Electrochimica Acta 280 (2018) 340–352

Contents lists available at ScienceDirect

Electrochimica Acta

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

Development and evaluation of a new ammonia boiling based battery thermal management system

Maan Al-Zareer*, Ibrahim Dincer, Marc A. Rosen

Clean Energy Research Laboratory, Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario, L1H 7K4, Canada

A R T I C L E I N F O

Article history:
Received 8 September 2017
Received in revised form
19 April 2018
Accepted 14 May 2018

Keywords:
Thermal management
Battery
Hybrid electric vehicle
Ammonia
Phase change material

A B S T R A C T

An efficient and safe operation of lithium ion battery packs for electric and hybrid electric vehicles requires maintaining the operating temperature of battery packs within the optimum range. This paper models and assesses the performance of an ammonia boiling based battery thermal management system to maintain the operating temperature of possible future ammonia based hybrid electric vehicles within the optimum operating range. A battery pack design of an ammonia boiling based thermal management systems is proposed, modeled and analyzed. In the proposed design, the batteries are partially submerged in a liquid ammonia pool, and the ammonia pool boils through absorbing part of the heat generated by the battery at the surface submerged in the liquid ammonia. This cools the battery and produces ammonia vapor. The ammonia vapor cools the unsubmerged part of the battery through forced convection heat transfer. The generated ammonia vapor passes to the vehicle electrical generator, where it is used to produce electrical energy for driving the vehicle or charging the batteries. The performance of the each proposed design is assessed for various design parameters, for a 600 s discharging and charging cycle at a high rate of 4C. The results show that the ammonia boiling based battery thermal management system performs better than liquid and air cooling systems. The electrical energy use of the proposed system is nearly negligible compared to that for liquid and forced air cooling systems.

1. Introduction

In recent years, lithium ion batteries have become one of the most promising electrical energy storage technologies [1]. Compared to other rechargeable batteries, lithium ion batteries have higher energy density, no memory effect, lower mass density and low self discharge rates [2]. The high energy density and the high discharge rate of lithium ion batteries permit them to provide long driving ranges and high acceleration capabilities to electric vehicles (EVs), plug-in hybrid electric vehicles (PHEVs) and hybrid electric vehicles (HEVs) [3]. The emergence of what is known as electric and hybrid electric high performance sport cars attracted the world's attention including car manufacturing companies and the public, due to their higher efficiencies, higher acceleration capabilities and lower environmental impacts compared to conventional vehicles. An example of an electric high performance sport cars is the Tesla Model S P100D, which has the ability to go from 0 to 100 km/h in 2.7 s [4]. The development of hybrid electric high performance sport cars encouraged car manufacturers to develop and offer hybrid electric vehicles for regular use, such as BMW i3, Ford Fusion, and Chevrolet Volt. The rapid development of EVs, HEVs and PHEVs has led to increased research and development on lithium ion battery technology. Since manufacturing technology and materials are significant factors in determining the energy density, life cycle and allowable charging and discharging rates for lithium ion batteries, they have been subject to extensive research and development in the recent years [1,5,6]. The thermal performance of lithium ion batteries also can greatly affect their performance, energy density and life cycle, but has received comparatively less attention [7].

The importance of the thermal performance of lithium ion batteries has been highlighted by Doughty and Roth [8]. The capacity fading of a specific lithium ion battery type, the Sony 18650 cell, with the cycle time and the battery temperature have been investigated by Ramadass et al. [9]. They found that high battery operating temperatures accelerated the capacity fade of the

* Corresponding author.
E-mail addresses: maan.al-zareer@uoit.ca (M. Al-Zareer), ibrahim.dincer@uoit.ca (I. Dincer), marc.rosen@uoit.ca (M.A. Rosen).

https://doi.org/10.1016/j.electacta.2018.05.093
0013-4686/

lithium ion cells. Battery capacity fading is not the only result of high battery operating temperatures. For instance, batteries easily get overheated due to the heat accumulation, if not cooled properly, which results in thermal runway [10]. Due to the importance of the temperature of a lithium ion battery on its performance, efforts are expended to improve the thermal performance of batteries. These efforts mainly involve (i) reducing the heat generation rate of the battery and (ii) increasing the heat dissipation rate from the battery.

The heat generation rate from a charging or discharging lithium ion battery can be reduced by modifying the internal structure of the battery cell. Studies have shown [1] that the part of the battery that is responsible for most of the heat generation by the battery is the electrode, due to the resistance to electron and ion travel. However, increasing the dissipation rate of the generated heat can be done without the need to modify the structure of the battery. Such an external system is known as a battery thermal management system (BTMS). A BTMS can help relieve a lithium ion battery of the generated heat and thereby to keep its temperature within the optimum operation range, without structural or manufacturing modifications to the battery [11]. The goal is often to equalize the heat removal from the battery with the heat generated by it. But less research has been dedicated to BTMS compared to internal battery modifications [12].

