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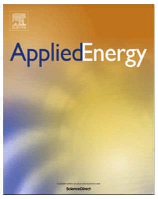

Experimental and numerical investigation of the application of phase change materials in a simulative power batteries thermal management system

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HIGHLIGHTS

- Performances of a PCM-based battery thermal management system are investigated.
- The PCM with the optimal thermo-physical properties is presented.
- Numerical simulation is carried out and results fit with experimental data well.

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ABSTRACT

The thermal management systems using EG-based phase change materials (PCMs) can provide power batteries with a proper operating temperature, slow temperature rise rate and uniform temperature distribution. In this study, a systematical investigation on the effects of thermo-physical properties of the used PCMs on the performance of the systems has been conducted. A series of paraffin/expanded graphite (EG) composites have been applied to a simulative battery thermal management system and to find out the PCM with the best thermal properties. The performances of PCMs varying with the kind of paraffin used, the paraffin mass fraction in composites and the packing density of the composites have been compared. It is found that the paraffin with the melting point of 44 °C offers batteries the best operating temperature. Furthermore, the synergetic effect of the mass fraction of paraffin in the composite PCM and the packing density of the composite in the thermal management system has been studied. The temperature rise can be slowed down by increasing the composites density and the temperature uniformity can be improved by the increase in EG mass fraction and composite density. After cycle tests, the paraffin/EG composite with paraffin mass fraction of 75% and density of 890 kg m^{-3} shows the best thermal management performance. In addition, numerical research with the computational fluid dynamics (CFD) software, FLUENT was also carried out. The numerical results are in a good agreement with the experiment data.

1. Introduction

Transport sector accounts for a significant share of global fossil fuel combustion-related CO_2 emission and so urgent is it to replace fossil fuel with high energy density and low greenhouse gas emission substitutes [1]. Electric vehicles (EVs) and hybrid electric vehicles (HEVs), which have high efficiency and nearly zero emissions are likely the best candidates to stand out from the traditional transport tools. Li-ion batteries, with high specific energy and high operating voltage are considered to be the best power sources for EVs/HEVs [2]. However, the overheating of Li-ion batteries gives rise to battery capacity fades [3,4] or thermal runaways [5], which degrade the battery performances or even possibly trigger potential risks of fire or explosions. It was recommended by Väyrynen and Salminen [6] that Li-ion batteries be operated within the temperature range −20 °C to 60 °C. Pesaran [7] also presented that the best operating temperature for Li-ion batteries ranged between 25 °C and 40 °C, and the maximum temperature difference in the battery pack should not exceed 5 °C. Therefore, a good thermal management system is essential for Li-ion batteries with the purpose of improving their safety and working life.

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Nomenclature

Q	heat power for each heater (W)
U	voltage applied to each heaters (V)
R	electric resistance of each heater (Ω)
ΔQ, ΔU, ΔR	corresponding errors
P	density kg m^{-3})
H	specific enthalpy (J kg^{-1})
ΔH	specific enthalpy change (J kg^{-1})
t	time (s)
k	thermal conductivity (W m^{-1} °C^{-1})
T	temperature (°C)
$\dot{q}$	heat density (W m^{-3})
H	specific sensible heat (J kg^{-1})
c_p	specific heat (J kg^{-1} °C^{-1})

Greek letters

β	liquid fraction of PCM
γ	specific latent heat (J kg^{-1})

Subscripts

0	initial condition
h	heater
PCM	phase change material

Different techniques have been applied to battery thermal management [8–10]. Compared with traditional ways of cooling by forced air and liquid convection, a passive thermal management system using phase change materials (PCMs) shows high efficiency and simplicity. Al-Hallaj et al. [11] first proposed to apply PCMs to the battery thermal management system, which can absorb the heat generated inside batteries by the phase change with large latent heat to keep the temperature in the battery pack within the safety range for a long time. Their further works [12–19] have proved that PCM-based thermal management system have a good temperature control performance. By distributing PCMs into Al-foam [15] or compositing PCMs with EG [13] to improve the thermal conductivity of PCMs, the temperature difference in battery pack could be decreased significantly. There were low capacity fades for batteries under the thermal management of PCMs. Compared with the way of forced air cooling, lower temperature rise and more uniform temperature distribution in the passive thermal management system prevented the contagious thermal runaway [17]. The mostly used PCM in the series of researches was pure RT 42 and RT 42/EG composites with the phase change temperature of 42 °C and the specific enthalpy of 187 kJ kg^{-1} and 127 kJ kg^{-1}. However, these studies used just a single kind of PCM to characterize its temperature control performance and no one examined the performances of battery thermal management using different PCMs to find out the best material.

