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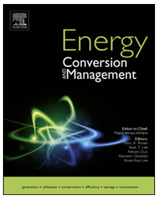

Performance assessment of a new hydrogen cooled prismatic battery pack arrangement for hydrogen hybrid electric vehicles

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ABSTRACT

This paper proposes a new novel battery cooling system for hydrogen fueled HEVs that achieves more efficient cooling and driving, which increases vehicle driving range and enhances vehicle safety by maintaining the batteries at optimum operating conditions. The proposed system offers a novel use of the vehicle fuel and a novel cooling plate design. The cooling plate design is optimized in terms of battery's temperature uniformity and battery's maximum temperature. The optimum performance of the design is then investigated through a 600 s high intensity discharging and charging cycle of 4C. The results show that when hydrogen is at a temperature of 10 °C and has an inlet velocity of 0.01 m/s, the maximum temperature is maintained at lower than 30.5 °C. The lowest difference through the battery obtained by the proposed system is less than 7 °C. The performance of the proposed system is compared with the performance of liquid, air and evaporative cooling based systems. The comparison shows that the proposed system is able to perform better than liquid, air and evaporative cooling based cooling systems. The performance of the proposed cooling system demonstrates the advantage of integrating the hybrid vehicle fuel system with the battery cooling system.

1. Introduction

The environmental impact associated with fossil fuel consumption, mainly emissions of greenhouse gases and harmful air contaminant, are a global concern. According to data presented by the Intergovernmental Panel on Climate Change (IPCC) in 2015, 28% of Canada's emissions is caused by the transportation sector and its use of fossil fuels [1]. Most of these emissions are due to on-road passenger and freight vehicles, such as cars, trucks, heavy duty trucks, trains and busses. Environmentally-benign transportation technology options for sustainable transportation solutions are badly needed by the transportation sector. Such technologies are always linked to energy conversion and management in the transportation applications.

Pressures due to global warming and governmental environment protection regulations related to the transportation sector have increased interest globally in electric vehicles (EVs) and hybrid electric vehicles (HEVs) [2]. For EVs and partially for HEVs, driving range, acceleration and achieved speeds depend greatly on the energy content and performance of the battery pack. One of the most efficient energy storage technologies is the rechargeable lithium ion (Li-ion) battery [3]. Li-ion batteries perform better than other rechargeable batteries in terms of having higher energy densities, lower self-discharge rates, and little detrimental memory effect [4]. Besides the performance, the safety and the life of the battery pack are also important factors in the success of EVs and HEVs [4]. In order to reduce the charging time (EV refueling), high charging rates are required. However, to achieve high acceleration of the EVs and HEVs, high discharging rates are required [5]. However, the charging and discharging rates that the battery can manage are limited by the battery operating temperature, the battery materials and the manufacturing technology. As a result, extensive research has been dedicated in recent years towards improving battery materials and manufacturing methods [3,6,7]. However, one important performance factor, battery operating temperature and its control, has received less attention, even though there has been research directed towards the development of battery thermal management systems (BTMSs) [8].

Batteries generate heat when they are charging or discharging, which raises the operating temperature of the battery if not removed. High operating temperatures can lead to safety issues such as thermal runaway and electrolyte explosion [9–13]. Research has shown for Li-ion batteries (Sony 18,650 cell, which is the battery that was considered in Ramadass et al. [14]) as their operating temperature increases beyond the optimum operation range, where the battery performance at a temperature more than 40 °C suffers from critical battery capacity loss

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Nomenclature

a	specific interfacial area (m^2/m^3)
b_{Li}	concentration of lithium ions in solid (mol/dm^3)
b_s	salt concentration (mol/dm^3)
b_t	maximum salt concentration (mol/dm^3)
b_i	concentration of salt at layer i (mol/dm^3)
c_p	specific heat capacity (kJ/kg K)
D_s	salt diffusion coefficient (cm^2/s)
D_{Li}	lithium diffusion coefficient in solid electrode (cm^2/s)
E	specific energy (Wh/kg)
F	Faraday constant (96,485 C/mol)
f	activity coefficient
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
$\dot{Q}$	heat rate (W)
R_s	radius of positive electrode (m)
t	time (s)
T	temperature (°C or K)
V_{oc}	open circuit voltage (V)
V	operating voltage of battery (V)
S	entropy (kJ/K)

