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Heat and mass transfer modeling and assessment of a new battery cooling system

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ABSTRACT

A novel refrigerant based battery thermal management system for electric vehicles is proposed, modeled, simulated and analyzed. The system is modeled and simulated with a one-dimensional electrochemical model integrated with a three dimensional heat and mass transfer model. The proposed battery cooling system uses phase change through boiling to cool the batteries. Refrigerant R134a is the phase change fluid in the proposed system, which changes phase by absorbing the heat generated by the batteries in a battery pack. The R134a liquid partially fills the battery pack forming a pool, in which the batteries are partially submerged. When the liquid refrigerant absorbs part of the heat generated by the batteries, it evaporates forming R134a vapor. The R134a vapor cools the surface of the battery that is not covered by the liquid R134a. Then the superheated R134a vapor exits the pack and enters a return channel. The return channel with the help of the car air conditioning system condenses the R134a vapor back to a liquid. The R134a condensate is returned to the R134a tank to be used again in cooling the batteries. The performance of the proposed battery cooling system is assessed for a 600 s charging and discharging cycle at a rate of 5C and for 10 min of an Artemis motorway drive cycle. The results show that better performance is obtained through the use of a refrigerant based thermal management system compared to air and liquid based cooling systems, in terms of maximum battery temperature and temperature difference between the batteries in the pack.

1. Introduction

In recent years, energy shortage and environmental protection pressure have increased interest globally in electric vehicles (EVs) and hybrid electric vehicles (HEVs) [1]. The performance of EVs and HEVs, including driving range, speed and acceleration, is greatly influenced by the performance of the battery pack. Recent developments of lithium ion batteries have made them useful and efficient for electrical energy storage [2]. Among rechargeable batteries, lithium ion batteries have the lowest self-discharge and mass density, no memory effect, and the highest energy density [3]. To achieve long driving ranges and good vehicle acceleration respectively for EVs and HEVs, batteries with high energy density and high discharge rates are required [4]. Other than long driving range and good acceleration, the life cycle of the batteries also is an important factor in the success of EVs and HEVs. Some of the decisive factors in determining the allowable charging and discharging rates and life cycle of batteries are operating temperature, manufacturing technology and materials. Recent research on improving battery life cycles was mostly directed towards the advancement of the battery materials and manufacturing technology, in order to improve battery energy density [2,5,6]. However, little effort has been focused on the development and improvement of battery cooling systems (BCSs) [7].

Battery thermal management is required since battery packs generate heat when charging or discharging. The heat generation of the operating batteries increases when EVs or HEVs are accelerating, starting and undergoing fast charging. If the heat generation rate of the battery is not equalized or overcome by the heat rejection rate, the temperature of the battery pack increases. The high operating temperatures of lithium ion batteries can lead to fading of the battery capacity [8]. The effect of high operating temperatures on the performance of a lithium ion battery, specifically the Sony 18650 cell, was investigated by Ramadass et al. [9]. They found that capacity fading is not the only negative effect associated with high battery operating temperature; it also can lead to thermal runway and electrolyte explosion [8]. The main goal of a BCS is to maintain the operating temperature of the battery within

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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	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
$\dot{Q}$	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
J	joule heat
+	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

the optimum operation range. BCSs can do this by equalizing the heat generation and rejection rates of the battery.

There are more than one criteria on which BCSs can be categorized, e.g., they can be categorized based either on the operation principle of the cooling systems or on the phase of the coolant. BCSs can either operate passively without dependence on a control system and without consuming power, or actively using a control system and consuming power. Based on the phase of the coolant used in the BCS, BCS can be categorized into: air or liquid or phase change material (PCM) based. In air based BCSs, air cools the batteries by flowing through the battery pack between the batteries. The air flow in the battery pack can either result from the movement of the vehicle, and such systems are called natural air based BCS, or be induced by power assisted devices that force air to flow through the battery pack, and such systems are referred to as forced air based BCS. Liquid based BCSs use coolants in the liquid phase, and such systems typically use power assisted devices to drive the coolant through the battery packs.

The cooling effect provided by the PCM is related to its latent heat, unlike the air and liquid based BCS in which the cooling is provided through sensible heat. One of the advantages of PCM based systems over liquid and air based systems is that they can achieve better temperature uniformity throughout the battery pack [10]. In general, BCSs have received limited attention from researchers, as air based BCSs have received most of the focus over the past decade. Air based BCSs suffer the disadvantage of the low specific heat capacity of air. The air flowing direction for air based BCSs is often perpendicular to the cylindrical batteries axes, which leads to a temperature gradient throughout the pack. Saw et al. [11] proposed a novel system that injects air in a parallel direction to the axes of the pack's cylindrical batteries, in order to reduce the temperature gradient throughout the pack. Liquid based BCSs are used in Tesla EVs, providing an ability to cool sufficiently batteries for high acceleration rates and short charging durations, compared to EVs that depend on air based BCSs.

Al-Hallaj and Selman [12] were the first to use a PCM undergoing a solid to liquid change, when they cooled cylindrical shaped 18,650 lithium ion batteries in 2000. Al-Hallaj and Selman [12] used a paraffin mixture of pentacosane and hexacosane as the PCM in the BCS. In addition to being a passive cooling system, PCM based BCSs cost less, occupy smaller volumes, and achieve better temperature uniformity than air and liquid based BCSs [2]. However, according to Zhao et al. [2], PCM based BCSs have disadvantages, including low thermal conductivity and variation of the PCM overall volume during the phase change process. Paraffin wax is the most investigated PCM for lithium ion battery BCSs. Paraffin wax is a mixture of various hydrocarbon groups [2]. The main characteristic that made paraffin wax of such interest for battery thermal management (BTM) is its broad range of phase change temperatures. The phase change temperature of a paraffin wax depends on the number of the main chain carbon atoms. PCM based BCSs where the cooling effect is provided by the PCM changing phase from solid to liquid can be used independently or in an integrated configuration that enhances PCM heat conduction [2]. The PCM can be integrated with a conductive filler, or used in various configurations of different types of PCMs [13]. Javani et al. [14] varied the layout of n-octadecane based PCM to achieve two main configurations. Ramandi et al. [13] used numerical simulations to investigate the performance in terms of energy and exergy efficiencies of various integrations of four types of PCM (eicosane, capric acid, zinc nitrate hexahydrate, and sodium sulfate decahydrate). Ramandi et al. concluded that the single shell PCM configuration underperforms the double shell PCM configuration.

In addition, PCMs can be integrated with metals or higher conductivity materials to improve the overall thermal conductivity of a PCM based BCS. Zhao et al. [2] proposed the use of conductive filler to improve the overall thermal conductivity of a PCM. Metal foam/matrix structures integrated with PCM can improve the overall thermal performance of a BCS. Khateeb et al. [15] proposed and analyzed the performance of a BCS based on a PCM integrated with an aluminum foam for electrical scooters battery packs. The aluminum foam is made from Duocel aluminum, has 40 pores/in and possesses an overall porosity of 90–92%. Other conductive fillers that have been integrated with PCMs in BCSs to enhance PCM thermal conductivity are: graphene, carbon fiber, and carbon nanotubes. Compared to PCM based BCSs, liquid cooling systems