Phase-change materials (PCM) for automotive applications

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Abstract

In this paper, an extensive review of battery thermal management systems (BTMSs) such as phase-change materials (PCMs) in the state of art is proposed. Nowadays, PCMs are particularly attractive and chosen as one of the most interesting cooling system in terms of high-energy storage density. In addition, they are less bulky, complex and expensive than traditional cooling methods such as forced-air cooling or liquid cooling. Nonetheless, the integration of PCMs in a battery application calls for an analysis that will enable the researcher to proposed optimized BTMSs. Indeed, due to the lack of literature in this domain, the paper proposed to review all the existing studies on battery applications involving PCMs. Numerical analysis description, heat transfer theory along with the classification of the existing components for PCMs are also presented. This paper is based on previous reviews to help to update the thin number of references, which is considered by the authors as the major contribution.

Keywords: Phase-change material, automotive application, cooling system, battery system.

1. Introduction

Dwindling natural resources and global climate change are currently two of the most important challenges in the world. They drastically our way of living, thinking and working to make more eco-friendly changes. In this regard, fingers have been pointed toward automobile manufacturers because the current way of transport with the internal combustion engine (ICE) has to innovate even more related to a clean environment [1]. Thus, under the pressure of energy short age and environment pollution, hybrid vehicles (HEVs) and electric vehicles (EVs) have emerged as the first step and make nowadays the transition possible to the fully electrification of the automotive sector in the future [2, 3, 4, 5]. However, EVs and HEVs meet today still some restrictions related to autonomy [6], price [7], charge time [8] , local charge possibilities [9], lifetime battery [10], comfort aspects related to the cabin [11],... The majority of the problems are related to the battery system, which is the most crucial and expensive component of BEVs [12]. Accordingly, one crucial aspect for market penetration is the improvement of the power performance and lifetime of the battery system. To help the market penetration, large-scale battery system and endurable high-current rate are required to improve the power the energy embedded in EVs HEVs.

Nonetheless, at high-current levels, these batteries produce much heat during operation such as quick ac- celeration, long-discharge cycles or rapid charge [13, 14, 15]. Then, the safety risks, overheating ,and explosions become critical as they increase with the amount of thermal energy contained within the battery or whole system [16, 17]. In a less drastic way, uneven temperature distribute reduces the battery or pack's cycle life excessively [18, 19]. In brief, the batteries must operate between certain boundaries for optimal performance, lifetime and safety considerations. Therefore, a battery thermal management

system (BTMS) as part of the whole battery management system (BMS) needs to be implemented to maintain the operation temperature of the batteries between those limited boundaries. Depending on the application area and the type of battery, cooling and or heating are is required to work in the right temperature operation range. Two traditional BTMSs have been extensively investigated for automotive applications:

1. Forced air cooling [20, 21, 22, 23]
1. Direct indirect cooling fluid media [20, 24, 25, 26, 27].

Natural air-cooling is always indirect and natural convection is generally not adequate for a sufficient battery cooling [28] This is the reason that a fan is typically used for air cooling to create forced convection. Around the year 2000, preconditioned cabin air is used for heating cooling the HEVs, for example, Honda Insight and Toyota Prius [29]. In 2012, Nissan LEAF owners in Arizona were less enthusiasm for their electric vehicle [30]. The Leaf's power system relying only on air-cooling was losing battery capacity at a faster rate than advertised. The battery system uses essentially a single fan to distribute heat evenly throughout the interior of the sys- tem. In severe conditions, (about 50-60✍ C in Arizona), due to the lacking of an optimized thermal management system, the region's heat is draining the EVs' battery capacity and the driving range is nearly cut in half.

Fluid cooling with direct contact uses the coolant as media against the surface of the cell. This method is commonly applied when the thermal management has to be more elaborated. However, both methods intro- duce some disadvantages such as a level of complexity for the design because of the additional spaces in the vehicle used by the cooling system (i,e. fans and pumps) [28]. As proposed in this work, novel thermal management system (TMS) can be achieved by overcoming the disadvantages of the traditional techniques. One of them is passive cooling with phase-change material (PCMs).

PCMs introduce a less complex level of the battery design [28]. Indeed, the cells of the battery system are surrounded by this material and they use latent heat storage to regulate the temperature. Latent heat substances are systems that can capture and release the generated heat during the melting and solidification of the PCMs [31, 32].