There are three main BTMS categories: liquid based [13], air based [14] and phase change material (PCM) based cooling systems [15]. Liquid based BTMS uses a liquid coolant to cool the batteries in the pack, while the air based cooling system uses air, which can enter the battery pack either due to the movement of the vehicle (natural air flow based BTMS) or due to the use of power assisted devices such as compressors and fans (forced air flow based BTMS) [16]. PCM based battery cooling systems uses the latent heat of the PCM to cool the batteries, which does not consume power or need the use of power assisted devices [17]. BTMSs can also be categorized into passive and active categories. PCM based BTMS are usually passive systems [18]. Due to the simplicity, ease of maintenance and low cost, air based battery cooling systems are more commonly used in HEV and EV battery packs than liquid based and PCM based BTMS [2]. An example of commercial HEVs and EVs that have adopted air based BTMS are the Toyota Prius, the Honda Insight and the Nissan Leaf [19]. Tesla EVs use liquid based BTMS where the coolant is a mixture of 50% water and 50% glycol [20].

Although little research has focused on the development of BTMS, air based BTMSs have over the past decade been subject to more study than other types of BTMS [21]. For example, Saw et al. [22] proposed an innovative design for an air based BTMS that forces the air that enters the pack in a perpendicular direction to the axis of the cylindrical batteries in the pack to flow in the axial direction between the batteries in order to improve the temperature uniformity in the pack. Zolot et al. [23] investigated the performance of the air based BTMS of the Honda Insight observed that the performance of the NiMH batteries varies considerably with operating temperature. Fan et al. [24] found an important parameter of air based BTMSs to be the air space for the air to flow in the battery pack, which greatly affects the temperature of the batteries in the pack. It was seen that increasing the spacing between the batteries in the pack reduces the maximum temperature and improves the pack temperature uniformity in the flow direction. However, Fan et al. determined that temperature differences in the flow direction within the pack are unavoidable. Zhao et al. [1] highlighted in their review paper that a number of studies show that an air based BTMS can provide sufficient cooling and maintain the temperature of batteries within the optimum operation range, except at severe charging and discharging rates where the air based BTMS falls behind. But, liquid based BTMS can provide the required cooling loads to achieve sufficient cooling performance even at high discharging and charging rates, since at the same inlet condition to the pack, liquid coolant has a higher heat transfer coefficient and higher heat capacity (e.g., water has four times the heat capacity of air).

Air and liquid based cooling systems have also been compared. Chen et al. [25] compared air and liquid BTMSs, where two cooling cases were considered for each BTMS: direct and indirect. Direct cooling is defined as when the coolant is in direct contact with the surface of the battery, while indirect cooling occurs where the coolant is not in contact with the surface of the battery but rather the coolant cools a medium that cools the battery. In Chen et al.'s [25] study, the indirect air BTMS uses fins, and the indirect liquid BTMS uses flow channels inside a metallic plate. The four systems analyzed by Chen et al. [25] were compared based on weight, power consumption, and maximum temperature in the pack. Forced air based BTMS was observed to consume more power than liquid cooling based BTMS. It was found that increasing the flow rate of the coolant decreases the maximum temperature difference in the pack, and that using low mass flow rates in an indirect liquid cooling should be avoided. To enhance liquid cooling system performance, Huo and Rao [26] combined cooling water with Al_2O_3 nanoparticles. The authors found out that using a nanoparticle water mixture with a 0.04 vol fraction in the solution reduces the average temperature of the battery by 7% compared to using pure water. Further investigation of liquid indirect cooling was performed by Panchal et al. [27–29], who proposed and analyzed a mini-channel cold plate using water as the coolant.

PCM based BTMSs are recognized as relatively recent developments. They absorb battery heat by phase change. One advantage is the constant phase change temperature, which helps in maintaining a low operating temperature across the battery pack. The first PCM based BTMS was proposed by Al-Hallaj and Selman [30], who showed that the PCM based system provided better temperature uniformity through the battery pack compared to liquid and air cooling systems. Most of the proposed PCM based BTMSs involve solid-liquid phase change. Javani et al. [31] investigated the performance of a PCM based BTMS and reported that, to achieve steady state performance, a transient period was required first, which could last up to 3 h. Javani et al. [31] highlighted that the low thermal conductivity of the solid phase of the PCM limits its cooling effectiveness. Numerous options, e.g., carbon nanotubes, were proposed and used by Malik et al. [17] to increase the thermal conductivity of the PCM for more effective cooling, since the low thermal conductivity is one of the main drawbacks of PCM based systems. Another option is to use heat pipe based battery cooling system. With heat pipes, the heat is taken away by evaporating the liquid coolant inside the heat pipe from the side where the heat pipe in contact with the battery (evaporator). The evaporated coolant travels through the pipe to the condenser end and condenses by releasing the heat to the surrounding. Then, the condensed liquid travels back to the evaporator end of the heat pipe to repeat the cooling cycle again [32]. Wang et al. [33] proposed integrating a heat pipes with a PCM to provide efficient and uniform cooling for the batteries in the packs. Recently, the present authors proposed an efficient and novel PCM based BTMS, where the PCM changes phase from liquid to vapor [34,35]. The PCM based system in was applied to a cylindrical lithium ion battery pack of the 18650 type. The PCM based system exhibited better performance than conventional PCM based systems that involve solid-liquid phase change.

This paper proposes a novel PCM based battery thermal management system design, in which the phase change material is ammonia. The PCM changes phase from liquid to vapor by absorbing part or all of the heat generated by the battery. The