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Thermal management of lithium ion batteries using graphene coated nickel foam saturated with phase change materials

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ABSTRACT

Lithium ion (Li-ion) batteries are an integral part of electric vehicles and hybrid electric vehicles because of their high energy and power density. These batteries suffer from a high temperature rise during operation, thus affecting their life span and efficiency. In this study, thermal management of Li-ion batteries was accomplished by using a novel material (Graphene coated nickel (GcN) foam saturated with paraffin). The growth of graphene coated on nickel foam was carried out using chemical vapor deposition. The thermal conductivity of the pure paraffin wax was enhanced by 23 times after infiltrating it into the GcN foam. The paraffin was used as a phase change material (PCM). The melting and freezing temperatures of the GcN foam saturated with paraffin were increased and decreased respectively as compared to pure paraffin. The latent heat and specific heat of the GcN foam saturated with paraffin is decreased by 30% and 34% respectively as compared to pure paraffin. The thermal management for Li-ion batteries is also compared among five materials: nickel foam, paraffin wax, GcN foam, nickel foam saturated with paraffin and GcN foam saturated with paraffin. The battery surface temperature rise is 17% less using graphene coated nickel foam saturated with PCM as compared to using nickel foam under 1.7 A discharge current.

1. Introduction

Electric vehicles (EVs) and Hybrid electric vehicles (HEVs) are a developing market and an attractive substitute for traditional vehicles, particularly because of their lower environmental hazards and fuel intake [1]. However, there are still some specialized developments required to make EVs and HEVs more effective and attractive for purchasers. Cost, weight, battery life and driving range are a few of the foremost problems with HEVs and EVs [2]. Lithium ion (Li-ion) batteries have become an integral part of HEVs and EVs due to their prolonged life and high energy density [3]. Li-ion batteries generate excessive heat during operation due to their high power and energy densities. There is a requirement for efficient and compact thermal management systems (TMSs) to manage their extreme temperature upsurge. Active TMS [4,5] and passive TMS [6,7] are two popular thermal management techniques.

Tran et al. designed heat pipe modules for thermal management of lithium ion batteries [8]. They found that the heat pipe coupled with different ventilation arrangements proved to be a favorable thermal management solution for HEV batteries. Greco et al. developed a 1-D transient model combining a thermal heat pipe model with a thermal circuit [9]. They proved that the temperature of the lithium ion batteries dropped from 52 °C to 28 °C by using the 1-D transient model. Mohammadian et al. embedded aluminum foam into the heat sink to cool the lithium ion batteries [10]. They found that the surface temperature of lithium ion batteries was significantly reduced after using aluminum foam inside the heat sink as compared to the case without aluminum foam. Zhao et al. used a liquid cooled cylinder to cool lithium ion batteries [11]. They found that the surface temperature of 42 cylindrical batteries was kept under 40 °C by use of a liquid cylinder. All the active cooling approaches mentioned above are expensive due to the addition of heat pumps, heat sinks, fan components, etc.

An alternative technique, passive thermal management (e.g. a phase change material), has become an attractive approach in recent years as it is highly efficient, compact and lightweight. Phase change materials (PCMs) store thermal heat in the form of sensible and latent heat,

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Nomenclature

c_p	Specific heat capacity [J/(g.K)]
d	Thickness [m]
E	DSC calorimetric sensitivity
H	Enthalpy [J/kg]
k	Thermal conductivity [W/(m.K)]
M	Mass [kg]
r	Radius [m]
T	Temperature [°C]
t	Time [s]
V	Volume [m^3]

Greek symbols

α	Thermal diffusivity [m^2/s]
β	Impregnation ratio [-]
ε	Porosity [-]
ω	Pore density [PPI]
γ	Surface energy [J/m^2]
ρ	Density [kg/m^3]