Extensive reviews on the application of PCM types have been published by [33, 34, 35, 36, 37, 38]. Nonetheless, it may be mentioned that in the literatures that there are less than few comprehensive reviews on PCMs for battery applications. Therefore, the objective of this paper is to propose an elaborated review of passive cooling heating for battery applications. The paper is built on previous reviews [32, 31, 11, 39] to update the references.

First, in Section 2, it presents the fundamental classification of PCMs with their thermal properties and definitions. Then, it provides in Section 3, considered by the authors as the major contribution, overall review of all the automotive applications that combine PCMs and battery pack with a description of the modeling is- sues regarding PCM in a battery pack. At the end, a synthesis is provided in Section 4 to form a conclusion on these topics.

2. Phase-change materials

2.1. Thermal energy storage system overview

In 1983, Abhat [40] wrote an extensive review on thermal energy storage (TES) with the focus on PCMs, thermal conduction and its applications.

This classification, together with some other classification given by Zalba [33] gave good insights on the substances used for TES, as illustrated in Fig.1. According to Abha's classification, energy storage may be in the form of sensible heat in a liquid or solid medium, as chemical energy or products in a reversible chemical reaction, or as heat of fusion (latent heat).

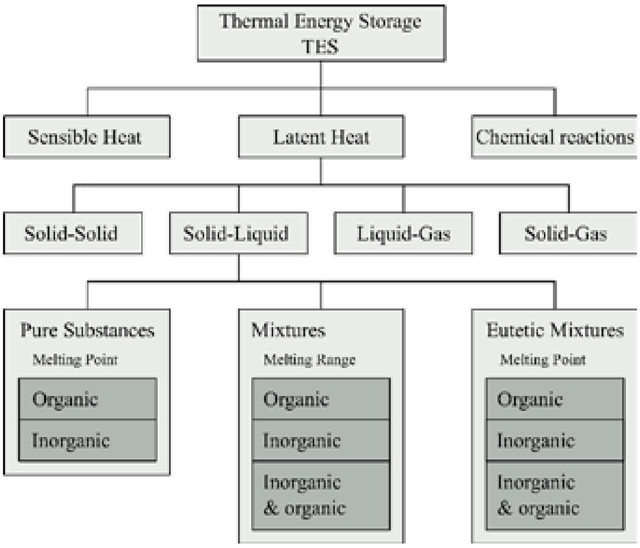

Figure 1: Classification of thermal energy storage systems and com- parison of the PCM latent heat with various materials [12].

The first class called sensible heat uses the specific heat capacity to store thermal energy. Un- fortunately, because the specific heat capacity of most materials is generally of two orders of magnitude lower than its latent heat, sensible heat storage is obsolete in a thermal management system. In deed, studies compar- ing the sensible heat and latent heat storage have con- clude that a larger storage volume is required employing sensible compared to latent heat [4].
For example, in Morrison and Abdel-Khalik [5], the authors showed that seven times the storage volume of Paraffin 116 Wax is required compared to rock (sensible heat storage element)

Chemical reactions. The second class of TES is the en- ergy storage in chemical reactions. This class has been investigated by Yan et al. [6]. They gave an interest- ing comparison between the advantages and disadvan- tages of chemical heat storage and the other TES. Ac- cording to them, energy storage through chemical pro- cesses possesses a long-duration potential ability as well as high energy storage density. Unfortunately, the setup is rather bulky and complex because it requires one or two reaction chamber for the di☛erent reactant which is the reason why chemical energy storage has not as yet been used in practical applications.

Latent heat. The last class are phase change materials. One of the most obvious benefits is the constant tem- perature (for pure substances) at which these processes occur. Phase change typically refers to the solid, liq- uid or gas phases. The energy utilized to change from one to the other phase is referred to as latent energy and many material have been studied as potential phase-change element, they are referred to PCMs. PCMs are of great use to store energy or to control the temperature of an element swings within a specific range. Basically, PCMs absorb heat in an endothermic process when the temperature rises, and changes phase from solid to liq- uid. Hence, PCMs have a great potential for heating and cooling in battery applications [7]. Depending on the targeted application, different initial states of PCMs are selected, namely: liquid-gas, solid-gas, solid-solid and solid-liquid.To illustrate their thermal storage potential Fig. 1 shows the heat store capacity compared to sensi- ble heat (over 15^{0} C difference).
The latent energy in liquid-gas transition is typically one order of magnitude higher the energy for the solid- liquid transition. The liquid-gas transition is however less practical resulting from the

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volumetric expansion. The liquid-gas transition is mainly used for heat extrac- tion with heat pipes
The solid-gas phase change requires a large amount of latent energy but is not always practical to apply in the application of battery thermal management.

