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Electrochemical modeling and performance evaluation of a new ammonia-based battery thermal management system for electric and hybrid electric vehicles

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ABSTRACT

The operating temperatures of lithium ion battery packs in electrical vehicles and hybrid electrical vehicles need to be maintained in an optimum range for better performance and longer battery life. This paper proposes a new battery pack cooling system that utilizes the low saturation temperature of the fuel in ammonia based future hybrid electric vehicles. In the proposed cooling system, the batteries are partially submerged in to the liquid ammonia, and the liquid ammonia cools the battery by absorbing the heat and evaporating and the ammonia vapor cools the part of the battery not covered by liquid ammonia. The relationships between the performance of the battery cooling system and the maximum temperature (and the temperature distribution) in the battery are investigated for practical applications. The effect of the length of the battery that is submerged in to the liquid ammonia on the thermal performance of battery is studied and evaluated. The present results show that the proposed ammonia based cooling system offers a unique opportunity to maintain the operating temperature of the battery in an optimum range for consecutive charging and discharging phases at a high rate of 7.5C.

1. INTRODUCTION

The need to mitigate environmental damage has resulted in efforts to diversify the energy sources to include as much as possible renewable energy sources, and have provided opportunities for electrical vehicles (EVs) and hybrid electrical vehicles (HEVs) [1]. Some of the advantages of EVs and HEVs are enhanced energy utilization, less noise, reduced environmental impact than conventional fossil fuel vehicles in terms of carbon and pollutant emissions, and the ability to utilize renewable energy sources (indirectly) [2]. The amount of energy a battery provides is a key factor in the development of EVs and HEVs [3]. A wide range of batteries has been developed over many years in terms of materials used to store the electrical energy and release it, geometrical aspects, number of usage cycles and other factors.

Examples of batteries used in EVs and HEVs based on chemical composition are lithium ion (Li-ion) and metal hydride batteries [3]. Li-ion batteries have advantages over other battery types in terms of higher energy densities, longer lifetimes and lower self-discharge rates [3]. These advantages of Li-ion batteries explain why some of the most successful EVs and HEVs are using them [3]. However, Li-ion batteries are temperature sensitive, which means that their performance changes with operating temperature. The operating temperature of the battery also effect its life cycle, efficiency, safety and reliability [4]. During the charging and discharging Li-ion batteries, internal electrochemical reactions and internal resistances lead to heat generation. If not removed from the battery, this heat raises the battery temperature and hinders its performance. Excessive increases in battery temperature can result in electrolyte fires and battery explosions [5]. The optimum temperature range for Li-ion batteries operation is between 25 °C and 40 °C, and it is recommended that the temperature in a battery or from one module to another be relatively uniform, i.e., within 5 °C [6]. Thus, an efficient and effective Li-ion thermal management system is needed.

Three main categories of battery thermal management systems (i.e., cooling systems) are currently used: air based, liquid based and phase change material (PCM) based. Cooling systems are usually classified into two main types, passive and active, although phase change material based systems are mainly passive [7]. Of the three categories of cooling systems, the most commonly used

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Nomenclature

a Specific interfacial area (m^2 m^{-3})
c_p Specific heat capacity (kJ kg^{-1} K^{-1})
c_s Concentration of lithium ions in the solid (mol dm^{-3})
c Salt concentration (mol dm^{-3})
D Salt diffusion coefficient (cm^2 s^{-1})
D_s Lithium diffusion coefficient in the solid electrode (cm^2 s^{-1})
E Specific energy (Wh kg^{-1})
F Faraday constant (96,485C mol^{-1})
f Conductive filler
g Gravitational acceleration (9.81 m s^{-2})
I Electrical current (A)
i_2 Superficial current density in solution phase (mA cm^{-2})
L Length (m)
n Number of electrons
$\dot{Q}$ Thermal energy rate (W)
R_s Radius of positive electrode (m)
t Time (s)
T Temperature (°C or K)
U Open circuit voltage (V)
υ Velocity (m s^{-1})
V Operating voltage of the battery (V)
ΔS Change in entropy

Greek letters
ρ Mass density (kg m^{-3})
υ Velocity (m s^{-1})
ε Volume fraction
ϕ Electrical potential (V)
η Electrode potential (V)
σ Solid matrix electronic conductivity (S cm^{-1})

Subscripts
b Battery
gen Generation
i Layer in lithium ion battery
J Joule heat
\+ Positive electrode
1 Solid phase of the electrode
2 Solution phase of the electrode

Acronyms
EV Electrical vehicle
HEV Hybrid electrical vehicle
Li-ion Lithium ion
PCM Phase change material

today for EVs and HEVs is the air cooling system. This is due to its simplicity, low cost and easy maintenance compared to liquid and PCM based systems [3]. Some EVs and HEVs with air based cooling systems are the Nissan Leaf, the Honda Insight and the Toyota Prius [8].