The EG-based composite PCMs prepared by absorbing organic PCMs into the porous EG, not only retain high specific enthalpy of phase change of paraffin but also integrate with high thermal conductivity of EG [13,20]. One can expect that the EG-based composite PCMs are a suitable kind of form-stable PCMs for passive battery thermal management systems. It is obvious that the temperature control performance of the paraffin/EG composite is significantly influenced by the thermo-physical properties like the phase change temperature, specific enthalpy of phase change, thermal conductivity, which vary with types of PCMs, density of the composites and mass ratio of paraffin over EG. Py et al. [21] and Mills et al. [13] presented that the increasing bulk density of the EG matrix helped increase the thermal conductivity of the composite. Rao et al. [22] and Sarı and Karaipekli [23] reported that at the cost of the specific enthalpy of phase change, by increasing the EG mass fraction in the composite, the thermal conductivity of the composite PCM was to be improved, leading to a faster battery temperature elevating rate but the higher temperature uniformity.

Therefore, it is necessary to conduct a systematical investigation on the effects of the phase change temperature and mass fraction of the PCM in the composite along with the packing density of the composite on the temperature control performance of an EG-based composite PCM.

In addition, numerical studies on the thermal storage/release process have been carried out. Al-abidi et al. [24] has reviewed the application of computational fluid dynamic (CFD) in modeling the phase change process of PCMs. The enthalpy-based numerical approach [25–29] is believed to be reliable and efficient in designing and optimizing the passive battery thermal management system.

In the present study, paraffin/EG composites with different phase change temperature, packing density and mass percentage of paraffin are applied to the thermal management of four heaters that simulate power batteries generating heat. The temperature regulating performance of each composite PCMs is compared to find out the best PCM. We use two parameters to characterize the performance of the PCM: 1. The time for the heater surface temperature to arrive at 60 °C; 2. The maximum temperature difference in the PCM module. A good thermal management system offers longer duration and lower temperature difference. The comparison of performances of three kinds of paraffin/EG composites with different phase change temperature is conducted first. With the paraffin/EG composite owning the optimal phase change temperature, the effect of its packing density and mass fraction of paraffin, which have a decisive influence on the thermal conductivity and specific enthalpy of phase change will then be discussed in detail. Besides the experiment study, a numerical research via the commercial CFD software FLUENT was also carried out and results of numerical study showed a great agreement with the experiment data.

2. Experiment and simulation

2.1. Preparation and characterization of paraffin/EG composite PCMs

The paraffin/EG composites were prepared by submerging EG into melted paraffin with a designed mass ratio of paraffin over EG. After the PCM had been fully absorbed into EG, cool the composites down to room temperature. To optimize the phase change temperature of the EG-based composite PCMs used in battery thermal management system, three kinds of paraffin with phase change temperature of 36 °C, 44 °C and 52 °C were used to prepare the EG-based composite PCMs. As presented by Zhang and Fang [20], the maximum mass fraction of paraffin in the EG-composite is 85.6%. Therefore, the maximum mass percentage selected in this paper is 85%. And the performance of the series of composite PCMs with the paraffin mass fraction of 75% is used to compare with that of 85%.

The enthalpy of phase change and heat capacity of PCMs were measured by a differential scanning calorimeter (DSC, Q20, TA Instruments Inc) with an average error of ±1.0%. The thermal conductivity was measured by the HOTDISK thermal constants analyzer TPS 2500. Sensor 5464 with the radius 3.189 mm was sandwiched between two Φ40 × 10 mm cylinders made of paraffin/EG composites which had been compacted into the required density.