The third class utilizing latent energy storage are the solid-solid TES. Since a solid is defined as a material with a crystalline structure and many crystalline struc- tures exist, it is not di✍cult to imagine a phase change from one to another structure [45].

The last class of PCM is the solid-liquid PCM, one of the most widely-used latent heat storage system used in many applications [8] specially in automotive application. For this reason, this paper focuses on the review of solid-liquid PCMs as shown in Fig. 2 and they are explained deeply in the next subsection.

2.2. *PCM classification*

Nowadays, solid-liquid PCMs show the highest po- tential in battery thermal management applications [47, 28]. As it can been seen in Fig. 2, where a classification of PCM is displayed, three main classes of PCMs can be dierentiated: organic, inorganic and eutectic.

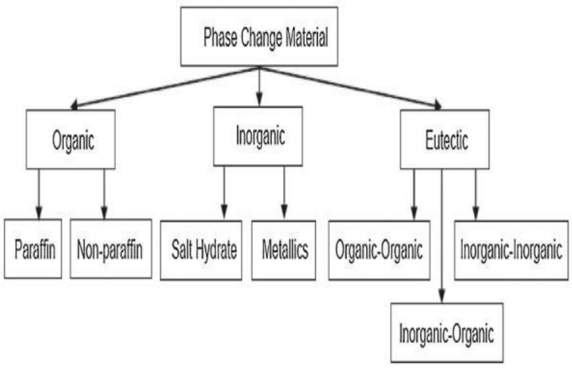

Figure 2: Classification of PCMs

2.2.1. *Organic PCMs*

Organic PCMs can be paeans and non-pagan, the former involves fatty acids, alcohols, ester, glycols, etc [39]. They are rather stable, safe, have a high latent heat of fusion (✕ 180 kJ\kg [12]) and also they are avail- able in large temperature range (15-45✍ C [10]) which makes them compatible with most construction materials [31]. However, these PCMs are also flammable [39], can be toxic and have low thermal conductivity (0.1-0.35 W (m.K) [11]. Examples of organic PCMs are paraffin wax and fatty acid. Fig. 3 shows an organic PCM from Rubitherm Technologies GmbH.

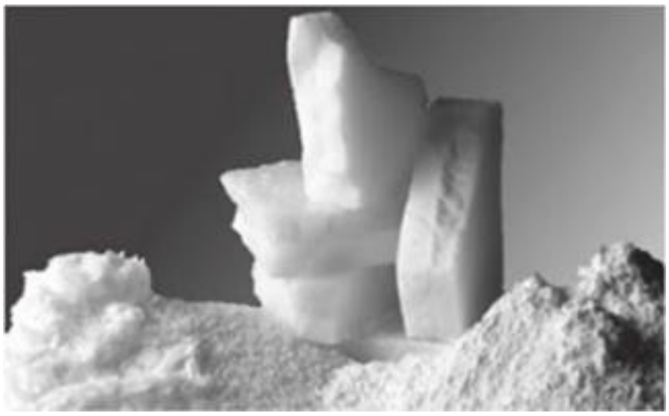

Figure 3: Picture of an organic PCM

Parafinn

Parafinn wax is a mixture of long alkane chains, the chemical formula for these molecules is $CH_3(CH_2)_nch_3$, with n the number chains often some cyclo-parafinn and iso-parafinn are also part of the mixture [9]. Its actual melting temperature depends on the chain length, the shorter the chain length, the higher its melting temperature,thus, a large range of melting points is available. How- ever, their low thermal conductivity (about 0.2 W(m.K)) constraint their full market penetration for automotive applications. Nonetheless, parafinn

Inorganic PCMs

Inorganic PCMs are by name composed of inorganic molecules, the typical examples are hydrated salts and metallic PCMs. Inorganic materials have attractive characteristics, not only they propose a wide melting temperature range (5-130 C)[53], they are also therwax has been used in the battery field [48, 49]. In mally safe and have a high latent heat rate[50], Babapoor et al., proposed an organic PCM for Li-ion battery in a battery system on order to uni- form the gradient temperature among the cells. A parafinn-based