During the past decade numerous investigations have been carried out, particularly on air based cooling systems. Saw et al. [9] proposed an air based thermal management system to maintain the battery temperature in the acceptable operating temperature range and reduce the temperature differences between the batteries in the pack. Zolot et al. [10] proposed and assessed the performance of a forced air cooling system for Ni-MH batteries. The cooling system was able to maintain a uniform temperature distribution throughout the battery and to reduce the maximum temperature of the batteries in the pack. In air cooling systems the air gap between the batteries in the battery pack has a major effect on their temperatures, an effect that has been investigated by Fan et al. [11]. They found that decreasing the air gap and increasing the air flow rate reduces the maximum temperature in the battery, but that a temperature gradient throughout the battery pack in the air flow direction is unavoidable. Air based battery thermal management systems usually provide sufficient cooling, except during severe charging and discharging conditions. Liquid based battery thermal management systems can handle the large cooling loads during high discharge rates, since liquids have higher heat transfer coefficients than air for the same inlet conditions.

Chen et al. [12] examined battery thermal management systems for cooling Li-ion battery packs and found that indirect liquid cooling systems produce the lowest maximum temperature in the pack. Chen et al. thus recommend indirect liquid cooling as more practical than direct cooling systems. A modified water cooling system that combines the heat transfer fluid (water) with nanoparticles (alumina, Al_2O_3) was proposed by Huo and Rao [13]. They found that the performance of the liquid cooling system was enhanced by the addition of nanoparticles to the heat transfer fluid, decreasing the battery average temperature by 7% when with a 0.04 volume fraction of nanoparticles. An oscillating heat pipe based battery thermal management system was proposed by Rao et al. [14], in which the startup temperature of the heat pipe is based on the maximum temperature difference in the battery. Rao et al. concluded that in order to meet the required cooling load, the heat pipe start up temperature must be lower than the desired maximum temperature of the battery. Huo et al. [15] proposed a system that exploits the cooling ability of the liquid more effectively by using a mini channel cold plate. They found that with the mini channel based cooling system the maximum temperature of the battery decreases as the mass flow rate of the liquid and the number of channels increase. Panchal et al. [16–18] proposed a mini channel based cooling system to control the temperature of prismatic Li-ion batteries. A mini channel design with an oblique channel plate was proposed by Jin et al. [19], who found that their system exhibited higher heat transfer rates than other mini channel plate based systems reported in the literature.

Of the three main categories of battery thermal management systems, phase change material systems are the most recently developed. In such cooling systems, the PCM absorbs the thermal energy generated by the battery during change phase. PCM based thermal management system was first proposed by Al-Hallaj and Selman [20], who found that the use of a PCM to cool the battery provides a more uniform temperature during the discharging phase than not using a PCM. The PCM based cooling system has the advantage of releasing the thermal energy it absorbed while cooling the batteries back to the batteries when their temperature drops below the phase change temperature of the PCM. Javani et al. [21] investigated the use of a PCM to manage the temperature of a square Li-ion battery pack. Javani et al. showed that a PCM cooling system was able to maintain a uniform temperature distribution throughout the battery pack and a safe operating temperature range for the batteries in the pack. An ageing Li-ion battery is one that has been subjected to large number of charging and discharging cycles, reducing its capacity. The thermal performance of an ageing $LiFePO_4$ battery when a PCM based thermal management system is used was investigated by Rao et al. [22], who found that the maximum temperature of the battery during operation depends greatly on the melting temperature and thermal conductivity of the PCM. A drawback of PCM based thermal management systems, which limits their use, is their relatively low overall heat transfer coefficient [23].

In this paper, a novel battery thermal management system is proposed that uses evaporative cooling of pressurized saturated