International Journal of Heat and Mass Transfer 112 (2017) 779–794

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Exploring the efficacy of nanofluids for lithium-ion battery thermal management

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ARTICLE INFO

Article history:
Received 5 November 2016
Received in revised form 25 April 2017
Accepted 26 April 2017

Keywords:
Lithium-ion battery
Battery module
Thermal management system
Nanofluids
Mathematical modeling and analysis

ABSTRACT

Thermal implications related to heat generation and potential temperature excursions during operation in lithium-ion batteries are of critical importance for electric vehicle safety, performance and life. Concurrently, appropriate thermal management strategies for lithium-ion batteries are crucial to maintain cell temperatures within a desired range. Different battery thermal management strategies have been proposed, each with various advantages and disadvantages depending on the applications. This work proposes the use of nanofluids, colloidal suspensions of nanoparticles in a base fluid, as a heat transfer fluid for active thermal management. To analyze the efficacy of nanofluids for thermal management in lithium-ion batteries, different nanofluids and their effect on the temperature distribution within typical battery modules are investigated for two different flow configurations. In particular, the study is focused on battery performance, heat dissipation capability under high discharge rates and ambient temperatures, and design considerations relevant to electric vehicle applications. This study underscores the potential of this innovative thermal management technique toward effective thermal safety without performance penalty of lithium-ion batteries for vehicle electrification.

1. Introduction

Lithium-ion batteries (LIB) provide the best solution for energy storage in both small and large format applications such as consumer electronics and electric vehicles, due to their high specific energy and power capability. A battery module includes multiple Li-ion cells connected in series and parallel for use in electric vehicles. However, lithium-ion batteries are very sensitive to temperature compared to other chemistries, and can suffer both in safety and performance if exposed to high or imbalanced temperatures [1–3]. This drives the necessity for thermal management systems in large Li-ion modules, particularly when longevity and safety are of paramount importance [4–11]. As such, there is a considerable effort to determine efficient methods and best practices for designing battery thermal management systems [12–22]. Pesaran discusses several aspects of battery thermal management system design, particularly for use in electric and hybrid electric vehicles [12]. Al Hallaj et al. [13] studied a simplified one-dimensional, mathematical model with lumped parameters to simulate temperature profiles inside cylindrical lithium-ion cells of 10 and 100 A h capacity for different discharge rates, operating conditions, and cooling rates. At lower cooling rates, the cell behaved as lumped system with uniform temperature and at higher cooling rates, a significant temperature gradient developed inside the cell. Consequently, this study suggests adequate thermal management using active cooling when a battery module is subject to high discharge rates or near-insulating ambient conditions due to significant rise in cell temperature and risk of thermal runaway. Sato detailed various heat generation components including reaction heat, polarization heat, and joule heat during charging and discharging through an experimental and analytical study [14]. In this study, analysis of the exothermic heat release during cycling not only provided quantitative analysis of heat generation for a Li-ion battery under realistic load conditions, but also provided guidelines for thermally-conscious design of Li-ion batteries for electric vehicles. Al-Hallaj and Selman [15] reported a passive thermal management system using phase change materials (PCM). This method has high potential for providing effective thermal cooling without the use of moving parts within the thermal management system. PCM cooling provides a relatively simple design and lower cost compared to active cooling systems, but is only capable of absorbing heat equal to the latent heat of the PCM, limiting its use to moderately energy dense cells.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.04.130
0017-9310/

Nomenclature

a	fitting parameter
A	electrode area
b	Fitting parameter or voltage correction factor
c_p	specific heat
DoD	depth of discharge
E_a	activation energy
h	heat transfer coefficient
J	current density
k	thermal conductivity
I	current
Nu	Nusselt number
q	heat rate
Q	heat generation
t	time
T	temperature
U	equilibrium voltage
V	velocity or voltage
Y	conductance

Greek

ρ	density
Φ	heat dissipation function
ϕ	volume fraction
μ	dynamic viscosity

Subscripts

avg	average
b	bulk
$cell$	cell
con	convection
eff	effective
f	fluid
gen	generation
p	particle
ref	reference
w	wall