Subscript

f	Fluid
l	Liquid
m	Melting
s	Solid

Abbreviations

A	Ampere
Ah	Ampere-hour
C	Charge/discharge rate
CVD	Chemical vapor deposition
DAQ	Data acquisition system
DSC	Differential scanning calorimeter
EV	Electric vehicle
GcN	Graphene coated nickel
HEV	Hybrid electric vehicle
PCM	Phase change material
PPI	Pores per inch
RT	Rubitherm
S	Series

mainly in the latent heat form due to the large latent storage capacity i.e. water, paraffin wax, etc. PCM changes state from solid to liquid or liquid to gas or vice versa at almost constant temperature during latent heat storage. PCMs classified as TMSs should be low cost, non-corrosive and with large latent heat [12]. PCMs also have benefits over other storage materials (e.g. refrigerants, water, glycol, oil, etc.) due to their low volume expansion, being non-poisonous and non-explosive nature [13]. It is also worth mentioning that common PCMs suffer from very low thermal conductivity (~0.1–0.3 W/(m.K)) [12]. The heat storage rate is affected by the low thermal conductivity of the PCMs. Many techniques have been mentioned in the literature to improve the thermal conductivity of PCMs. Goli et al. used graphene-paraffin composite to improve the thermal conductivity of a pure PCM [14]. They found that thermal conductivity of a graphene/paraffin composite reached 45 W/(m.K) as compared to 0.2 W/(m.K) of pure paraffin. They also observed that temperature rise of the lithium ion batteries using graphene/paraffin composite was 16 °C as compared to 37 °C with no graphene/paraffin wax composite under a 5A discharge current. Kizilel et al. used a graphite matrix to increase the thermal conductivity of paraffin [15]. They observed that the paraffin-graphite matrix had a thermal conductivity of about 17 W/(m.K). They found that hybrid PCM facilitates a uniform temperature for lithium ion batteries under normal and stressed conditions. Aadmi et al. enhanced the thermal conductivity of epoxy resin by 3–4 times by loading the paraffin wax inside metal hollow tubes [16]. They found that a higher energy storage capacity and lower temperature rise can be obtained by increasing the paraffin wax content in the composite. Zhang et al. used graphite nanoplatelets (GnPs) and found that the thermal conductivity of polyethylene glycol was enhanced by 9 times at 8% GnP mass ratio [17]. They also observed that the latent heat of the composite decreased as the concentration of GnP increased. Microcapsules, carbon fibers and nanoparticles have also been used to increase the thermal conductivity of paraffin wax as a PCM [18–20].

Metal foams have also been proven to be a viable option in enhancing thermal conductivity of PCMs. High porosity, good thermophysical properties and mechanical strength are salient features of metal foams. Li et al. [21] utilized a copper foam-paraffin wax composite to study the performance of the thermal management system of a 10 Ah Li-ion battery pack. They compared the result with two modes: natural air convection and pure paraffin. The battery surface temperature was 29% and 12% lower after using copper foam-paraffin wax composite as the thermal management source as compared to the air convection mode and the pure paraffin respectively under 1C discharge rate. Hussain et al. used a nickel foam-paraffin composite to experimentally investigate the battery surface temperature of a 3.4 Ah lithium ion battery pack [22]. They found a decline in battery surface temperature by 31% and 24% as compared to natural air and pure paraffin mode respectively under 2C discharge rate. Samimi et al. observed a drop of 15 °C in battery surface temperature after using a carbon fiber-paraffin wax composite [23]. They obtained an increase of 81–273% in thermal conductivity of composite material as compared to pure paraffin. Sabbah et al. utilized graphite to enhance the thermal conductivity of paraffin wax [24]. They treated an electric heater as a battery. They found that heater surface temperature was 5% lower by

Table 1
Summary of metal foams used to enhance thermal conductivity of paraffin wax.

	Metal foam	Paraffin melting temp. (°C)	Thermal conductivity of pure paraffin W/(m.K)	Thermal conductivity of metal foam-paraffin composites W/(m.K)	Nature of measurement
Khateeb et al. [25]	Aluminum	41–44	0.2	44	Theoretical
Wang et al. [46]	Aluminum	46–52	0.2	46	Theoretical
Li et al. [21]	Copper	42–49	0.2	11	Theoretical
Xiao et al. [27]	Copper	60–62	0.3	5	Experimental
Hussain et al. [22]	Nickel	38–41	0.2	2	Theoretical
Xiao et al. [47]	Nickel	60–62	0.4	2	Experimental
Ji et al. [48]	Ultrathin-graphite	58.9	0.2	4	Experimental
Sabbah et al. [24]	Expanded Graphite	52–55	N.A.	17	Theoretical
Fathabadi [49]	Expanded Graphite	58–60	0.2	17	Theoretical