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Computational fluid dynamic and thermal analysis of Lithium-ion battery pack with air cooling

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HIGHLIGHTS

- We designed and analyzed the thermal behavior of the Li-ion battery pack.
- We analyzed the heat generation of 38,120 Li-ion cell using ARC.
- We validated the simulation results with experimental studies.
- We developed the correlations of *Nu* and *Re* for the air cooling battery pack.

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ABSTRACT

A battery pack is produced by connecting the cells in series and/or in parallel to provide the necessary power for electric vehicles (EVs). Those parameters affecting cost and reliability of the EVs, including cycle life, capacity, durability and warranty are highly dependent on the thermal management system. In this work, computational fluid dynamic analysis is performed to investigate the air cooling system for a 38,120 cell battery pack. The battery pack contained 24 pieces of 38,120 cells, copper bus bars, intake and exhaust plenum and holding plates with venting holes. Heat generated by the cell during charging is measured using an accelerating rate calorimeter. Thermal performances of the battery pack were analyzed with various mass flow rates of cooling air using steady state simulation. The correlation between *Nu* number and *Re* number were deduced from the numerical modeling results and compared with literature. Additionally, an experimental testing of the battery pack at different charging rates is conducted to validate the correlation. This method provides a simple way to estimate thermal performance of the battery pack when the battery pack is large and full transient simulation is not viable.

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1. Introduction

Dwindling of fossil fuel supplies and environmental concerns has spurred worldwide interest in the development of advanced energy storage system for electric vehicles (EVs). There are various types of battery used as an energy storage system in EVs and Hybrid Electric Vehicles (HEVs) such as lead acid, Nickel Metal Hydride (NiMH) and Lithium ion battery [1,2]. However, low energy density and depth of discharge (DOD%), sulfation, toxicity, short shelf life and high self discharge rate have deterred automotive manufacturers away from selecting lead acid battery as the primary energy storage system for EVs and HEVs [3]. On the other hand, Li-ion batteries have high energy density, no memory effect, no periodic deliberate full discharge requirement, low maintenance, fast charging capability and low self-discharge rate as compared to Nickel Cadmium (NiCd) and Nickel Metal Hydride (NiMH) batteries [4]. There is a variety of Li-ion batteries available in the market with different specific energy and voltage for diverse applications. The potential candidates of Li-ion batteries for EVs are Lithium Cobalt Oxide ($LiCO_2$), Lithium Manganese Oxide ($LiMn_2O_4$), Lithium Iron Phosphate ($LiFePO_4$) and Lithium Nickel Manganese Cobalt Oxide (NMC) with different types of packaging such as spiral wound, elliptic and stacked plate make a good choice for the energy storage system [5–7].

Battery pack cycle life, capacity, charging duration, durability and warranty cost are the parameters that affecting the cost and

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Nomenclature

A_{ext}	external surface of cells, m^2
C	constant
C_p	gas specific heat capacity, $J\,kg^{-1}\,K^{-1}$
D	diameter of cell, m
Δp	pressure drop, Pa
$\dot{V}$	volume flow rate of air, $m^3\,s^{-1}$
H	height of tangential blower outlet
$\bar{h}$	averaged convective heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
h_f	enthalpy ($J\,m^3$)
i	internal energy, J
I_t	discharge current in amperes during one hour discharge
k	thermal conductivity of fluid, $W\,m^{-2}\,K^{-1}$
Nu	average Nusselt number
P	pressure, Pa
$\dot{Q}$	heat rate, W
T	temperature, K
t	time, s
U	average incoming air velocity, $m\,s^{-1}$
W	width of tangential blower outlet
μ	viscosity, $m^2\,s^{-1}$
u	velocity, $m\,s^{-1}$
Re	Reynolds number
S_i	source of energy per unit volume, J
S_{Mx}, S_{My}, S_{Mz}	body forces
σ	contraction ratio of the cross-sectional area, (A_c/A_{fr})
ρ	fluid density, $kg\,m^{-3}$
μ	fluid viscosity, Pa s
Φ	dissipation function

Subscript

c	cell
f	fluid (air)
m	mean (average)
w	wall
∞	for air at free stream conditions
$surf$	surface