To provide better insight into the thermal behavior of high-power LIBs under realistic discharge conditions, a three-dimensional thermal model was developed by Zhang et al. [16]. This study modeled an air-cooled battery module consisting of closely packed cylindrical cells. The results showed a significant effect of air flow rate on the temperature rise within the cells for all discharge rates, and an increase in required flow rate to maintain safe temperatures with an increase in discharge rate. Shadman Rad et al. [17] carried out a numerical study based on a simple radial-axial model to evaluate the thermal behavior of Li-ion batteries. Their results showed that the core temperature of a cell is much higher than that at the surface of the cell, as shown in previous experiments. To analyze the thermal behavior of a Li-ion battery module, a three-dimensional numerical study was carried out by Karimi and Li [18]. Different cooling strategies, including natural and forced convection with different cooling medium and PCM, were considered during the examination of battery thermal management system (BTMS) performance. Numerical analysis suggested that distributed cooling methods reduce the temperature non-uniformity between cells and improve the overall performance of the battery pack. Fan et al. [19] numerically studied an air-cooled module using a three-dimensional transient model available in commercial computational fluid dynamics software. The module contained eight prismatic lithium-ion cells subjected to an aggressive drive cycle. The effects of gap spacing between the cells and air flow rate on cooling effectiveness of the existing air-cooled battery module were studied. A reduction in temperature rise achieved by reducing the gap spacing between the neighboring cells and increasing the air flow rate. They also reported for the effect of different configurations such as one-side versus two-side cooling, and uneven versus even gap spacing and their combinations. The thermal performance of lithium-ion battery modules of various cell arrangements in the presence of forced air cooling was investigated by Wang et al. [20]. The effect of different module arrangements, fan locations and inter-cell distance on temperature distribution in the battery module were studied. Fathabadi [21] introduced a lithium-ion battery pack design with hybrid active-passive thermal management system. The active cooling system consisted of a distributed and thin air duct and the passive system utilized a phase change material and expanded graphite composite. A sandwiched cooling structure with copper metal foam and phase change material was analyzed by Li et al. [22]. This group experimentally investigated the thermal performance of the system with two control cases, which consisted of a cooling mode with pure phase change materials and an air-cooling mode. Their study reported that phase change materials could dramatically reduce and maintain the cell surface temperature below typical safety limits. He et al. [23] studied the thermal management of a multi-cell Li-ion battery module both experimentally and numerically under various flow velocities, charging and discharging current, and various module configurations. Cell temperatures and pressures measured during the experiment compared well with results obtained from computational fluid dynamics (CFD) simulations. Recently, a fully coupled electrochemical-thermal model was developed for a single spirally wound lithium-ion cell [24,25]. Anisotropic thermal conductivity of the cell and induced resistive heating in the current collectors were incorporated in their model. Using a liquid coolant significantly reduced the peak module temperature compared to an air coolant, but increased the module thermal gradient slightly. A new thermal management strategy based on edge and internal cooling was discussed to reduce the volume occupied by the entire battery and thermal management system [25].

It is clear from a survey of thermal properties that all liquid coolants in use today as heat transfer fluids exhibit rather poor thermal conductivity when compared to solid metals. Despite the obvious improvement over air-cooling, several methods to further increase the heat transfer performance of liquid coolants have been proposed. One way to improve coolant heat transfer is to enhance the fluid's thermal conductivity. Hence, dispersing solid particles with high thermal conductivity into a liquid coolant to enhance the thermal properties of conventional heat transfer fluids have been reported. Maxwell [26,27] was the first to propose the possibility of increasing thermal conductivity of a solid-liquid mixture by increasing the volume fraction of solid particles. However, large particles can cause low flow rate sedimentation, clogging, and erosion of channels and pipes, and as well as an increase in the pressure drop. Instead, smaller nanoparticles are used in a new class of fluid, called nanofluids, to improve both thermal conductivity and suspension stability [28–32]. Chol [33] presented the benefit of using the nanoparticles dispersed in a base fluid in different thermal systems to enhance the heat transfer rate. Eastman et al. [34] showed that a 0.3% volume concentration of Cu nanoparticles dispersed in ethylene glycol increased the base fluid thermal conductivity by 40%. Additionally, Das et al. [35] observed a 10–25% increase in thermal conductivity with 1–4% volume concentration of alumina nanoparticles added in water. Li and Kleinstreuer [36] presented a model for defining the thermal conductivity of a nano-