-ion (Li-ion), and nickel metal hydride (NiMH) batteries. However, a lot of attention has been focused on Li-ion batteries because of their increased efficiency, longer life, slow self-discharge rate, and high capacity [2]. Li-ion batteries require a very specific temperature and thermal requirements in order to perform efficiently, therefore, the operating temperature ranges from 0 °C to 40 °C [3]. Heat accumulation in the battery pack due to an ineffective thermal management system results in overheating of the Li-ion cells. The degradation of the cells accelerates once the temperature increases and moves out of the operating range of the cells, which can results in thermal runaway, reduced battery pack efficiency and reduced cell life [4].

Furthermore, the uniformity in the battery pack impacts the availability of the charging and discharging power. The power capability is limited by the cell with the lowest temperature at low temperatures, and by the cell with the highest temperature at high temperatures [5]. A large temperature variation across the battery pack causes the individual cells to charge and discharge at different rates resulting in electrically unbalanced cells and subsequently a reduction in the performance of the battery pack. For example, a temperature difference of 10–15 °C results in 30–50% degradation [6]. Therefore, it is important to maintain temperature uniformity at the cell level and pack level for optimum performance of the battery pack.

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Nomenclature

c_p	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
D	hydraulic diameter
E	total energy (J)
F_1	blending function in SST model
k	turbulence kinetic energy
k_T	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
k_s	scale factor
p	pressure (Pa)
q''	heat flux (Wm^{-2})
S	absolute value of shear strain rate
t	time (s)
U	average incoming air velocity ($m\,s^{-1}$)
V	cell voltage (V)
v	velocity ($m\,s^{-1}$)
$\vec{v}$	velocity vector ($m\,s^{-1}$)
x_i	tensor coordinate
y	nearest wall distance (m)

Symbols

α	SST model constant
β^*	SST model constant
ρ	density ($kg\,m^{-3}$)
μ	viscosity (Pa s)
ω	specific rate of turbulence dissipation
σ	diffusion parameters

Subscripts

i	tensor indices
x	x-direction
y	y-direction
z	z-direction

Acronyms

CAD	Computer Aided Design
CC	Constant Current
CC-CV	Constant Current-Constant Voltage
CFD	Computational Fluid Dynamics
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
LFP	Lithium Iron Phosphate
Li-ion	Lithium Ion
LiPO	Lithium-ion Polymer
NI	National Instruments
NiMH	Nickel Metal Hydride
NMC	Lithium Nickel Manganese Cobalt Oxide Battery
PCM	Phase Change Material
SOC	State of Charge
SST	Shear Stress Transport
TMS	Thermal Management System

The thermal management system (TMS) of a battery pack mainly consists of three different types of cooling methods, namely, air cooling, liquid cooling and phase change material (PCM) cooling. Li et al. [3] used a $LiMn_2O_4$ battery and compared the forced air cooling with natural air convection. As expected, the results showed that forced air cooling was more effective. Zhao et al. [6] undertook a detailed parametric study on cylindrical cells ($LiFePO_4$ cell) to investigate the effects of various ventilation types and forced air velocities. They also studied the effects of spacing between adjacent cells, environment temperature, and inlet air temperature. The results of their study showed that with the increase in air flow speed the local temperature decreased. Furthermore, a simulation was conducted by Zhao et al. to examine the effect of counter air flow between subsequent cell rows on the cooling effectiveness. The results showed that it is not an effective method. In addition, Wang et al. [7] used a $LiNiMnCoO_2$ cell and explored the thermal performance of a battery pack with different cell arrangements and concluded that the 5 × 5 cubic structure, with the inlet placed at the top and the outlet placed at the base of the pack, had the optimum thermal performance. Using the same Li-ion cell Wang et al. [8] also investigated the temperature range of the inlet air on the cooling of the cells using a 5 × 5 cubic structure and concluded that to effectively cool the cells the optimal temperature range of the inlet air should be between 20 °C and 35 °C. However, at higher ambient temperatures the inlet air velocity should be increased. Earlier, Cho et al. [9] investigated the ambient temperature effects on the cooling effectiveness. The results indicated that at low ambient temperatures temperature uniformity decreased and at high ambient temperatures temperature uniformity increased. Additionally, regardless of the ambient temperature, cells near the inlet had less maximum temperature than cells near the outlet. Yang et al. [10] investigated the staggered and aligned cell arrangements using $LiFePO_4$ cell. It was concluded that aligned arrangement is better in terms of uniform cooling of the cells when compared to the staggered arrangement and the optimum distances between the cells should be 34 mm in the longitudinal direction and 32 mm in the transverse direction. Saw et al. [6] used Lithium Iron Phosphate (LFP) cells and developed a battery pack in which the air enters from the top of the pack and is exhausted from the bottom of the pack. The results show that heat accumulation occurred at the center of the pack resulting in the highest temperatures of the cell. Additionally, due to flow separation from the inlet plenum there was lack of air flow at the front end of the pack, therefore, highest temperatures were observed at the front end. Mahamud and Park [11] investigated a reciprocating air flow in the pack using $LiMn_2O_4$ cells. The results concluded that reciprocating air flow increases the temperature uniformity, and reduces the temperature difference between cells by about 4 °C and the maximum cell temperature by 1.5 °C for a reciprocating period of 120 s. Liu et al. [12], using a Sony US-18650 cell, did a parametric optimization study on a reciprocating air flow system. A numerical analysis of a single row of cells was conducted by applying symmetry on both sides of the row. The results concluded that the most optimal conditions for the air velocity was 6 m/s, inlet temperature was 10 °C, and reciprocating air flow period of 67.5 s. Using these optimum conditions, a temperature variation between the highest and lowest temperatures of 3.76 °C was achieved. He et al. [13] also studied the reciprocating air flow system using A123 cylindrical (26,650) cells. The results concluded that the reciprocating flow reduces temperature non-uniformity and the temperature fluctuation of cells over time. However, the problem with reciprocating air flows is that it is an active system in

Table 1
Samsung INR18650-25R cell specifications [14]

Item	Specification
Nominal discharge capacity (mAh)	2500
Nominal voltage (V)	3.6
Standard charge (A)	1.25 A, (0.125 A cut-off)
Maximum continuous discharge (A)	20
Discharge cut-off voltage (V)	2.5
Cell weight (g)	45
Cell height (mm)	65
Cell diameter (mm)	18
Cathode material	$LiNiMnCoO_2$
Anode material	Graphite