Superscript

e	constant

reliability of the EVs and these parameters depend on the thermal management system of the battery pack. Battery temperature and uniformity have a strong influence on the battery pack power, cell balancing and charge acceptance during regenerative braking. Reaction heat, ohmic heat, reversible heat and external contact resistance heat are the heat sources of the battery during charging and discharging process. A rapid increase in the cell temperature during the end of state of charge (SOC) may cause the performance of battery deteriorate and reduce the cycle life of the cell [8]. Hence, this heat must be dissipated as fast as possible. The optimum operating temperature of Li-ion battery is between 25 °C and 40 °C and desirable temperature uniformity within a battery pack is less than 5 °C [1,9]. The energy storage and cycle life of the cell can be reduced significantly when the cell is operated at a temperature above 40 °C or below 0 °C. High temperatures promote growth of the solid electrolyte interface layer and increase the internal resistance which would cause a reduction in the power delivery. Under extreme conditions, the separator will melt, causing an internal short circuit and lead to uncontrollable temperature rise (thermal runaway) in the cell. The energy and gases released from this reaction are dangerous and can cause an explosion or fire depending on the battery chemistry. On the other hand, the capacity will be reduced if the battery is operated at temperatures below 0 °C and lithium plating during charging will occur [10–12]. This further emphasizes the need for a good understanding of the thermal issues of the Li-ion battery and a good thermal management system for the EVs battery pack.

Electrochemical models [13–16], equivalent circuit models [9,17–20] and finite element models [21–23] are commonly used for battery thermal management system design. However, electrochemical models are more suitable to predict the electrochemical performance of a single cell while equivalent circuit models are more suitable to predict the electrical and thermal behavior of a single cell and used in the battery management system. Both models cannot capture the heat transfer aspects of the actual battery geometry, cell arrangement and the interaction of the battery module with the cooling fluids. Although the finite element model is more robust in investigating the flow field of the cooling fluids and the effect of the cell arrangement to the heat transfer, the heat generation of the cell due to dynamic charging/discharging of the battery pack is not captured [24]. Besides, most of the studies only presented numerical simulation results of a single cell and did not validate with the experimental work [19–22].

Different types of cooling systems will affect the performance and cost of the EVs. The heat transfer medium could be air [25–27], liquid [11,27,28], phase change material [29–31], heat pipe [32–34] or a combination of them. The heat generated from the cell is dissipated by forced convection using ambient air or outside air directed into the pack. The disadvantages of air cooling are maximum heat load is limited to about 325–800 W, depending on vehicle cabin air temperature and the heat transfer performance is low [23,35]. The feasibility of reciprocating air flow to improve temperature uniformity and reduce the maximum temperature of Li-ion battery ($LiMn_2O_4/C$) was investigated by Mahmud and Park [25]. The numerical study revealed that when the reciprocating period is short, the temperature distribution is more uniform and maximum cell temperature is reduced. As compared to uni-directional flow, reciprocating period of 120 s is effective to reduce the cells temperature difference of the battery system by 4 °C and maximum temperature by 1.5 °C [25]. Ghosh et al. designed a battery pack cooling system for Ford Fusion Hybrid and Mercury Milan Hybrid [36,37]. CFD simulation was used to evaluate the performance of the cooling system. The configuration of battery pack comprised of 4 D-size NiMH cells arranged in series and 8 D-size NiMH cells arranged in parallel. A small temperature gradient of 1.2 °C within the battery cell is achieved by controlling the wrap angle around the leading cells [36,37].

Liquid cooling is more complex, but offers a higher cooling capacity than air cooling system. Liquid cooling of the battery pack is realized by using a cold plate or heat spreader sandwich between the cells or submerging the cell in a dielectric fluid. Mineral oil, water, dielectric fluid and ethylene glycol mixture are normally used as a heat transfer medium. The disadvantages of liquid cooling system are the necessity of large space and the increase of vehicle total weight, higher cost, high pumping power, potential leakage of cooling fluid and poor thermal contact between the cold plate and cell [23,35]. The operating characteristics of the cold plate used in the battery pack are determined by the geometry of

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