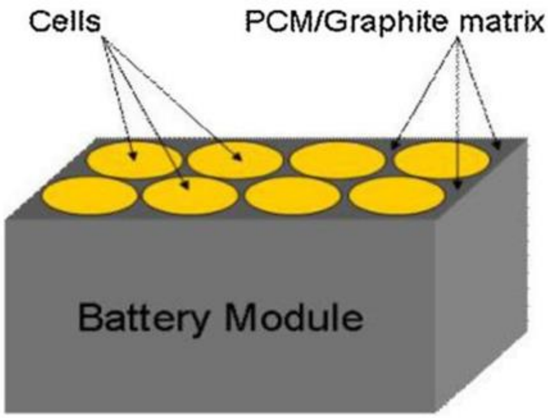

Figure 4: (a) Optical image of the resulting molded disks of the hybrid graphene-PCMcomposite.(b)Correspond scanning

Applications	PCM properties	Reference
Cylindrical NiMH and rectangular lithium-ion batteries	PCM✳graphite matrix	[19]
For a large lithium-ion battery pack targeting at HEV✳EV	PCM✳graphite matrix	[23]
	PCM✳graphite matrix module	[32]
	PCM✳aluminium foam	[44]
	PCM✳copper metal foam	[49]
Cylindrical rectangular lithium-ion batteries	PCM✳graphite matrix	[91]

was chosen as phase-change mate- rial and the of PCM fiber length was investi- gated. Results showed that using 2-mm long fibers leads to the best thermal performance. Longer fiber lengths cannot reject the in a uniform way. Additionally, in order to show possible enhance- ment of thermal properties of Paraffin wax, Goli et al., demonstrated the combination of the mix- ture between Paraffin and graphene (carbon fibers) [51]. A micro-Raman spectroscopy (Renishaw In-Via) was used for the intercalation of graphene into parafinn matrix, as it is shown in Fig. 4. Exper- imental data showed that the initial parafinn-PCM increased its thermal conductivity by more than two orders of magnitude while preserving its latent heat storage ability. The improvement was done by the mixture of graphene fiber to Paraffin hy- drocarbones which results in a enhanced thermal binding. At the end , the described heat storage systems using Paraffin approach can lead to a inno- vative change in thermal management of Li-ion.

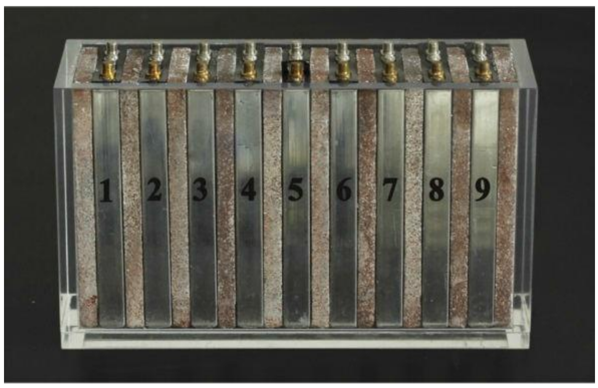

Figure 5: Battery pack design (a) using the copper foam-paraffinn composite.

Since eutectic mixtures are becoming po- tentially innovant PCMs, less than few studies report the use of this blend for automotive applications

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Table 3: State-of-the-art of PCM cooling systems for battery applications

Material	Melting point	Latent heat (kJ/kg)	Note
Emerest 2325	17-21	138-140	[31, 12]
Hexadecane	18	236	[31]
Heptadecane	18	214	[31]
KF, $4H_2O$	18	236	[31]
Butyl stearate	19	140	[31, 12]
Paraffin C16-C18	20-22	152	[31]
Paraffin RT20	20-22	172	[31]
Paraffin FMC	20-23	130	[31]
Dimethyl sebacate	21	120-135	[31]
Eutectic E21	21	150	[31]
Capric-lauric 45∗55	21	143	[31, 12]
Salt Hydrates	21	198	[31]
ClimSel C 21	21	122	[31]
Octadecane C 21	22	144	[31]
Capric-palmitate C 21	22.1	153	[31]
Paraffin RT25	24	164	[31]
$CaCl_2$	24-29	192	[31, 12]
Paraffin R27 C 21	26-28	179	[31]
SP27	27	180	[31]
Eutectic E23	29	155	[31, 12]