Greek letters

ρ	mass density (kg/m^3)
υ	velocity (m/s)
ϵ	volume fraction
ϕ	electrical potential (V)
η	electrode potential (V)
σ	solid matrix electronic conductivity (S/cm)

Subscripts

b	battery
gen	generation
i	layer in lithium ion battery
+	positive electrode
1	solid phase of electrode
2	solution phase of electrode

Acronyms

BCS	battery cooling system
EES	engineering equation solver
EV	electric vehicle
HEV	hybrid electric vehicle
PCM	phase change material

and hence performance degradation, while the performance of the battery will drop drastically at the operating temperatures below −10 °C. The capacity loss rate increases as the temperature increases for the same number of cycles [14]. For example, increasing the operating temperature of a battery from 25 °C to 50 °C increases the battery capacity loss by 100% for 300 cycles. Battery thermal management systems work to maintain the battery operating temperature from rising above or dropping below the optimum operation range. Thus, the battery thermal management system must cool the batteries at times and heat them at others. Regarding the heating function of battery thermal management systems, battery packs are often insulated tightly and usually equipped with electric heating coils to raise the temperature of the battery pack [15,16]. The fact that battery thermal management systems uses electrical heating coils to prevent the battery pack temperature from declining indicates the importance of focusing on the cooling function of BTMSs. Another important fact, which also highlights the importance of the cooling function of BTMSs, is that they generate heat when they are charged or discharged and that the generated heat increases with the battery's internal resistance. The battery internal resistance increases as the temperature drops below the optimum operating battery temperature, which means that cold batteries generate more heat and, if the heat is not removed, the batteries warm themselves [17].

Based on operation principle, BTMSs can be categorized into two main categories, active and passive. Other categorization criteria exist, such as the nature of contact between the battery and the coolant (i.e., whether there is a direct contact or not), and the phase of the coolant during the cooling process. Active BTMSs have one or more power assisted devices, and an active controller to adjust the power sent to the system devices to ensure that the batteries receive the cooling they need. Since the battery's heat generation rate varies throughout the drive cycle, the required cooling load varies accordingly [18–20]. Passive systems, such as phase change material (PCM) based systems, are able to satisfy the required cooling load without the need to consume power. PCM based systems change phase at a specific temperature, so the systems cool the battery only when the battery temperature rises above the phase change temperature. Since the temperature of the PCM remains constant during the phase change process, the heat rate from the battery to the PCM changes as the temperature of the battery changes, giving the system more responsive control of the cooling load with negligible if any electric power consumption. The coolant in a BTMS can be in indirect contact with the battery surfaces or in direct contact, i.e. a connection element between the coolant and the battery surfaces. There are three main categories of BTMSs based on the phase of the coolant used in the system: gas, liquid and PCM based. BTMSs that use a coolant in the gaseous phase are often referred to as air based systems since air is the dominant fluid used in gas based systems, mainly because it is safe in terms of toxicity, not combustible and widely available in the outside environment [10,21,22]. In an air based BTMS, the air cools the batteries in the pack by either flowing around the batteries, or through channels that are in contact with the batteries, removing heat [2,23]. The air flow can either be induced through a power assisted device, such as a fan or a compressor, or the air flow can be induced by the vehicle movement. In the first case, the BTMS is referred to as forced-air flow based and the second it is referred to as natural air flow based. Liquid based BTMSs use a liquid coolant, and a water-glycol mixture is the coolant used in most electric vehicle liquid based BTMSs [16]. Liquid based BTMSs use power assisted devices to force the flow of the coolant in the battery pack. However, liquid based BTMSs require the use of supporting heat removal devices in order to remove the absorbed heat in the coolant and recirculate the coolant back into the pack. The third category in BTMSs in terms of the phase of the coolant is PCM based. In such systems, the heat generated by the batteries is absorbed by the PCM as it changes phase, often solid to liquid [24–26]. However, when the temperature of the batteries drops below the melting temperature of the PCM, the PCM releases the heat back to the batteries, warming them. PCM based BTMSs are mostly passive, since they do not consume power or use power assisted devices to ensure system operation and they do not require supporting devices to remove heat from the PCM.

Of the main types of BTMS, the PCM based systems consume the least energy and operate passively. As they achieve the required cooling rate through latent heat transfer, they absorb or release heat at a constant phase change temperature. Having the cooling load satisfied through latent heat transfer results in achieving higher battery pack temperature uniformity than air and liquid cooling systems [27].