Figure 6: Picture of a hydrated salts

1. High latent heat, high specific heat and high ther- mal conductivity;
2. Melting point in the desired operating temperature range.;
3. Little or no subcooling during freezing;.
4. Small volume changes during phase transition;
5. Stability, non-poisonous, non-flammable and non- explosive; Available in large quantities at low cost

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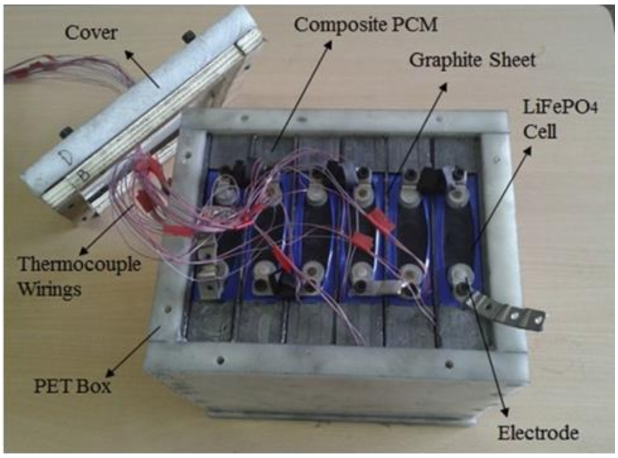

Figure 7: Battery system prototype with the passive TMS

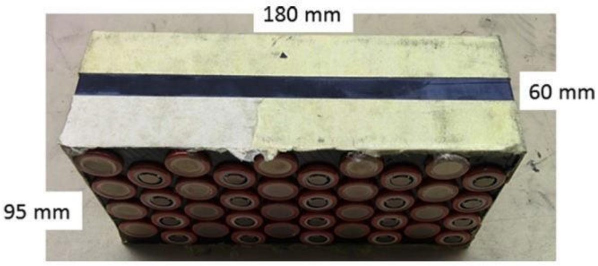

Figure 8: 18650 Li-ion cells embedded in phase-change composite

4. Conclusion

An extensive review of passive battery thermal man- agement systems in the state of art revealed the impor- tance to control the temperature for large-scale

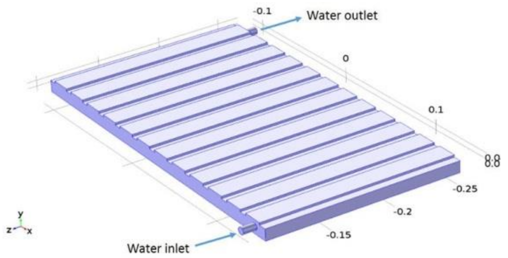

Figure 9: Geometry representation of the cooling plate

battery system in HEVs∗EVs. BTMS is very crucial to en- hance the battery operation, indeed, when the temper- ature variable is involved, the premature failure of the battery system (thermal runaways) and possible safety

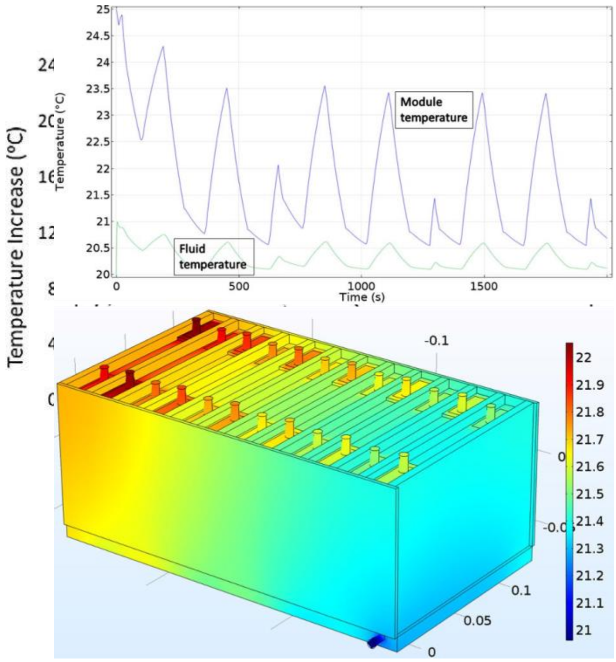

Figure 10: Temperature evolutions of the module and the water- cooling liquid with the associated 3D representation

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